Lean Six Sigma Green Belt Training Developed for Starbucks Corporation

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Lean Six Sigma Green Belt Course
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Course Outline with Slide Numbers

1 Lean Overview

The goal	• Provide the greatest value for customers using the fewest resources
The methods	• Principles and practices based on the Toyota Production System (TPS)
The barrier	• Culture always defeats methodology
The path forward[*]	• Create a culture of continuous improvement (*kaizen*) • Integrate improvement cycles into the daily work of all employees • Improve all processes, every day

[*] See **Toyota Kata** (2010) by Mike Rother.

Basic principles of Lean

- *Value* is defined from the customer's point of view

  → Reduce or eliminate activities that do not add customer value

- *Value stream* — all activities required to provide a specified family of products or services to the customer

  → Organize workflows by value stream, not by department

Customer defines value

Customer value adding (CVA)

- Activities that are required, from the customer's point of view, to provide the desired products and services
- What the customer is willing to pay for
- Changes the form or function of the product
- Goal: Optimize and standardize these activities

Non-value adding (NVA)

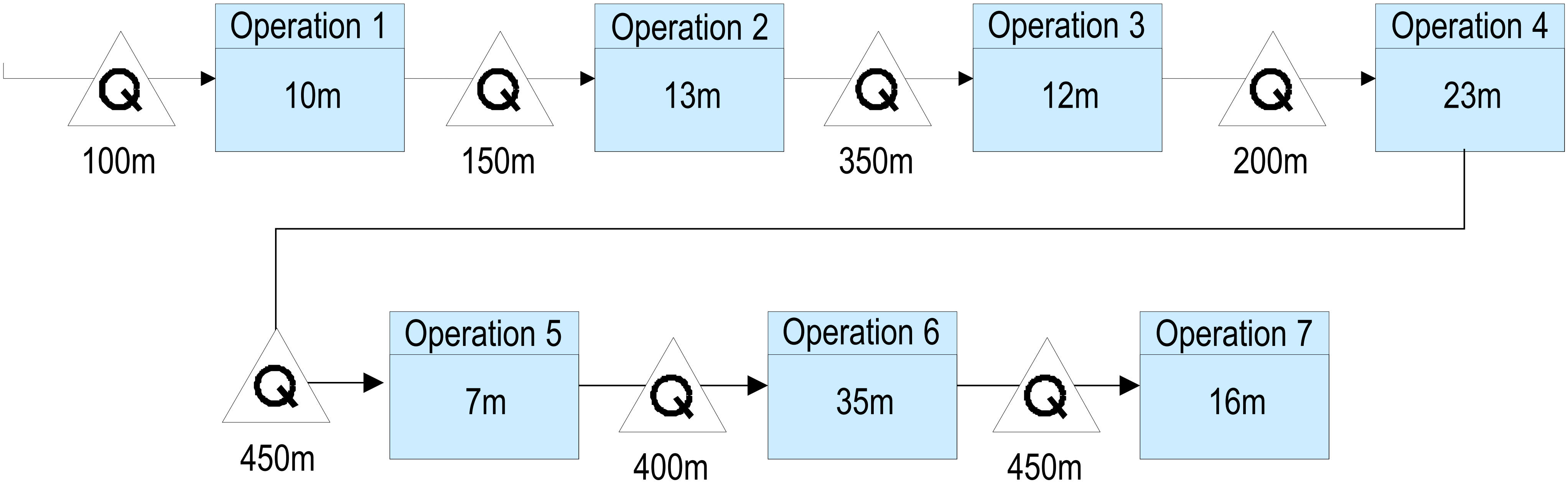
- There exists a feasible future state in which the desired products and services can be provided without these activities
- Goal: Eliminate or reduce

Non-value adding but necessary

- Activities that are not CVA, but cannot feasibly be eliminated under current constraints
- Examples include audits, reporting, regulatory compliance, etc.
- Goal: Question and reduce

Common example of CVA and NVA

Typical current state value stream



Q 100m → Operation 1 10m → Q 150m → Operation 2 13m → Q 350m → Operation 3 12m → Q 200m → Operation 4 23m

Q 450m → Operation 5 7m → Q 400m → Operation 6 35m → Q 450m → Operation 7 16m

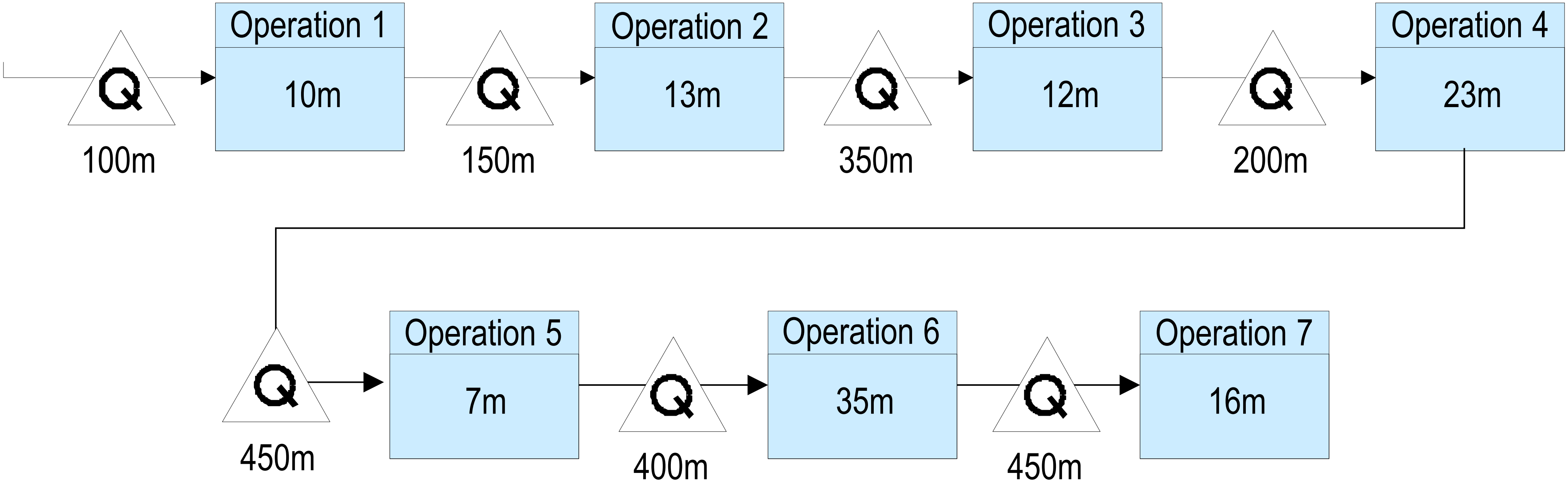
Lead time = 2,216 mins

Process time = 116 mins (5.3%)

Wait time = 2,100 mins (94.7%)

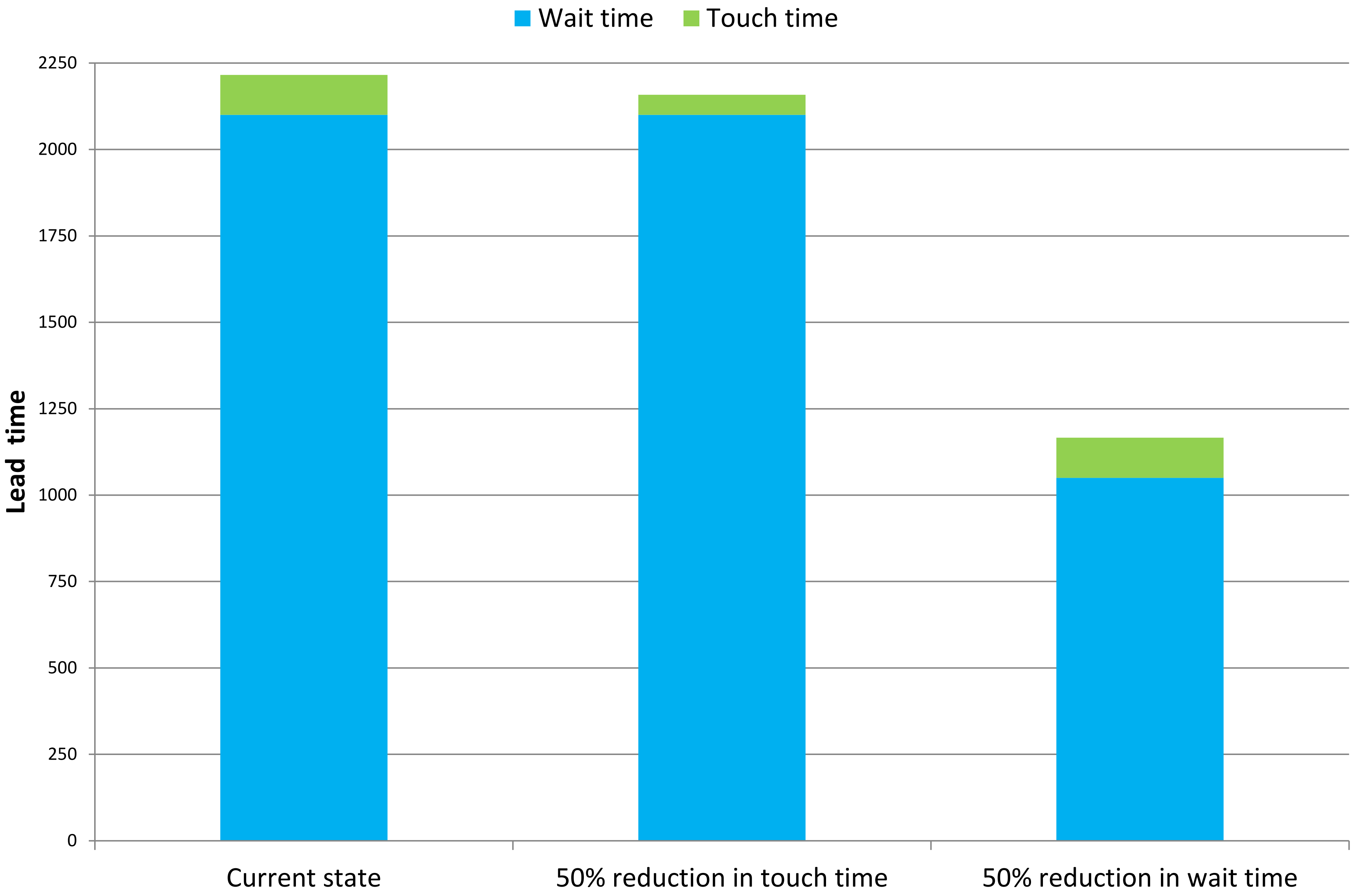
Q Queue (material or transactions waiting to be worked on) → 100% NVA

What is the priority: reducing CVA or reducing NVA?



	Current state	50% reduction in process time	50% reduction in wait time
Process time	116 m	58 m	116 m
Wait time	2,100 m	2,100 m	1,050 m
Lead time	2,216 m	2,158 m	1,166 m
Reduction in lead time →		**2.6%**	**47.4%**

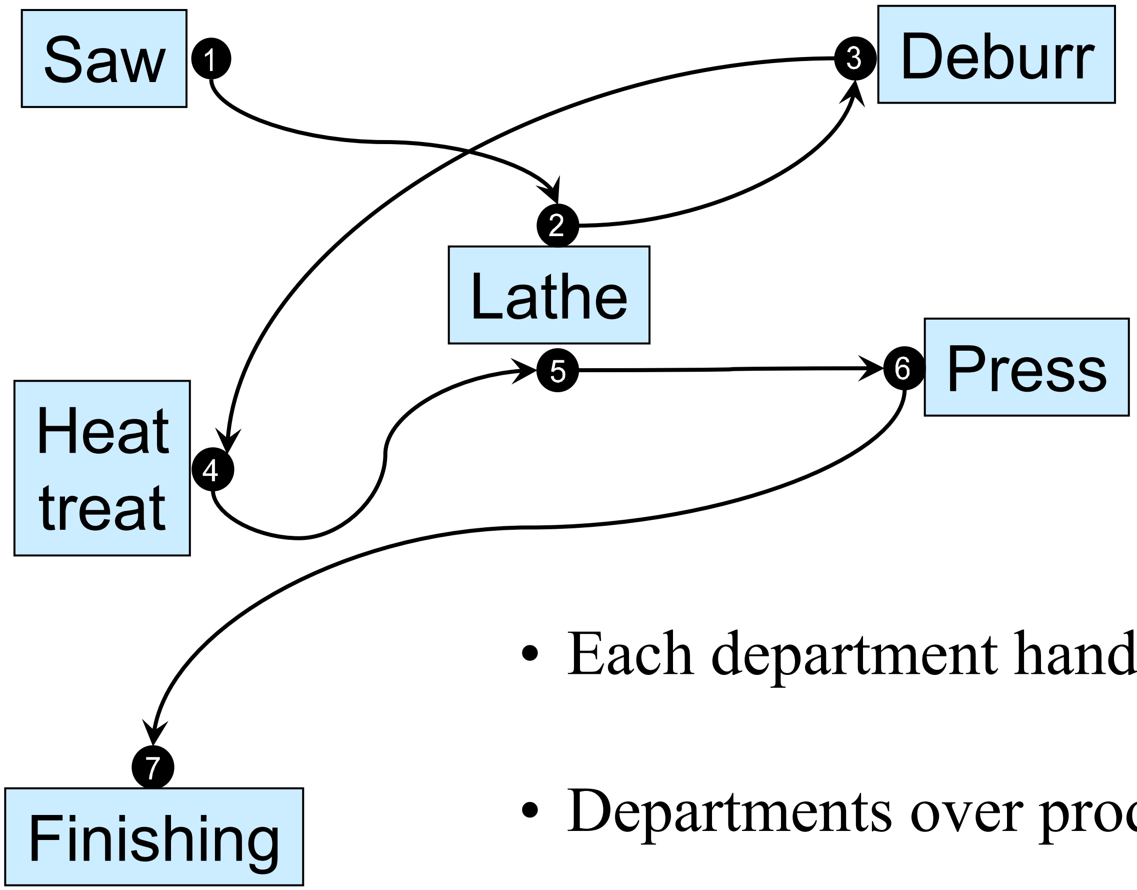
Reduce NVA, not CVA!



Categories of NVA (expanded definitions)

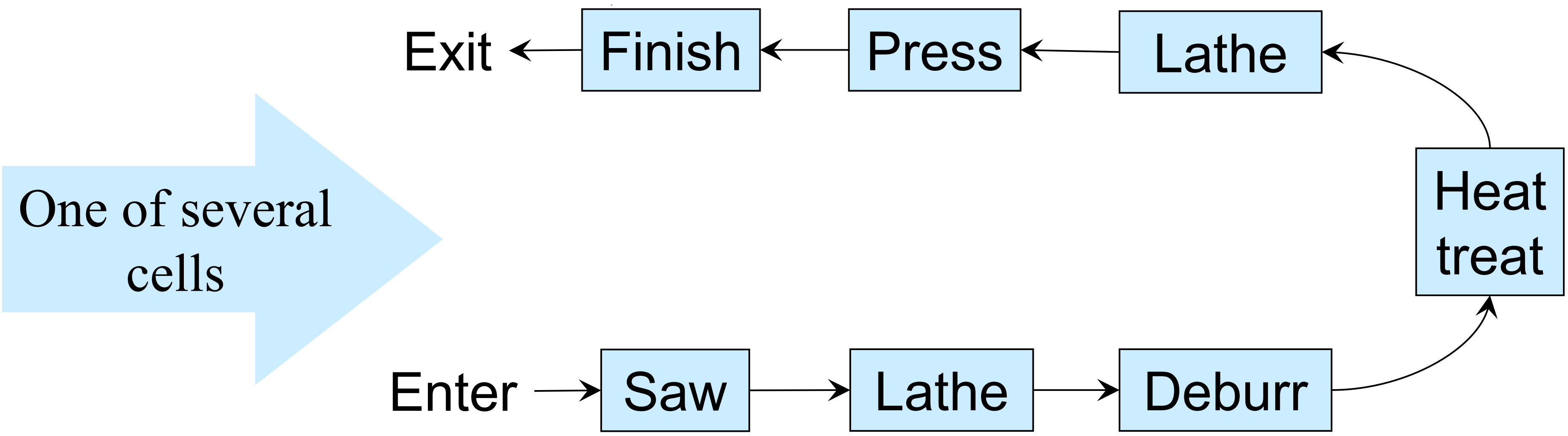
D	*Defects*: Failure to meet expected standards of quality or delivery
O	*Over production*: Making or doing more than is needed at the time
W	*Waiting*: People waiting to work, or things waiting to be worked on
N	*Not utilizing creativity*: Failure to integrate improvement cycles into the daily work of all employees
T	*Transportation*: People or things being moved from one place to another
I	*Inventory*: Supplies, WIP, or finished goods beyond what is needed
M	*Motion*: Excessive motion in the completion of work activities
E	*Extra processing*: Producing or delivering to a higher standard than is required

Example of organizing work by department



- Each department handles all products → inefficient
- Departments over produce → high levels of WIP
- WIP is valued as an asset — in reality it’s a cash sink
- WIP moves between departments in large batches → long lead times, long lags before defects are discovered
- Poor layout → excessive transport

Example of organizing work by value stream



- Each cell handles particular, similar products → efficient
- Cells produce only to current customer demand → low levels of WIP, less cash tied up
- WIP moves through each cell in small batches → short lead times
- Proximity of operations → minimal transport, defects identified immediately

2 Six Sigma Overview

- Process spread
- Pursuit of perfect quality
- Pragmatic business initiative

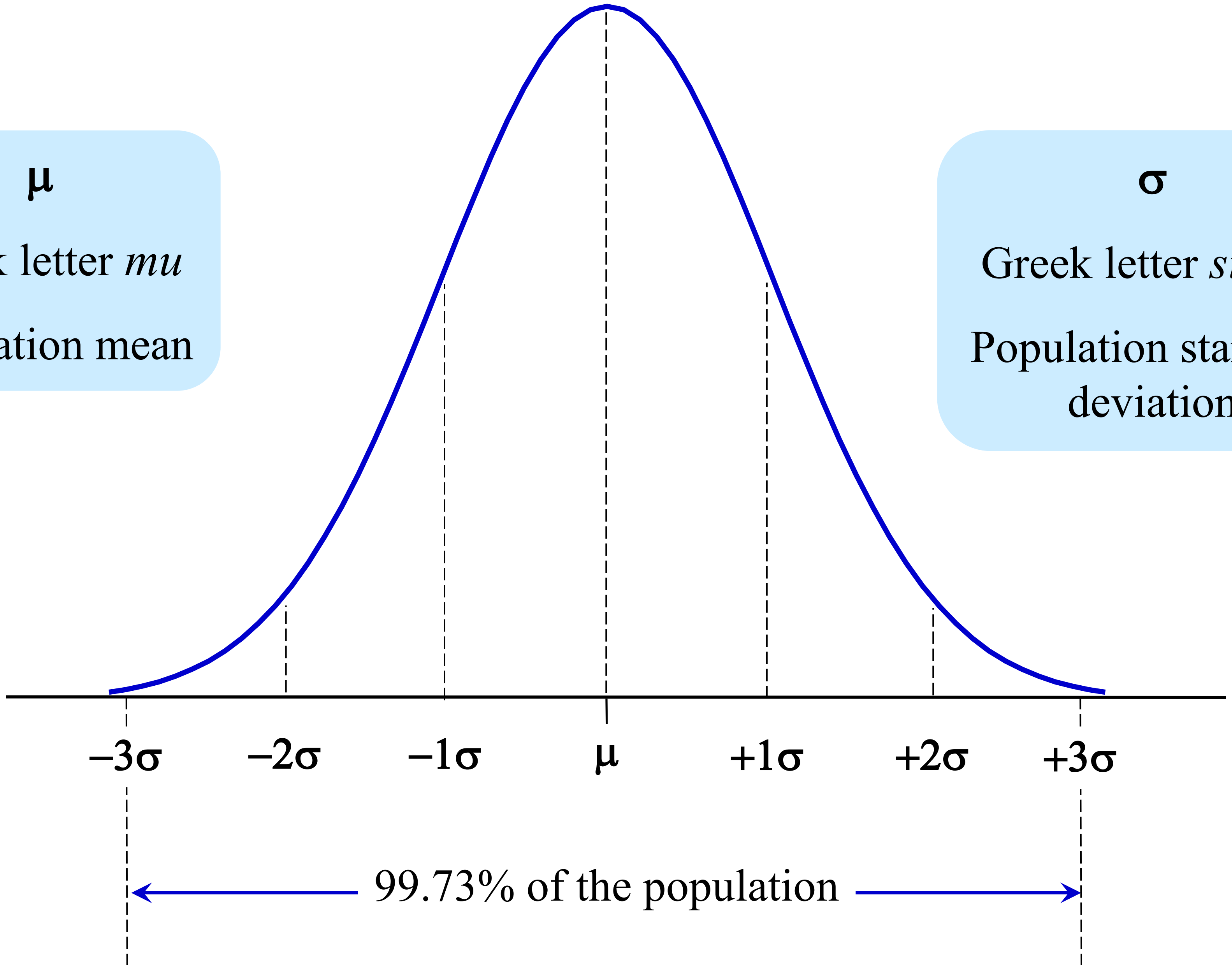
Process spread

Normal distribution (bell curve)

μ

Greek letter *mu*

Population mean

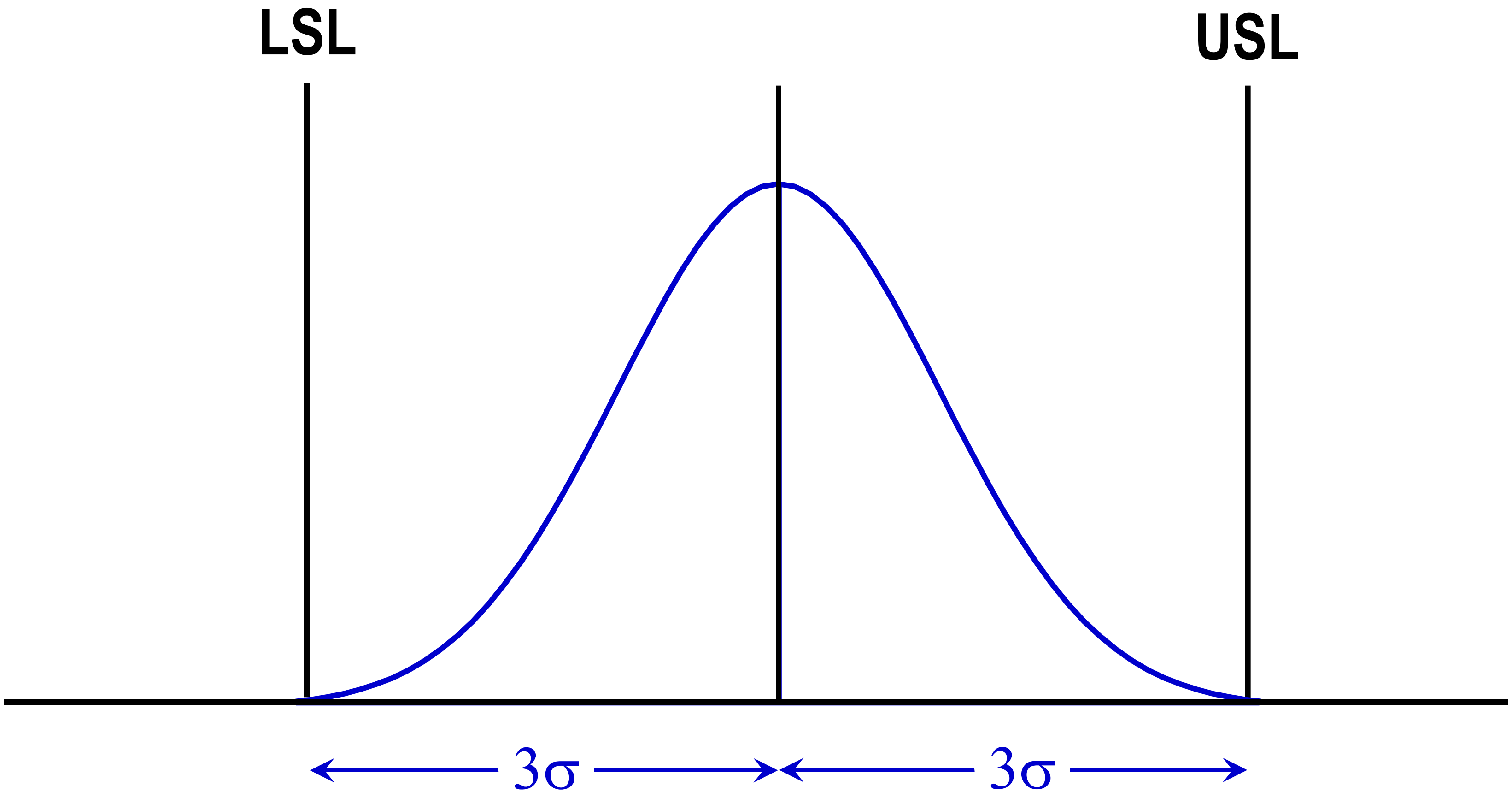


σ

Greek letter *sigma*

Population standard deviation

Process capability



0.27% defective (first pass)

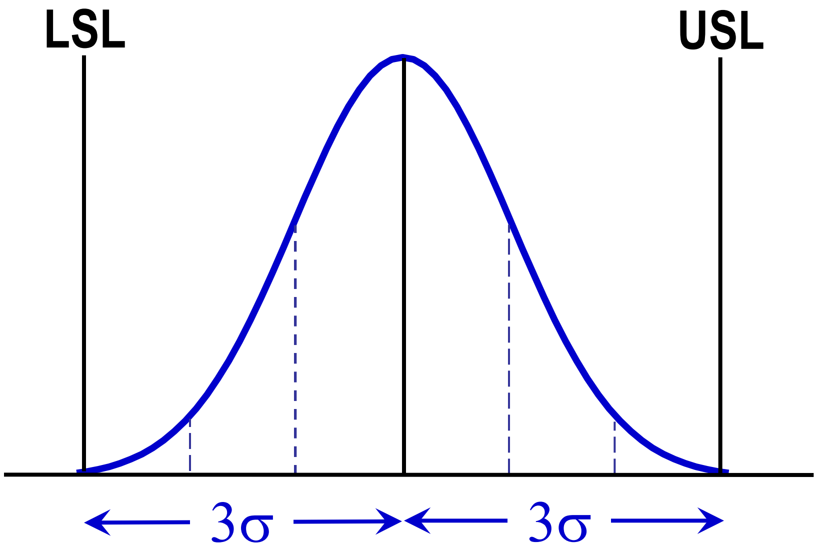
Process capability (cont’d)

USL stands for *Upper Specification Limit*, LSL stands for *Lower Specification Limit*. Specification limits represent the Voice of the Customer with regard to measureable characteristics of products or services.

For the Normal distribution shown above, the mean (μ) is equal to the midpoint of the specification range, and the process spread (6σ) is exactly equal to the width of the specification range (USL minus LSL). This means that 99.73% of product or service outcomes produced by this process satisfy the spec limits. Equivalently, 0.27% of outcomes lead to scrap, rework, do-overs, or other costly measures to prevent or respond to customer dissatisfaction.

Pursuit of perfect quality

In the 1980s, Motorola questioned the adequacy of 0.27% defective as an improvement objective



2,700 defective parts per million

2,000 pieces of mail lost each hour

20,000 wrong prescriptions per year

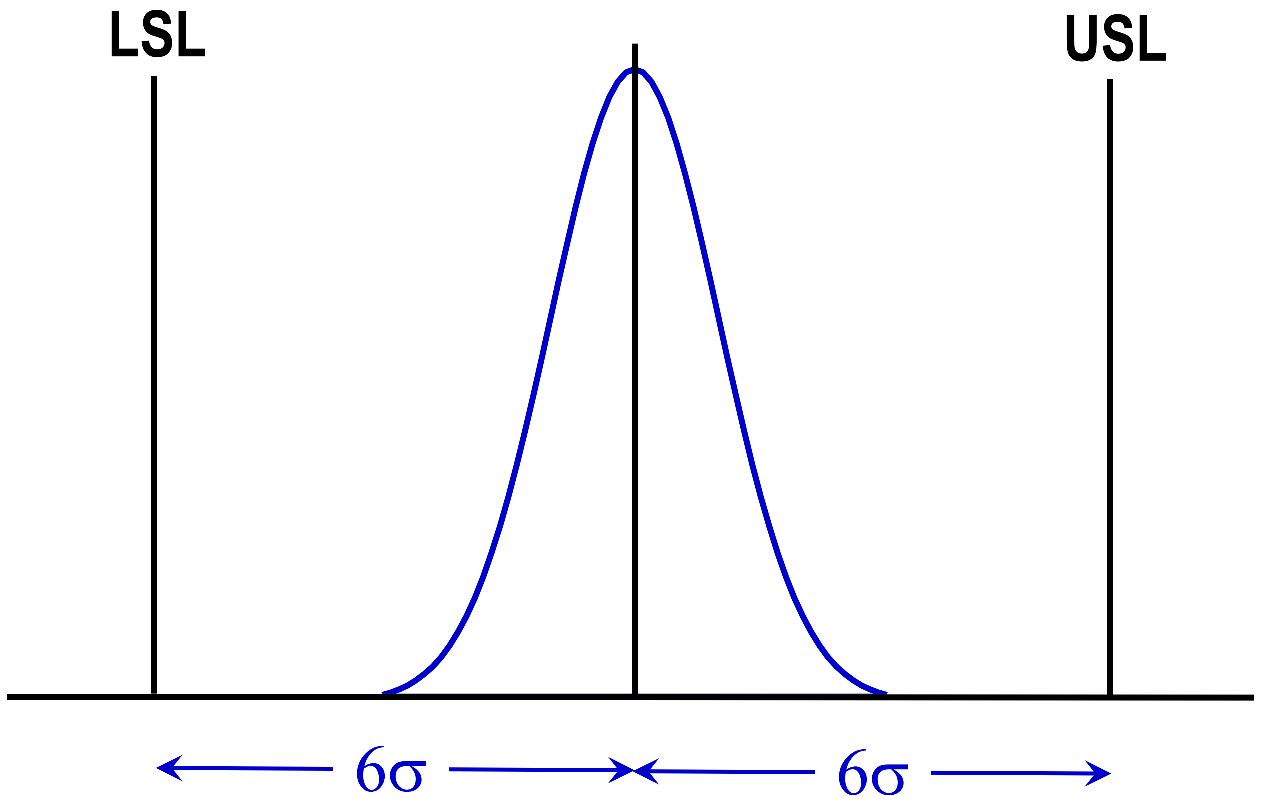
15,000 newborn babies dropped per year

No electricity or water 8.6 hours per month

500 incorrect surgical procedures each week

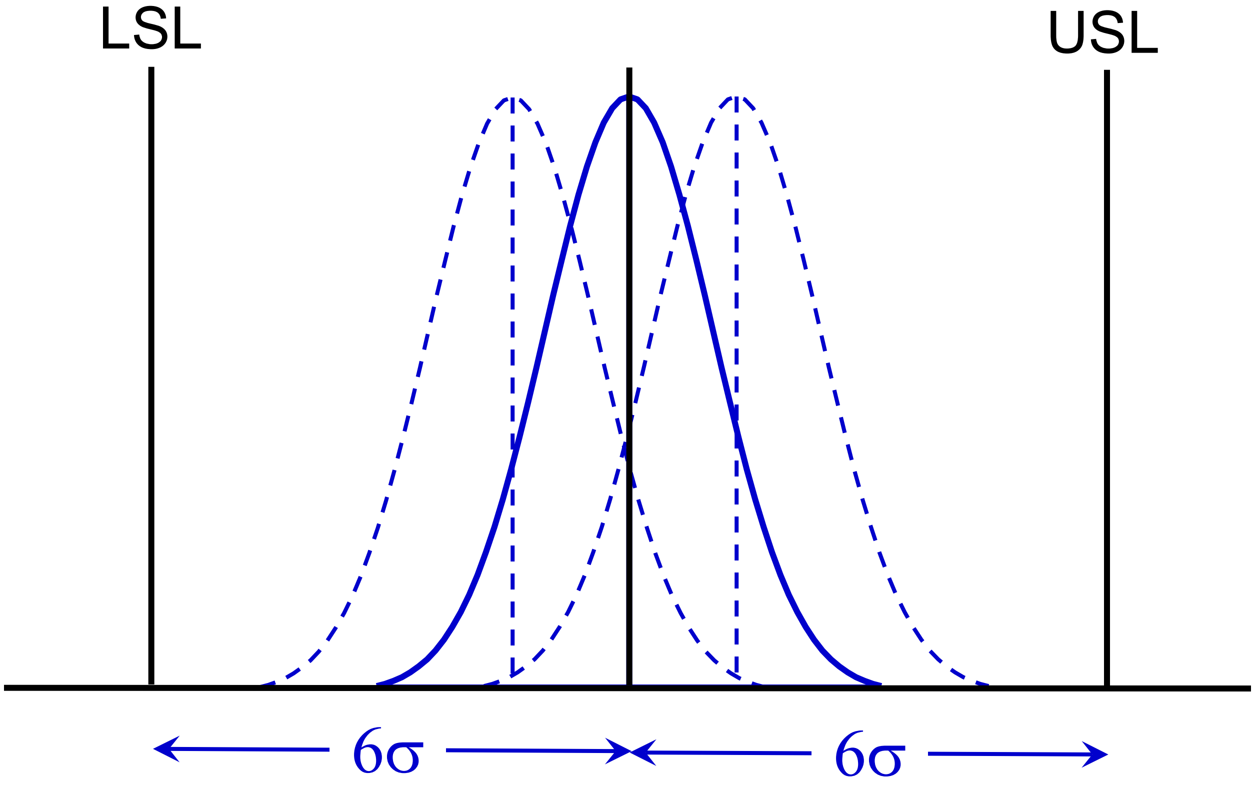
Pursuit of perfect quality (cont'd)

Motorola proposed a more aggressive objective



2 defective parts per *billion*

Allowing the mean to wander



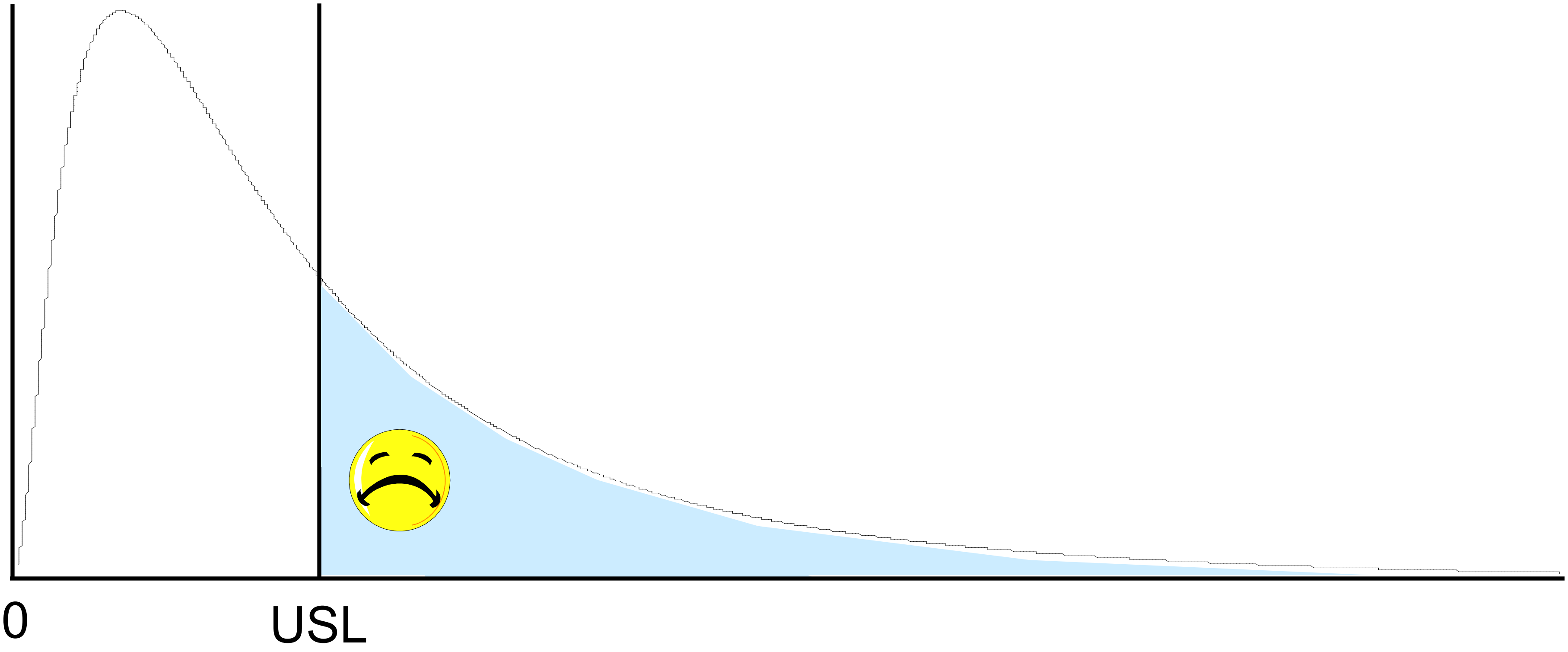
At most 3.4 defective parts per million (DPPM)

Wandering mean (cont’d)

- Motorola backed away from 2 defective parts per billion as the stretch goal
- They allowed that the process mean might wander as much as 1.5σ away from the spec midpoint
- At these extremes, the process would produce 3.4 defective parts per million (DPPM)
- The ± 1.5σ offset was somewhat arbitrary, but 3.4 DPPM became the definition of “Six Sigma quality”

Doesn't have to be a Normal distribution . . .

Before improvement project

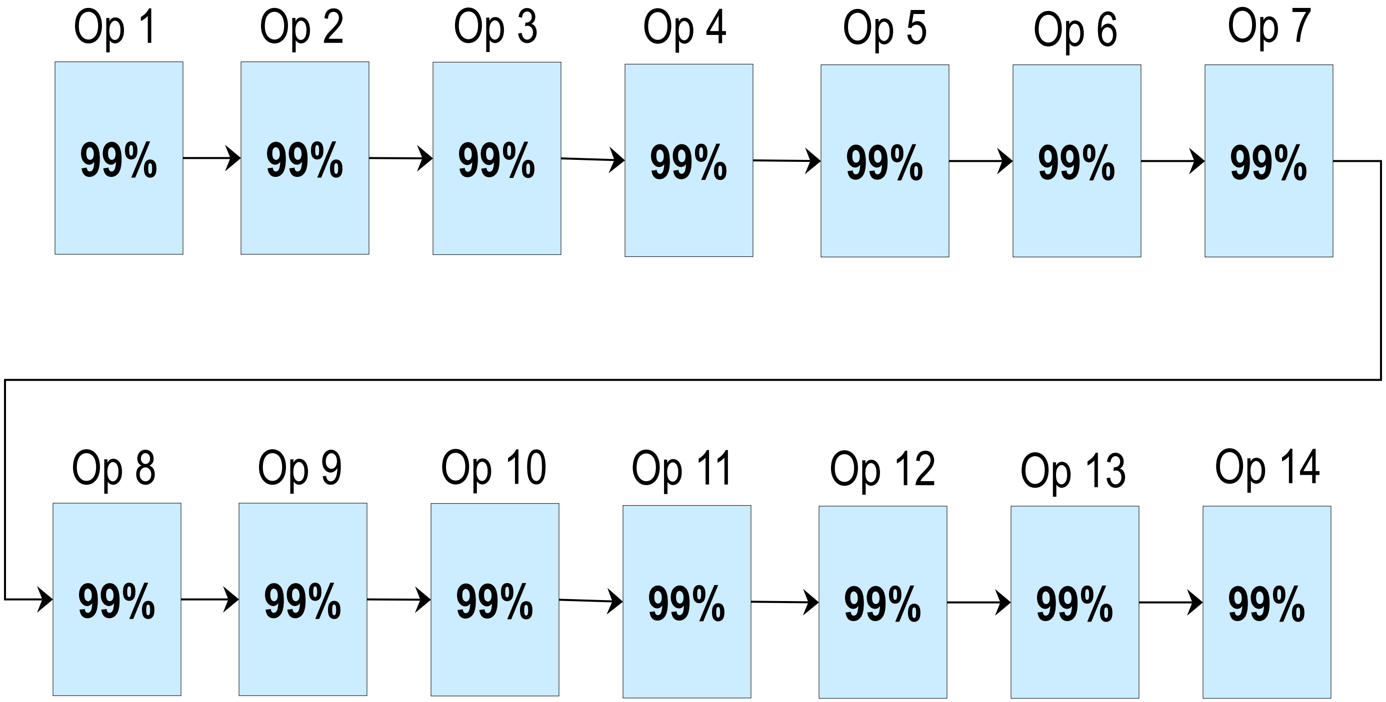


. . . in fact, often it isn't

After improvement project

Why set the quality bar so high?

Suppose we have 10,000 DPPM (99% yield) for each operation



Area manager: "Our overall yield is 99%"

Is this true?

We can’t repeal the laws of probability!

$$\text{Rolled Throughput Yield}^{*} = \text{Probability of no defect in 14 operations}$$

$$= 0.99 \times 0.99 \times \cdots \times 0.99 \text{ (14 times)}$$

$$= (0.99)^{14}$$

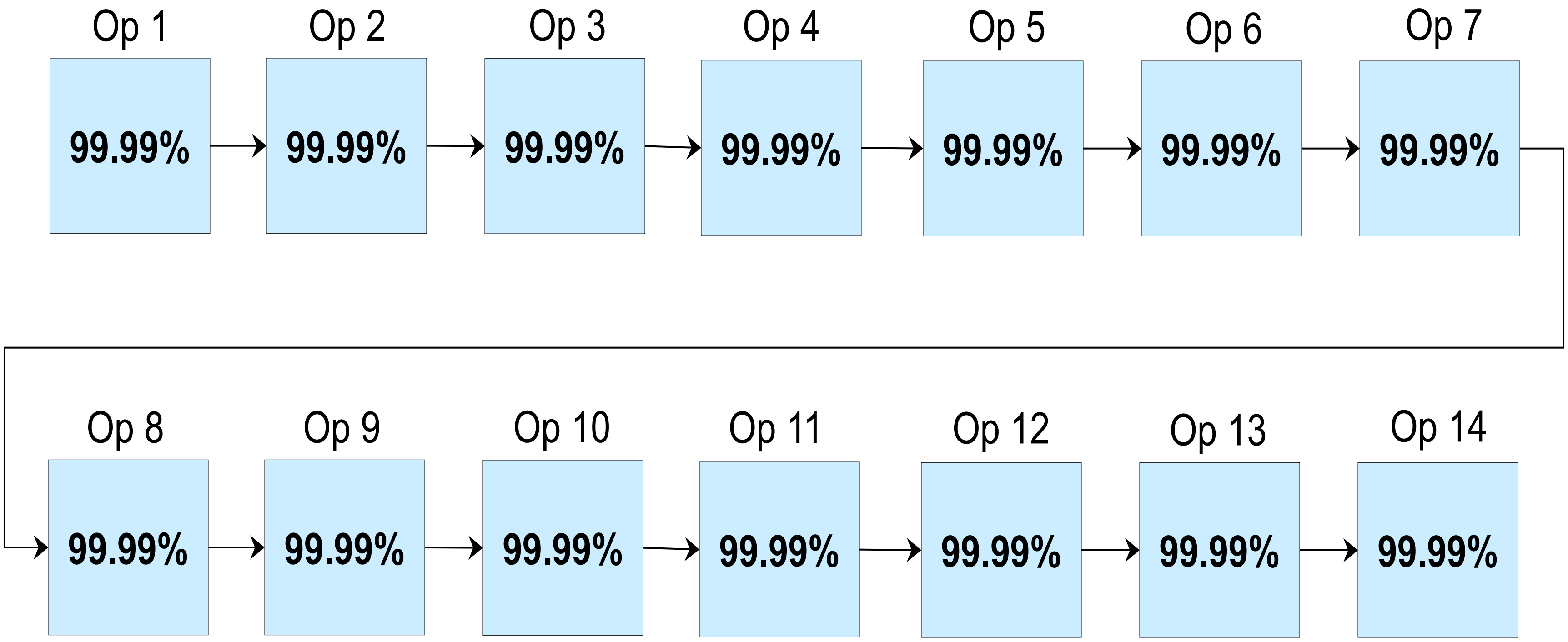
$$= 0.868746 \rightarrow 86.9\%$$

$$\boxed{131{,}254 \text{ DPPM}}$$

[*] Also known as **overall yield**, **cumulative yield**, and **end-to-end yield**

Setting the quality bar (cont'd)

100 DPPM (99.99% yield) in each operation

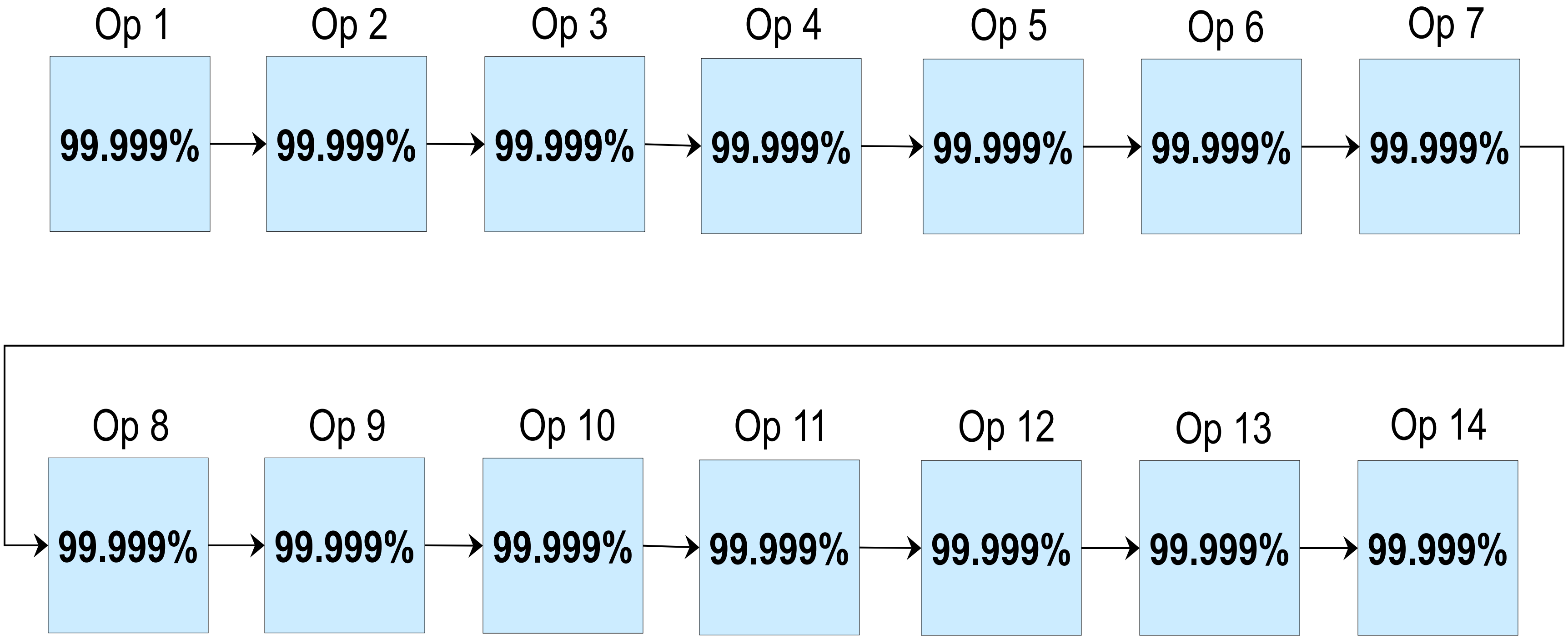


$$\text{Overall yield} = (0.9999)^{14} = 0.998601 \rightarrow 99.86\%$$

1399 DPPM

Setting the quality bar (cont'd)

10 DPPM (99.999% yield) in each operation



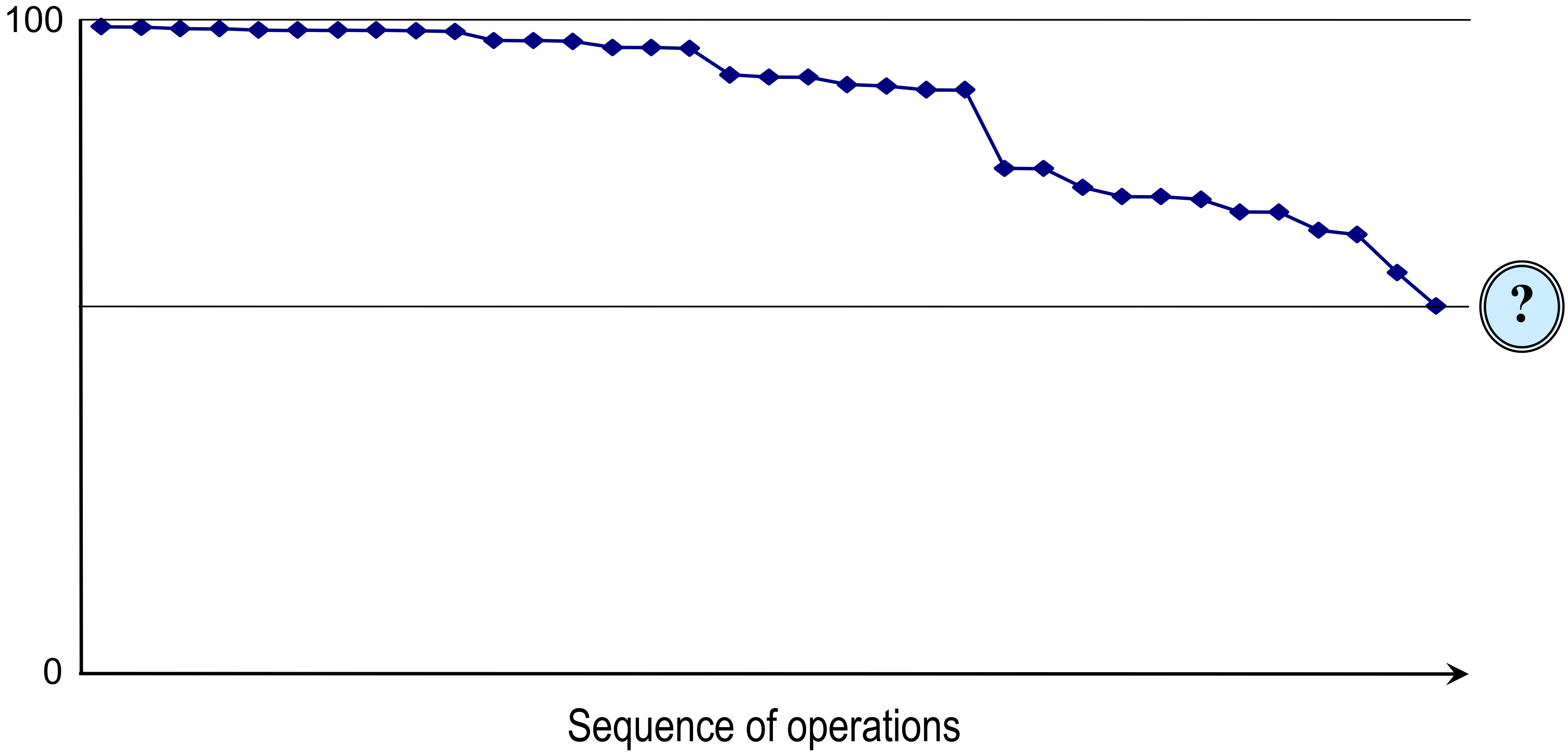
Op 1	Op 2	Op 3	Op 4	Op 5	Op 6	Op 7
99.999%	99.999%	99.999%	99.999%	99.999%	99.999%	99.999%
Op 8	Op 9	Op 10	Op 11	Op 12	Op 13	Op 14
99.999%	99.999%	99.999%	99.999%	99.999%	99.999%	99.999%

$$\text{Overall yield} = (0.99999)^{14} = 0.999860 \rightarrow 99.986\%$$

$$\boxed{\text{140 DPPM}}$$

Exercise 2.1

The average yield for 35 operations in an assembly process is 98.4%. Calculate the rolled throughput yield under the simplifying assumption that the yield for each operation is exactly equal to 98.4%. (The real answer would be the product of the actual operation yields.)



Exercise 2.1 (cont’d)

The area manager reported 98.4% as the overall yield of the operation. His reaction to the correct analysis followed the classic grief cycle:

Denial	*“This can’t be right. There must be a mistake in your calculation.”*
Anger	*“This is ridiculous. You’re wasting my time.”*
Bargaining	*“Isn’t my method just as valid as your method?”*
Depression	*‘This is really bad. What am I going to tell everyone?”*
Acceptance	*“I guess you can’t solve a problem if you don’t know you have it.”*

We can count ***defects*** instead of ***defective parts***

- Each potential defect on a part, or potential error in a transaction, is called an *opportunity*
- We can use DPMO (defects per million opportunities) instead of DPPM (defective parts per million)
- DPPM is more *customer* focused

The fact that **anything** is wrong is primary — the **number of things** wrong is secondary

- DPMO is more *process* focused

DPMO is a finer measure than **DPPM** — it responds more rapidly to process changes

- Requirements for using DPMO
  - ✓ A finite number of identifiable opportunities per part or transaction
  - ✓ Statistical independence of defect occurrence at different opportunities

In many cases, failure rates are quantified as percentages

Definition of "opportunity"	Fraction defective	Expressed as a percentage	Focus
Each part	$\frac{\text{Defective parts}}{\text{All parts}}$	% Defective	Customer
Each possible defect on a part	$\frac{\text{Defects}}{\text{(All parts)} \times \text{(possible defects per part)}}$	Defects per 100 opportunities (DPHO)	Process
Each transaction	$\frac{\text{Defective transactions}}{\text{All transactions}}$	% Defective	Customer
Each possible error in a transaction	$\frac{\text{Errors}}{\text{(All transactions)} \times \text{(possible errors per transaction)}}$	Defects per 100 opportunities (DPHO)	Process

Pragmatic business initiative

- In the 1990s, GE shifted the emphasis from the Six Sigma quality goal to *Six Sigma projects* — the way to pursue the goal
- Leaders and Champions define *key performance indicators* (KPIs) — a "balanced scorecard" including but not limited to $$ measures
- KPIs drive a prioritization process
- Prioritization tells us which project(s) should be first in line
- "Black Belts" or "Green Belts" lead the project teams
- "Champions" provide resources and remove barriers for the teams

Examples of projects

Project	Annual $$ benefit
Reduce alpha case on large titanium castings	20,800,000
Reduce cost and lead time to develop extrusion tooling	2,000,000
Reduce wasted medication in hospital central pharmacy	1,100,000
Reduce roll stock inventory in box plant	768,000
Reduce cost of belt grinding in casting finishing	500,000
Improve the court collections process in city government	400,000
Reduce DOA replacement parts in field service	216,000
Reduce DPMO and amount of testing of circuit boards	192,000
Reduce electricity consumption in manufacture of airline storage bins	65,000
Reduce RFQ turnaround time (not counting increased PO hit rate)	34,000

3 Why Combine Lean and Six Sigma?

- They require the same culture
- They employ common strategies
- They focus on complementary problem areas
- They employ complementary methods
- They emphasize fact over opinion and use data to inform decisions
- One improvement infrastructure is better than two

Common strategies

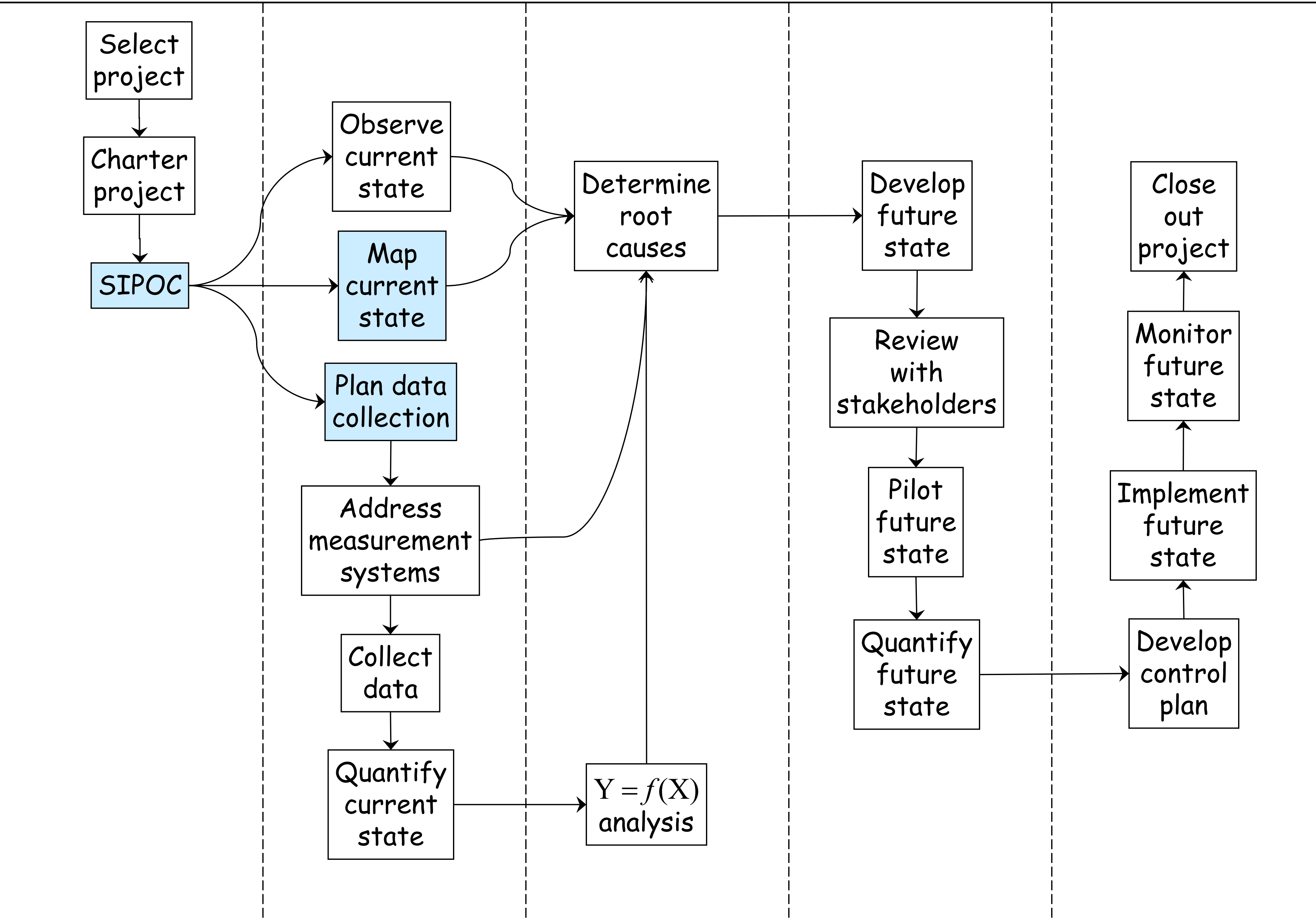
- Driven by Voice of the Customer
- Focus on eliminating waste
- Focus on processes and process improvement
- Improve processes via team projects
- Keep the improvement cycles going

Complementary problem focus and methods

Lean	Six Sigma
Lead time WIP Other visible waste	Defects “Invisible” waste
Defects caused by chaos and confusion	Defects caused by materials and equipment
Root causes easier to determine. (Processes directly observable.)	Root causes harder to determine. (Processes often not observable.)
Value stream mapping Geographic mapping	Basic process mapping Cross functional process mapping
Defines and standardizes the “Wisdom of the organization”	Data collection and analysis to discover a new solution
Common TPS solutions can be adapted to many circumstances	Project roadmap provides a method for finding solutions

Define Phase

4 Project Scope and SIPOC



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

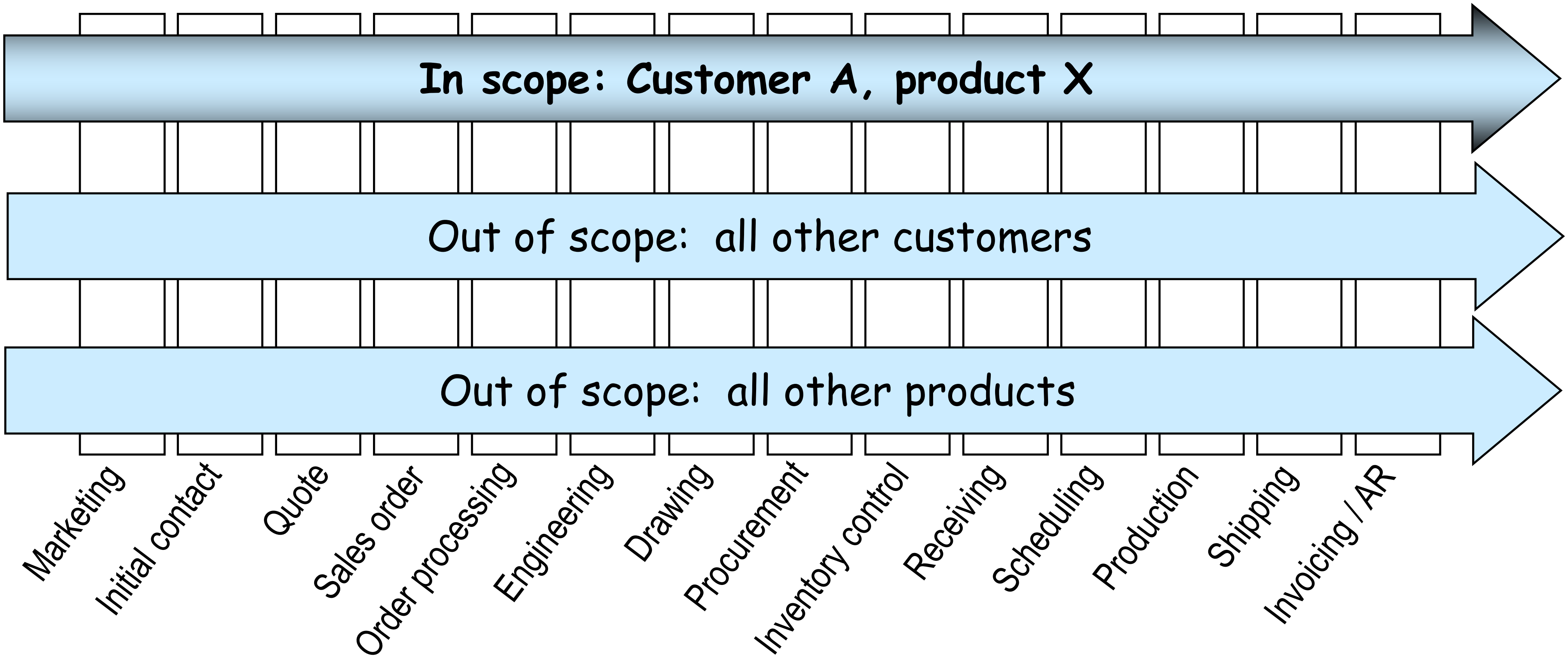
Value stream scope

Defines the project scope in terms of . . .

- ✓ Which customers?
- ✓ Which products?
- ✓ Which locations?
- ✓ Which materials?
- ✓ Which suppliers?
- ✓ . . .

Value stream	All activities needed to provide a specified family of products or services to customers

Value stream scope (cont'd)



Example of value stream scope

Project to reduce cost and lead time of extrusion tool development

In scope

- PVC products
- Location A

Out of scope

- Composite products
- Locations B & C

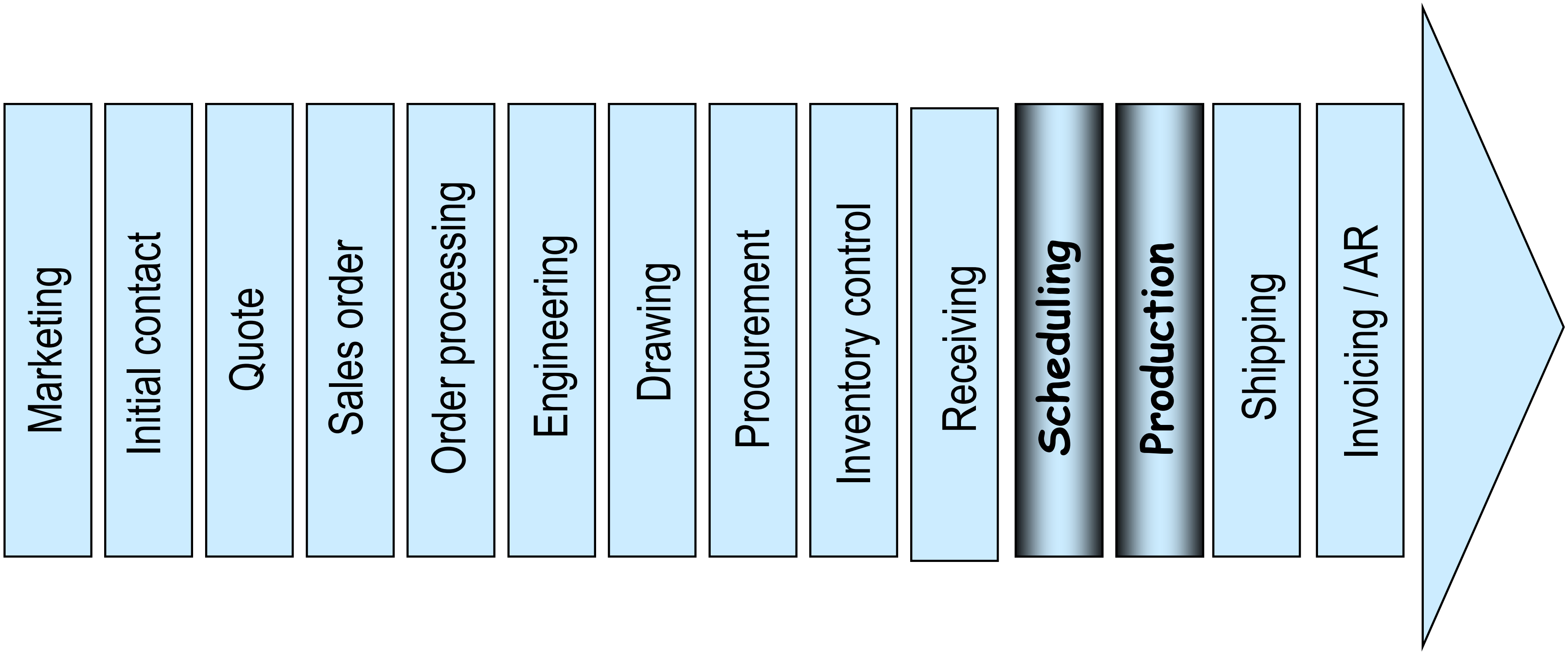
Workflow scope

Defines the project scope in terms of . . .

- ✓ Which activities?
- ✓ Which operations?
- ✓ Which processes?
- ✓ Which areas?
- ✓ Which departments?
- ✓ . . .

Workflow scope (cont'd)

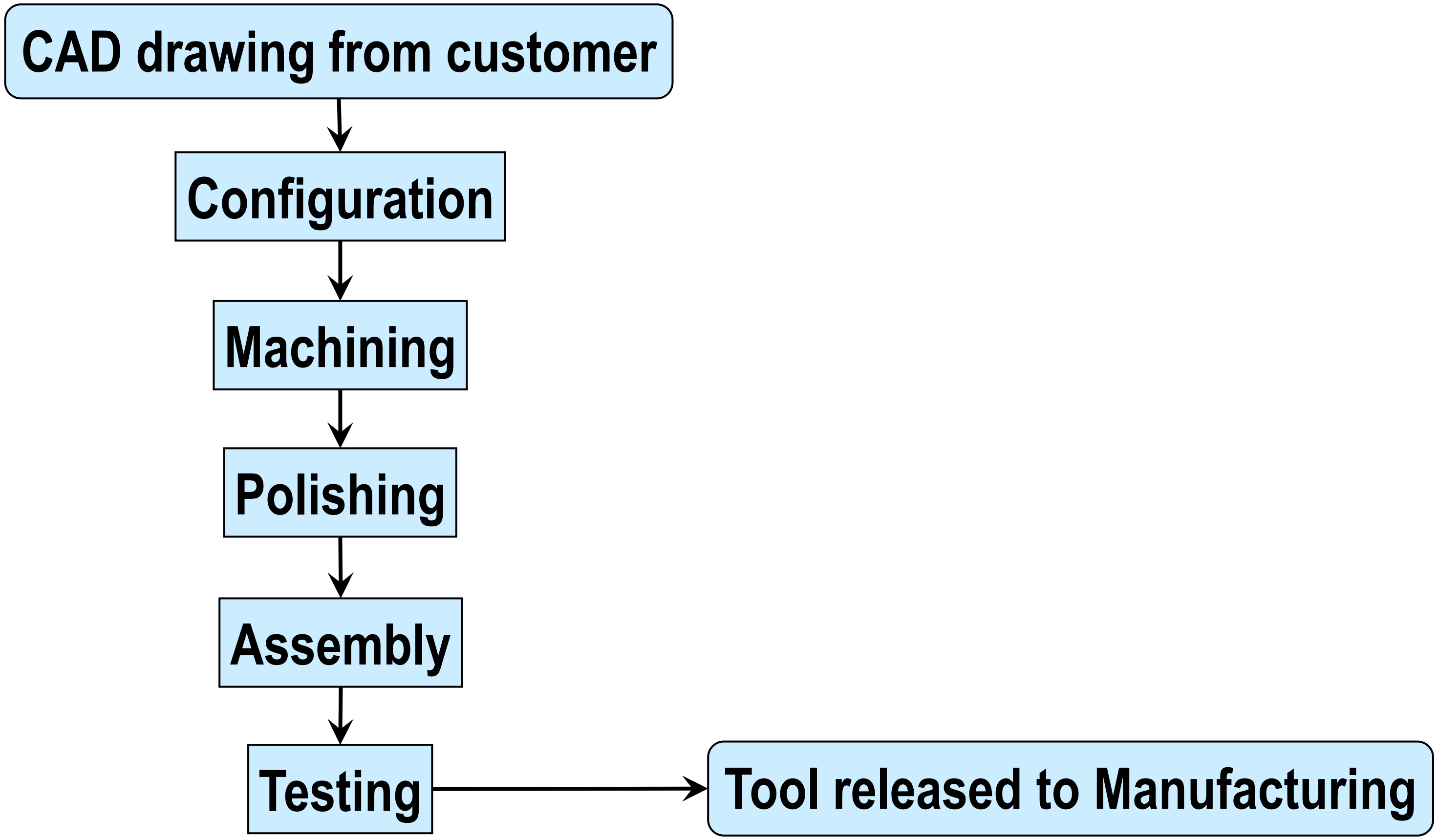
Which *activities* in the value stream are addressed by the project?



- **Scheduling** and **Production** are in scope
- Everything else is out of scope
- How will this affect the activities of the project team?

Example of workflow scope

Project to reduce cost and lead time of extrusion tool development



CAD drawing from customer

Configuration

Machining

Polishing

Assembly

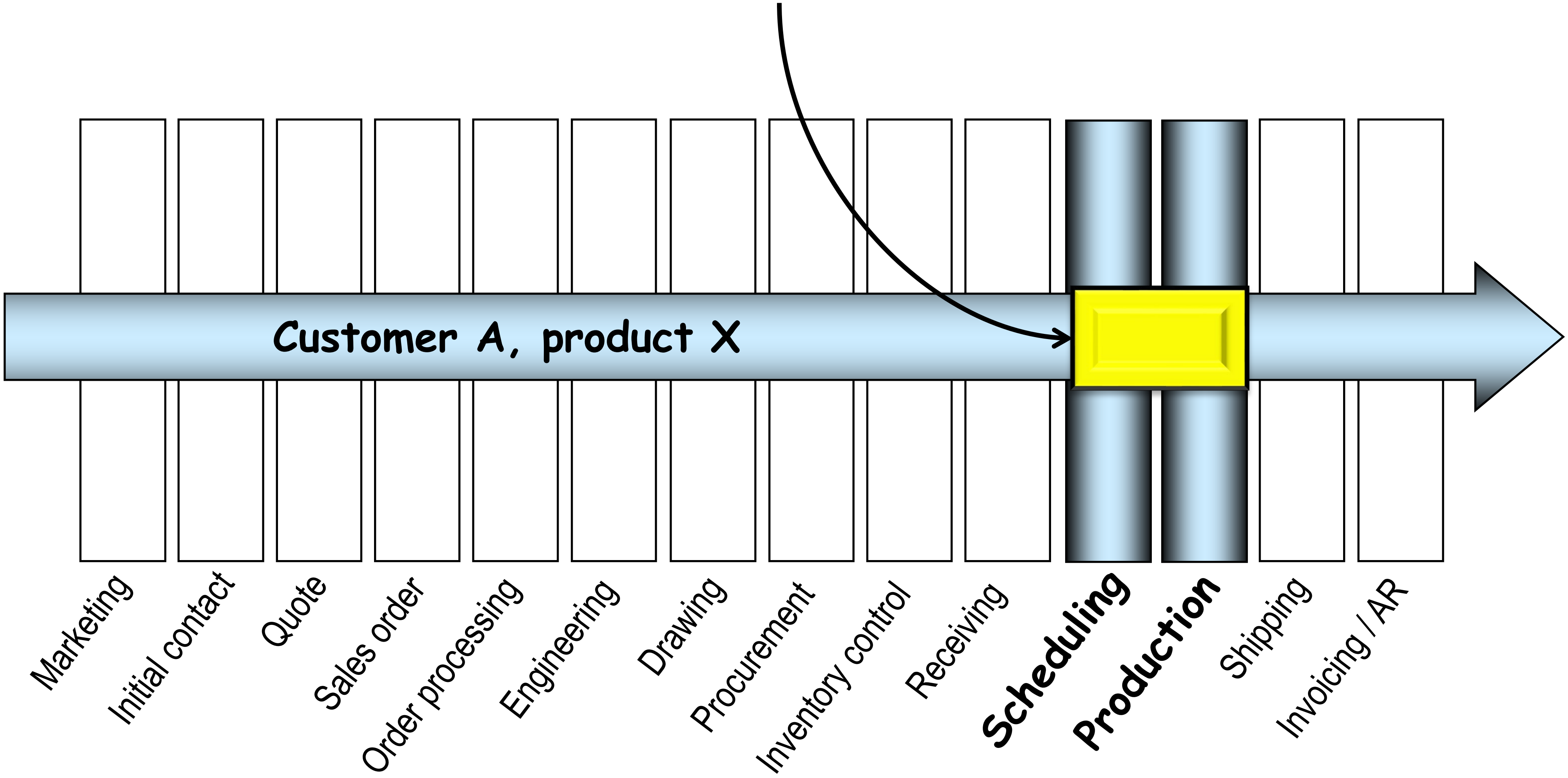
Testing

Tool released to Manufacturing

- Manufacturing is out of scope
- The project is not chartered to analyze and improve Manufacturing
- What is the relationship between Manufacturing and the workflow scope?

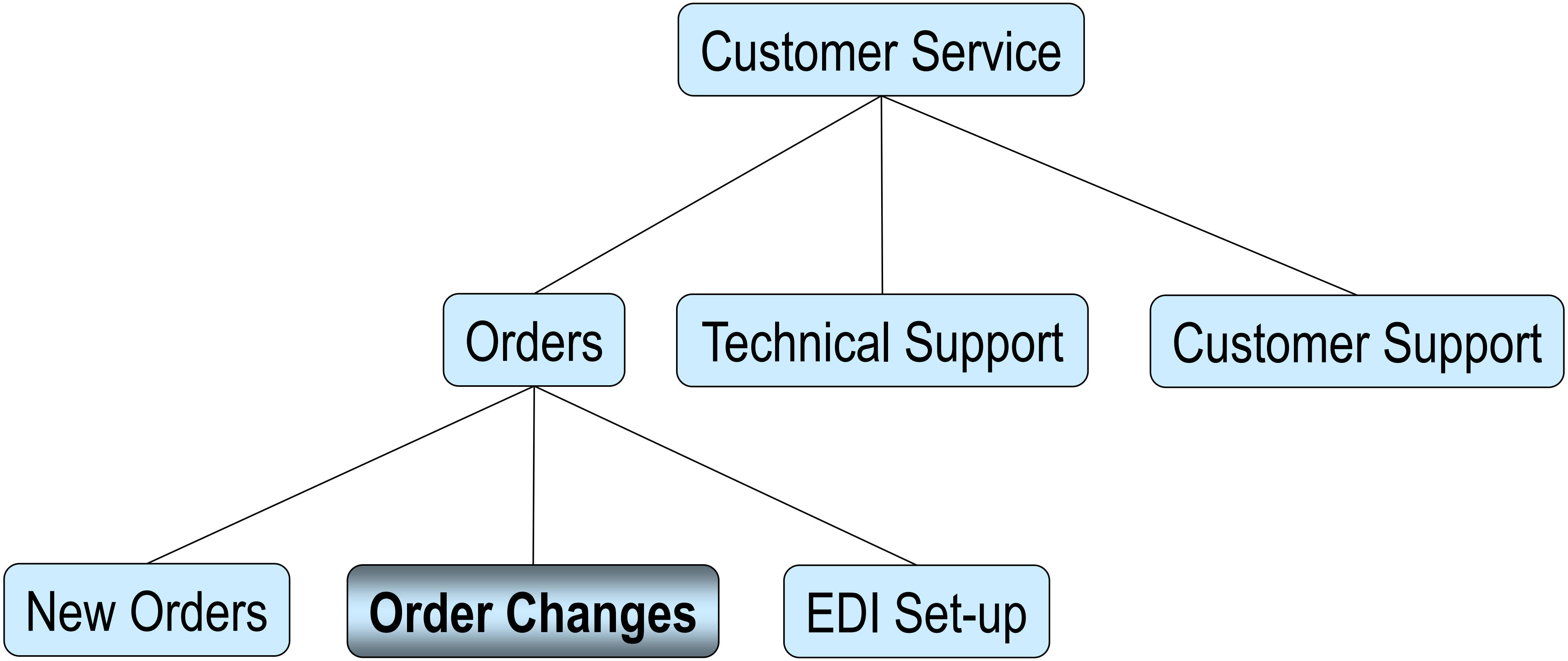
Project scope

The *intersection* of value stream and workflow scope



An example of value stream scope

The project will address only *order changes*


Customer Service

Orders

Technical Support

Customer Support

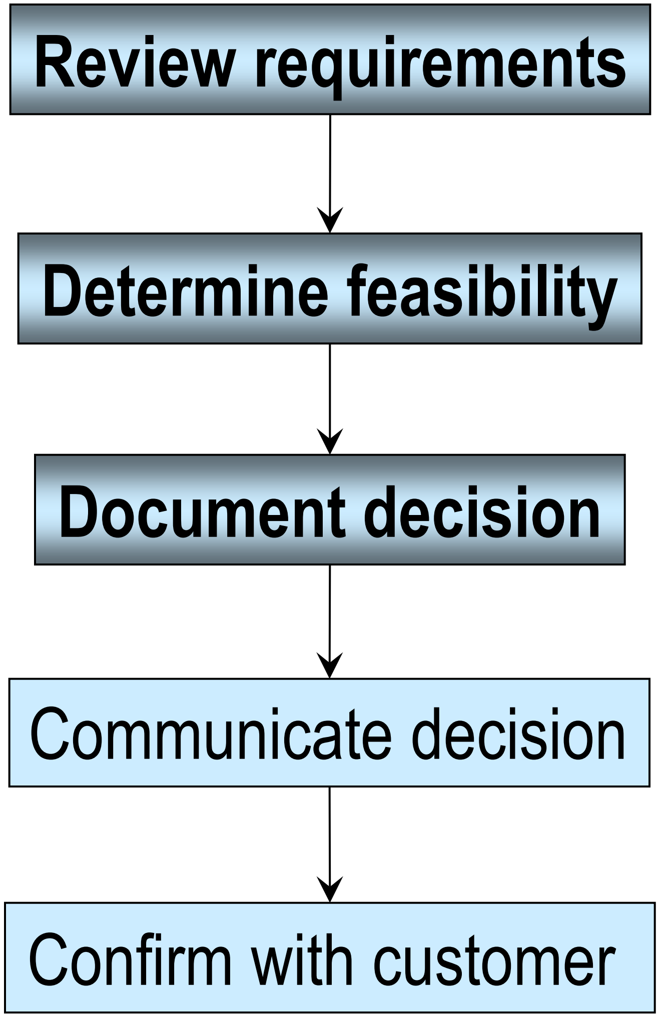
New Orders

Order Changes

EDI Set-up

An example of workflow scope

The project will address only the *first three steps* of the order change process



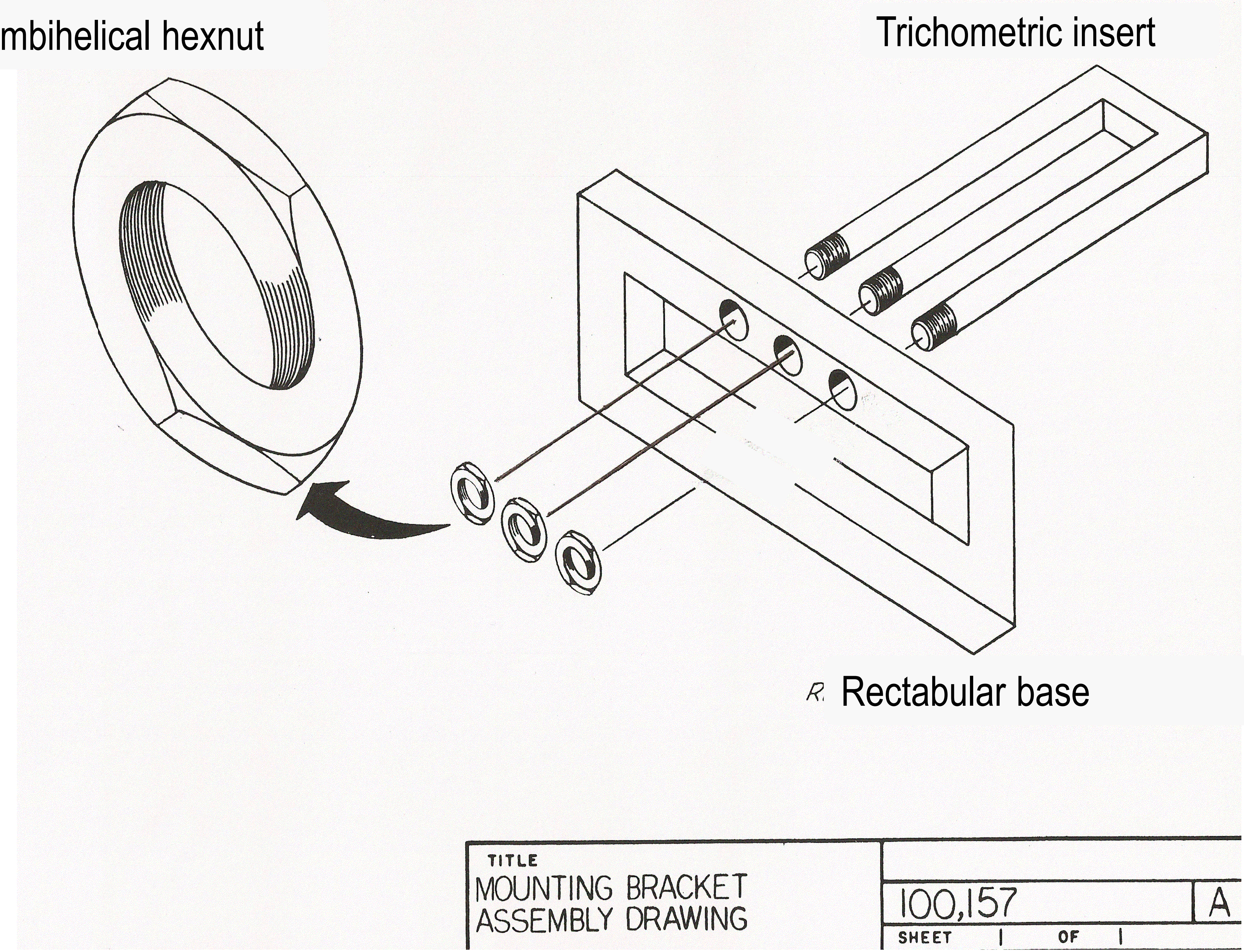
Exercise 4.1

Our company makes prototypes for various types of mounting brackets. These are classified as either standard or non-standard. A project has been launched to reduce the lead time for designing and building prototypes for non-standard brackets (see slide below for a typical example).

What is the value stream scope for this project?

What is the workflow scope for this project?

A non-standard mounting bracket



Ambihelical hexnut

Trichometric insert

Rectabular base

Introduction to SIPOC

- SIPOC is a document that frames the project in the *process* space:

  Suppliers → **I**nputs → **P**rocess → **O**utputs → **C**ustomers

- SIPOC also documents the *data collection* needed for the project

- The five elements of SIPOC are defined on the slide below.

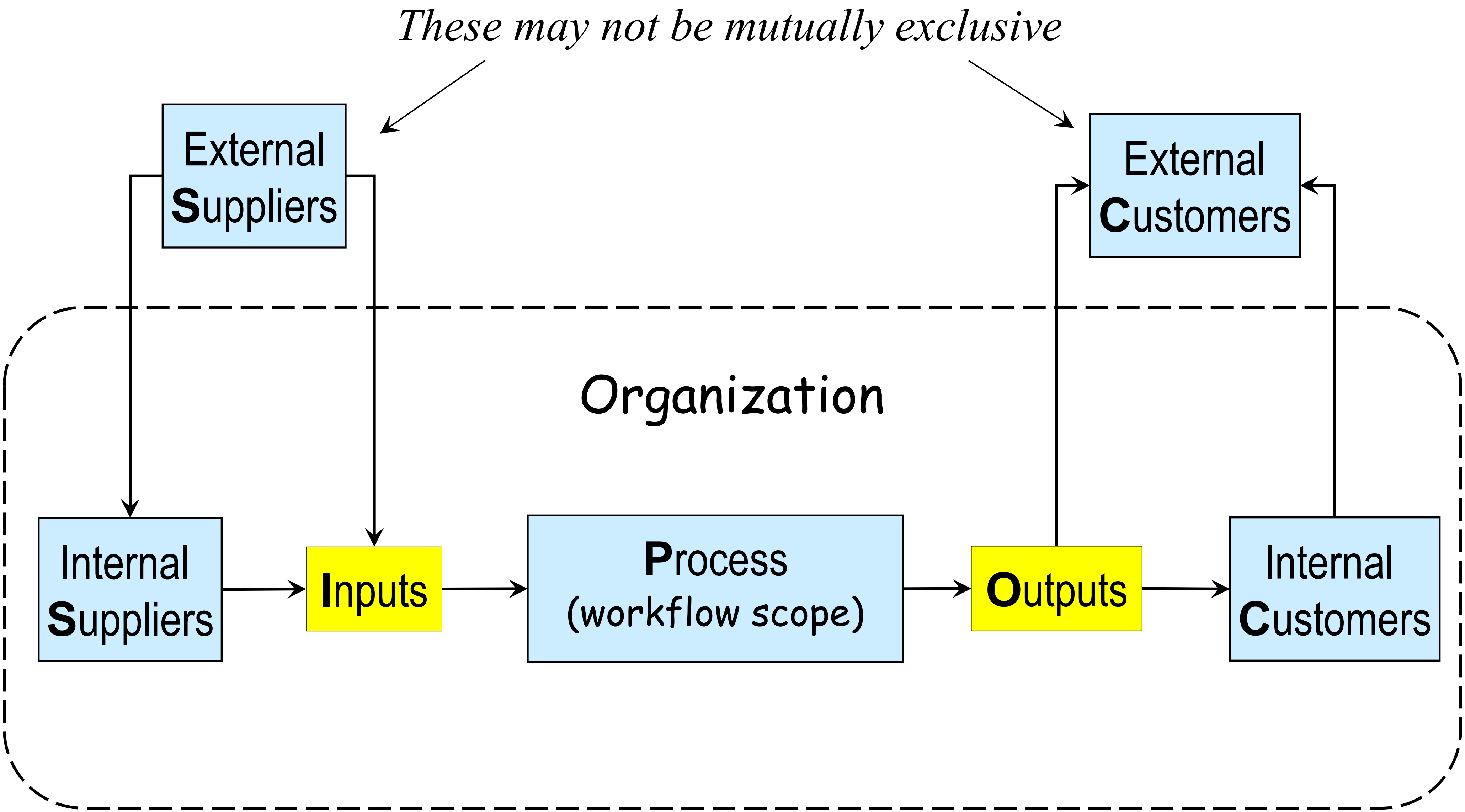
- The logical sequence for reading or creating a SIPOC:

  P → **O** → **C** → **I** → **S**

SIPOC definitions

5) Suppliers	Entities who provide necessary *inputs* to the workflow scope. Suppliers may be internal or external to the organization.
4) Inputs	Products, services, or information provided to the workflow scope by suppliers.
1) Process	The workflow scope: the activities to be analyzed and improved. A *high-level* description including first step, main intermediate steps, and last step.
2) Outputs	Products, services, or information provided by the workflow scope to customers.
3) Customers	Entities who receive *outputs* from the workflow scope. Customers may be internal or external to the organization.

Graphical presentation of SIPOC



These may not be mutually exclusive

External **S**uppliers

External **C**ustomers

Organization

Internal **S**uppliers

Inputs

Process (workflow scope)

Outputs

Internal **C**ustomers

Y variables

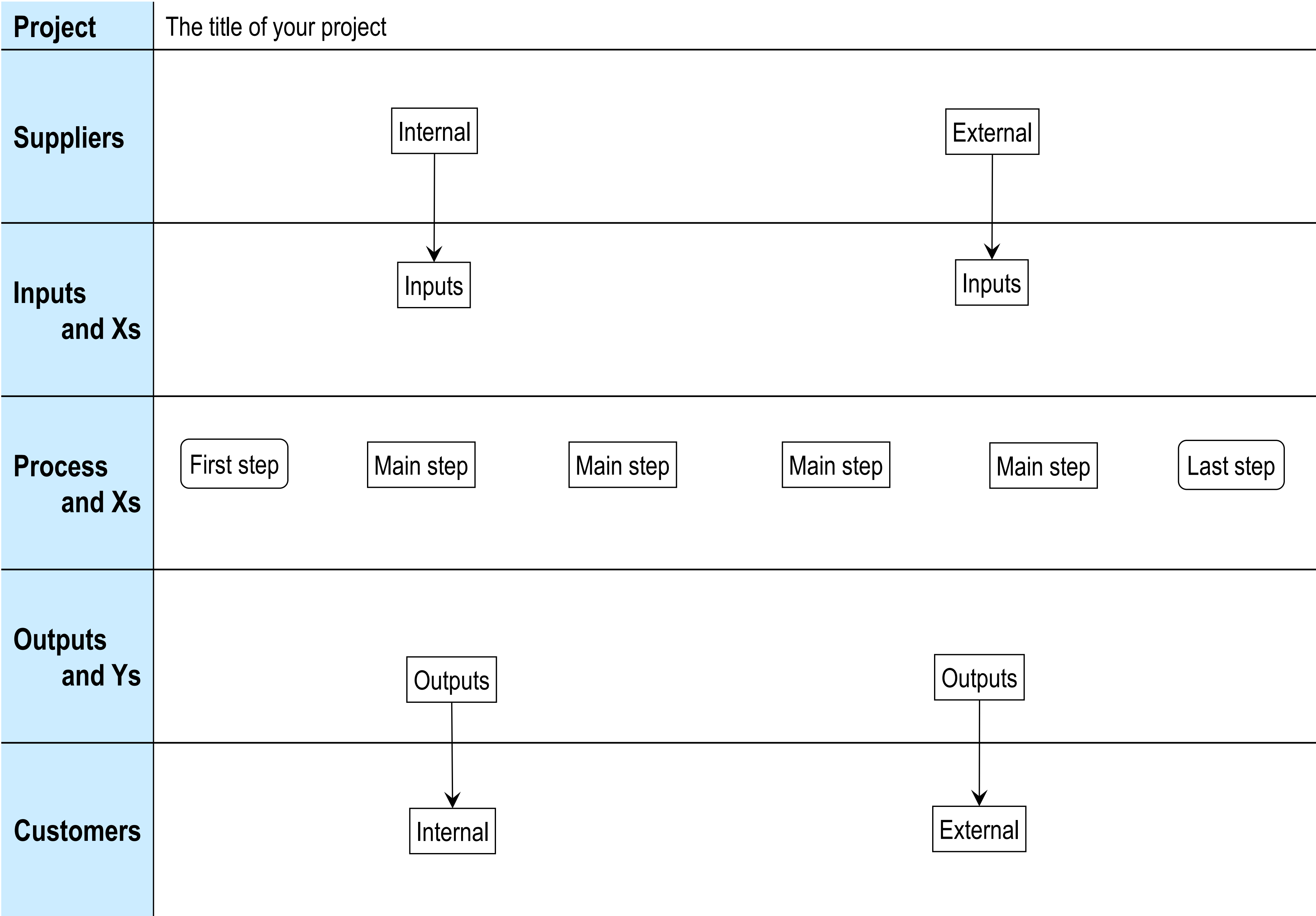
- A *data variable* is measurable characteristic defined for individual parts or transactions (What does "variable" mean?)
- *Y variables* are measurable characteristics of *outputs* from the workflow scope
- They are the data variables from which the statistical **project metrics,** such as average or percent defective, are calculated
- Examples: lead time, pass or fail, quantitative measures of poor quality
- The Y variables are the reason we are doing the project (Why?)

X variables

- Data variables that are possible causes of variation in the Ys are called *X variables*
- Examples: Who, What, Where, When, Which, . . .
- The greater the number of X variables identified, the greater the chance of solving the problem (Why?)
- The Fishbone Diagram will be used in the Measure Phase to identify and document the X variables

The SIPOC will contain only products, services, or information provided to the workflow scope by suppliers.

Blank SIPOC template



Project The title of your project

Suppliers

Internal

External

Inputs and Xs

Inputs

Inputs

Process and Xs

First step

Main step

Main step

Main step

Main step

Last step

Outputs and Ys

Outputs

Outputs

Customers

Internal

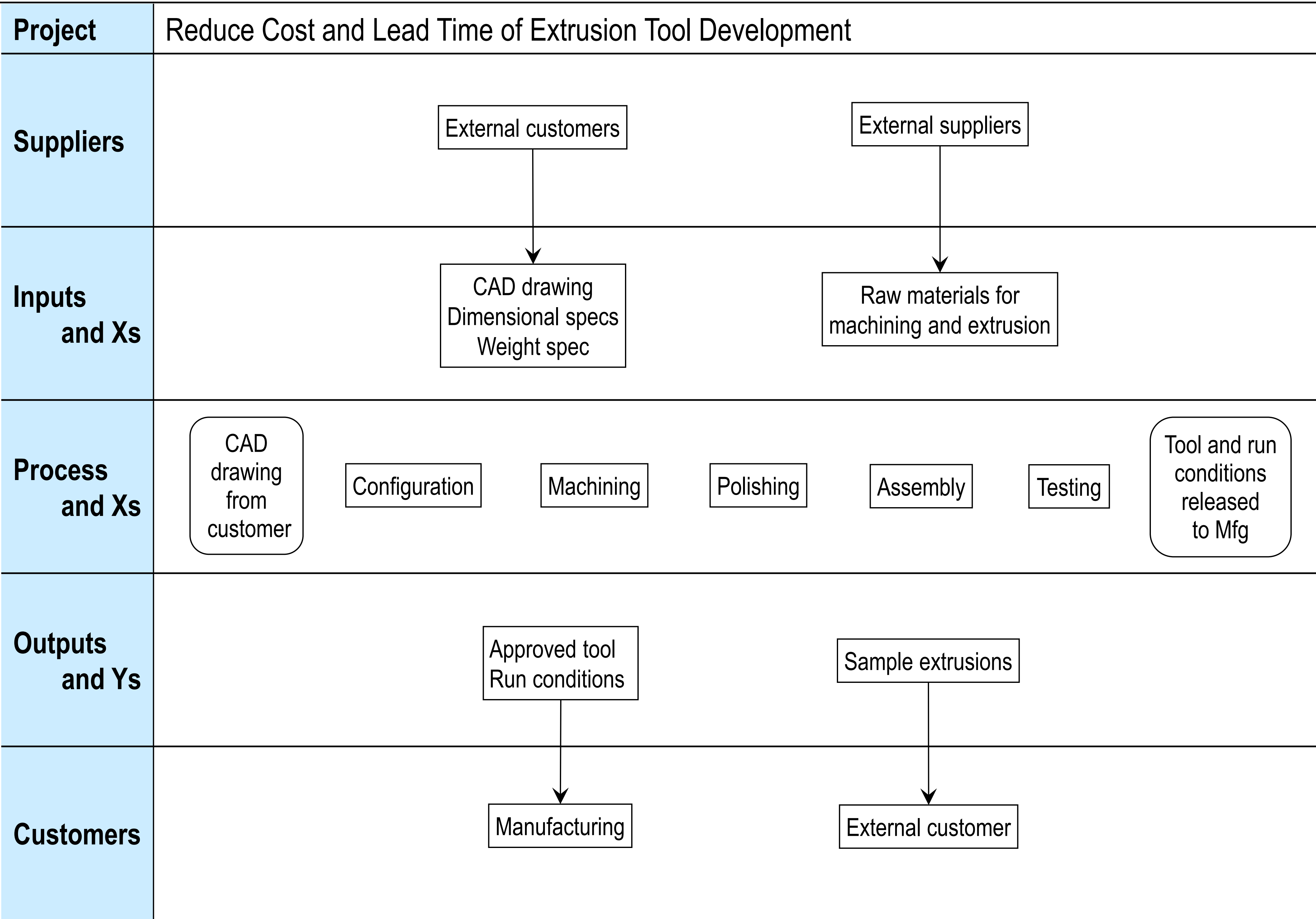
External

Blank SIPOC (cont'd)

The slide shows a graphical SIPOC template. All you have to do is edit the various boxes and text. You can also add or delete boxes or text.

The following two slides show the graphical SIPOCs for two case studies.

SIPOC example 1



Project Reduce Cost and Lead Time of Extrusion Tool Development

Suppliers

External customers

External suppliers

Inputs and Xs

CAD drawing
Dimensional specs
Weight spec

Raw materials for machining and extrusion

Process and Xs

CAD drawing from customer

Configuration

Machining

Polishing

Assembly

Testing

Tool and run conditions released to Mfg

Outputs and Ys

Approved tool
Run conditions

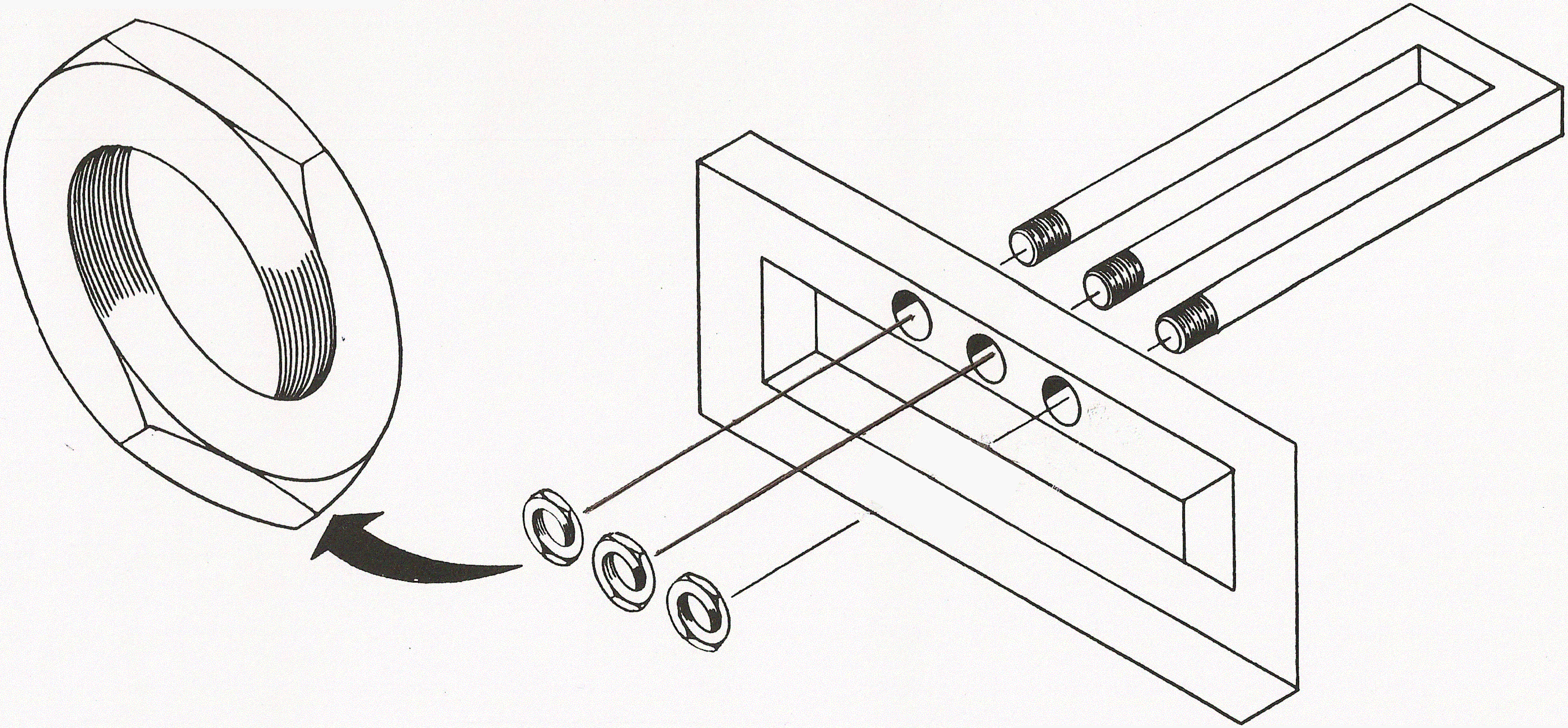
Sample extrusions

Customers

Manufacturing

External customer

A non-standard mounting bracket



Ambihelical hexnut

Trichometric insert

Rectabular base

TITLE

MOUNTING BRACKET
ASSEMBLY DRAWING

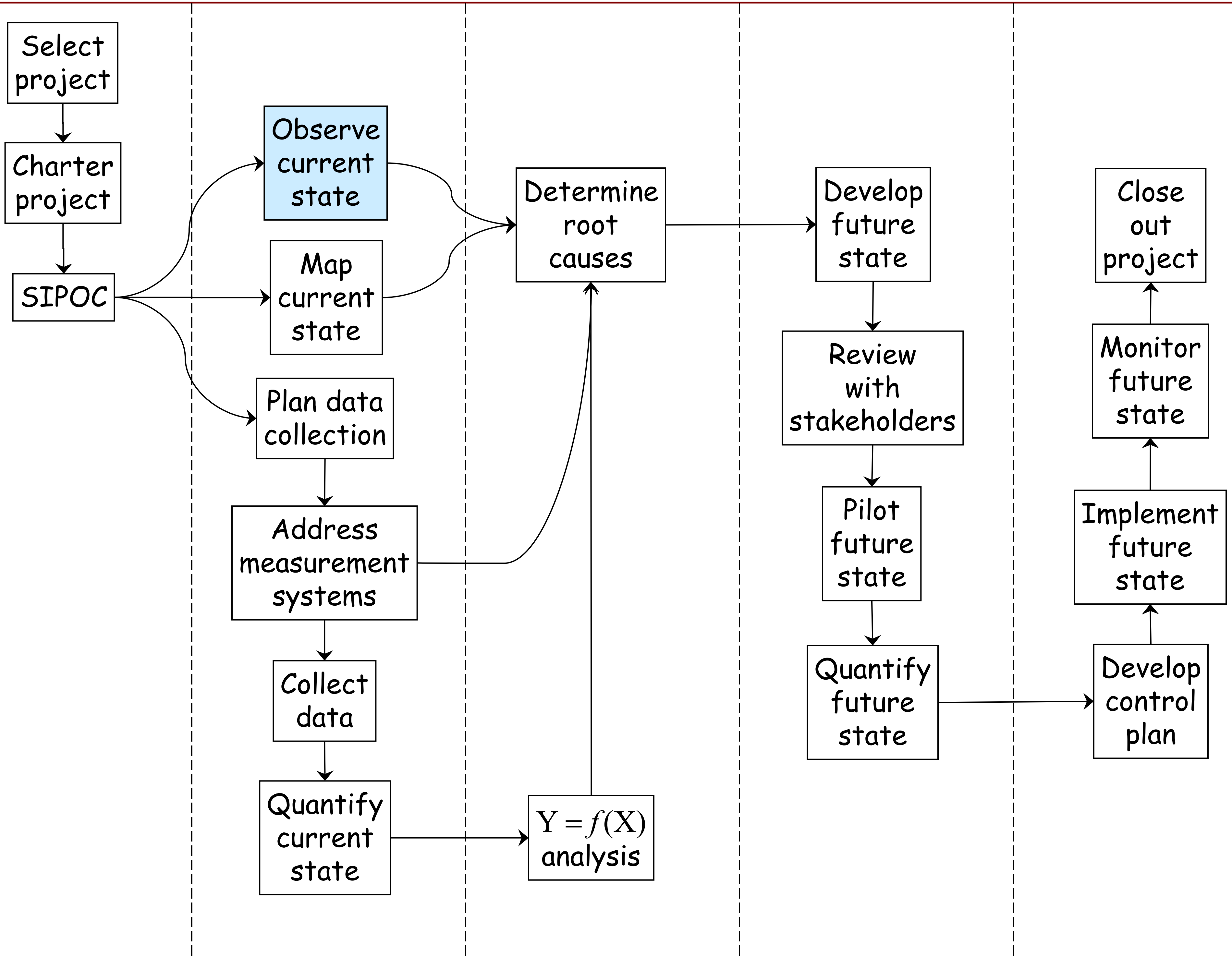
100,157

A

SHEET 1 OF 1

Measure Phase

5 Observing the Current State



Guidelines

- The purpose is to improve the process, not to audit work performance
- Workflow observation periods should be scheduled in advance with appropriate supervisors and/or managers
- Workflow participants must be briefed on the project charter
- Participants must have adequate advance notice of observation periods
- Observations should be limited to the value stream and workflow scopes for the project

Guidelines (cont'd)

- Don't "gang up" on a few participants or process steps—deploy team members effectively to get as many perspectives as possible
- Ask permission to take notes, photographs or videos — this helps team members get the information they need without having to repeat questions later
- Observations should begin with introductions and guided tours, in some cases
- This should be done on all relevant shifts
- Subsequent "unguided" observations are often needed

Typical elements of workflow observation

- Interview workflow participants within the project scope
- Identify data variables and inspection points for inputs provided by internal suppliers
- Interview internal suppliers and customers of the workflow scope
- Identify data variables and inspection points for outputs provided to internal customers
- Identify NVA activities — these may be opportunities for improvement within the project scope
- Confirm or revise process map(s)

Team roles & responsibilities

	Bob	Carol	Ted	Alice	Moe	Larry	Curly
Interview workflow participants	✓			✓			
Observe and record changes to process map		✓			✓		
Identify workflow data variables and inspection points			✓			✓	
Identify data variables and inspection points for workflow inputs				✓			✓
Interview internal customers	✓				✓		
Identify data variables and inspection points for workflow outputs		✓				✓	
Focus on measurement systems			✓				✓

Asking questions

- The *way* you ask questions can affect the usefulness of the answers you get

- *Closed* questions can be answered with “yes” or “no” — if the person is reluctant to talk to you, closed questions will not get you anywhere

- *Open* questions start with words like *what, why, when, where, who, which, how,* etc.

- Open questions are much better for eliciting information, ideas, opinions, etc.

Asking questions (cont’d)

Open questions	Closed questions
“How do you do that?”	“Can you see from where you’re sitting?”
“Why is it done this way?	“Can you hear me in the back?”
“How do you think that would help?”	“So, you agree with the schedule change?”
“When you say ___ , what do you mean?”	“Have we decided to meet on Fridays?”
“What would be an example of that?”	“We covered that earlier, didn’t we?”
“What are some possible causes of ___ ?”	
“Why do think that could be a cause?”	• *Closed questions are useful for moving a conversation along* • *Try to phrase them so that the answer you want is “yes”*
“Why do you think that happens?”	

Correcting bad listening habits

Concentrate . . . . on what is being said.

Observe . . . . .facial expressions and body language.

Respond . . . . with eyes, voice, gestures, and posture to communicate empathy and understanding.

Reflect . . . . information by paraphrasing.

Elicit . . . . information by asking questions.

Control . . . . the urge to interrupt, judge, or change the subject.

Take . . . . advantage of lags between question and answer to record observations or further questions.

Lean checklist

- ☐ Are there opportunities for reducing batch size?
- ☐ Where is the greatest amount of work-in-process (WIP)?
- ☐ What are the most common do-overs?
- ☐ Is the physical layout causing excessive movement of people or material?
- ☐ Is there unnecessary complexity?
- ☐ Where are the most time-consuming changeovers?
- ☐ Are there opportunities for mistake proofing?

Lean checklist (cont'd)

- ☐ Are there serial activities that could be parallel?
- ☐ Are there separate steps that should be combined into a single step?
- ☐ Are there single steps that should be split into separate steps?
- ☐ Are work instructions missing, outdated, or not visible?
- ☐ Are there problems with availability of equipment or material?
- ☐ . . .

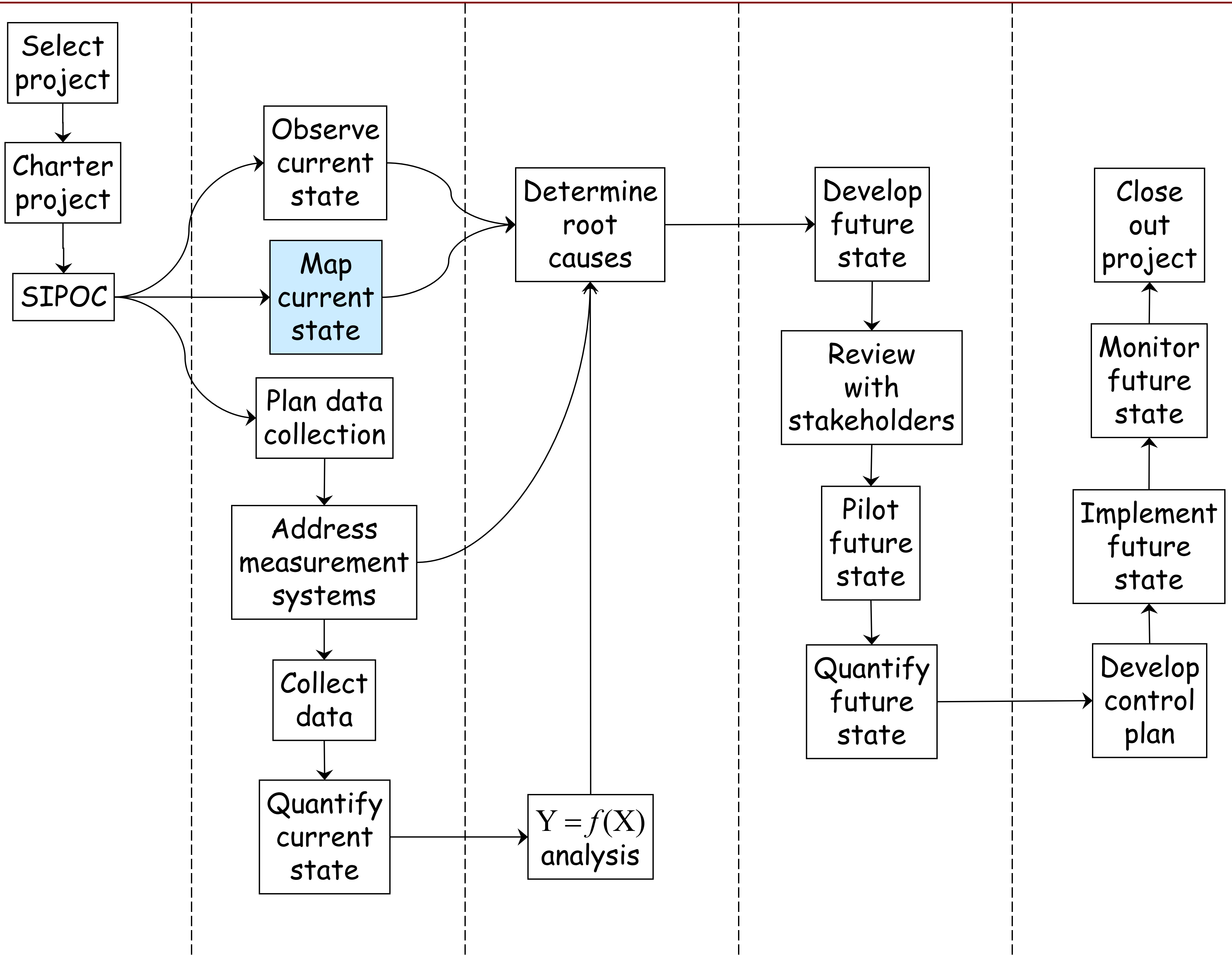
Observation log

- Team members may see possible causes of problems and solutions as soon as they start observing and mapping the current state
- These observations should *not* be publicized until the appropriate point in the project roadmap
- These observations *should* be logged as they arise, preferably in Excel (facilitates categorization and prioritization)
- The possible causes will be reviewed in the *Analyze* phase, along with data analysis results, to determine root causes
- The possible solutions will be reviewed in the *Improve* phase to develop the future state

Observation log (cont'd)

Team member	Date	Location	Possible cause	Possible solution

6 Basic Process Mapping



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

Monitor future state

Close out project

Basic process mapping (cont'd)

Process mapping is easy to learn and produces useful documentation of the current state. It is also a great team building activity.

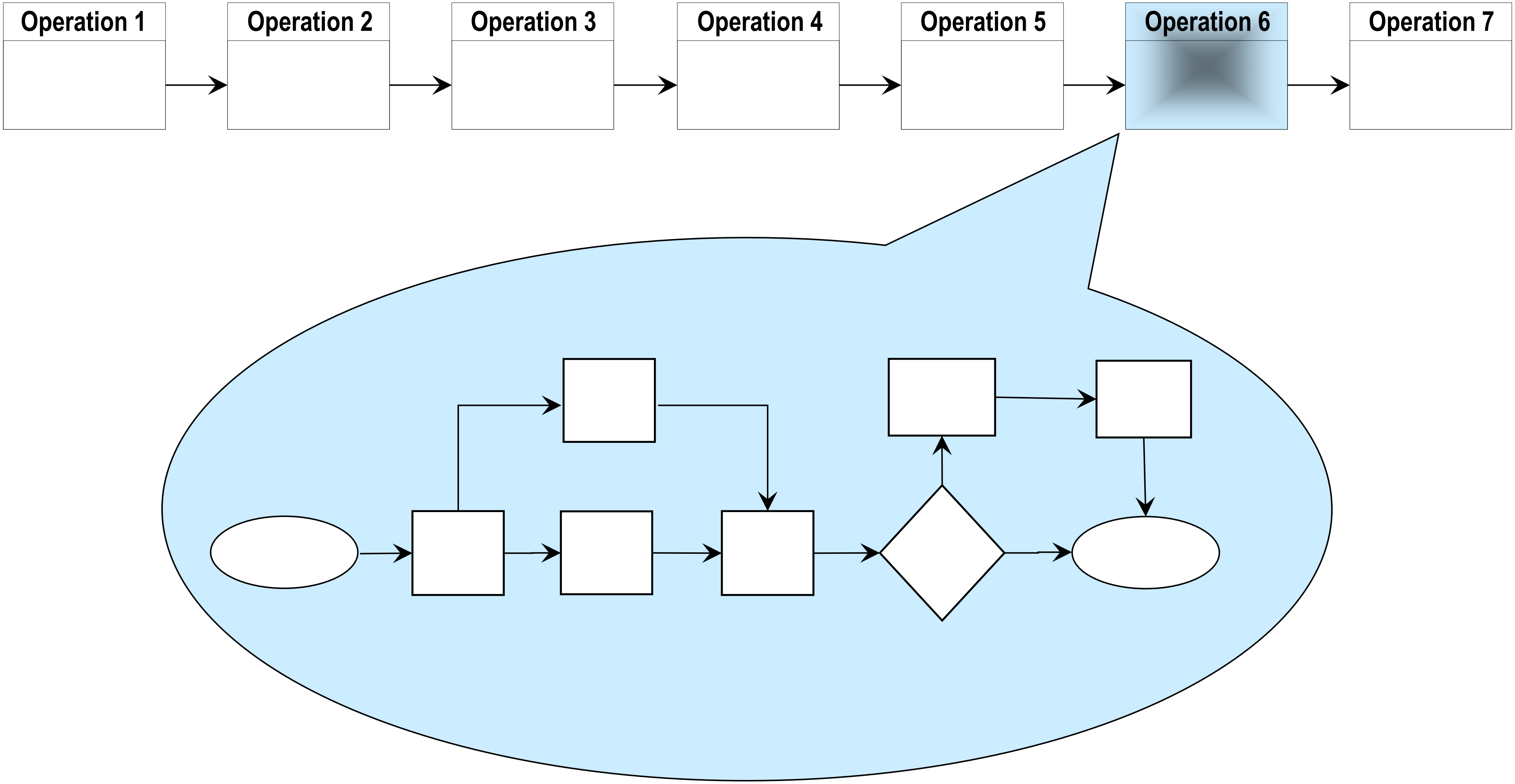
The key to successful application of any mapping technique is to focus on the appropriate *level of activity* for your project. In SIPOC we identify the first, last, and main intermediate steps of the in-scope workflow. This gives you a high-level process map.

A high-level map is a good starting point for more detailed mapping. A basic process map, discussed in this section, shows individual tasks and decision points within the main steps. A cross functional or swimlane maps shows who is responsible for each task and decision. This and other common mapping formats are discussed in the next section.

A high-level map is also the usual starting point for value stream mapping (VSM). VSM combines visualization of what is happening with certain forms of data analysis. VSM will be discussed later in the program.

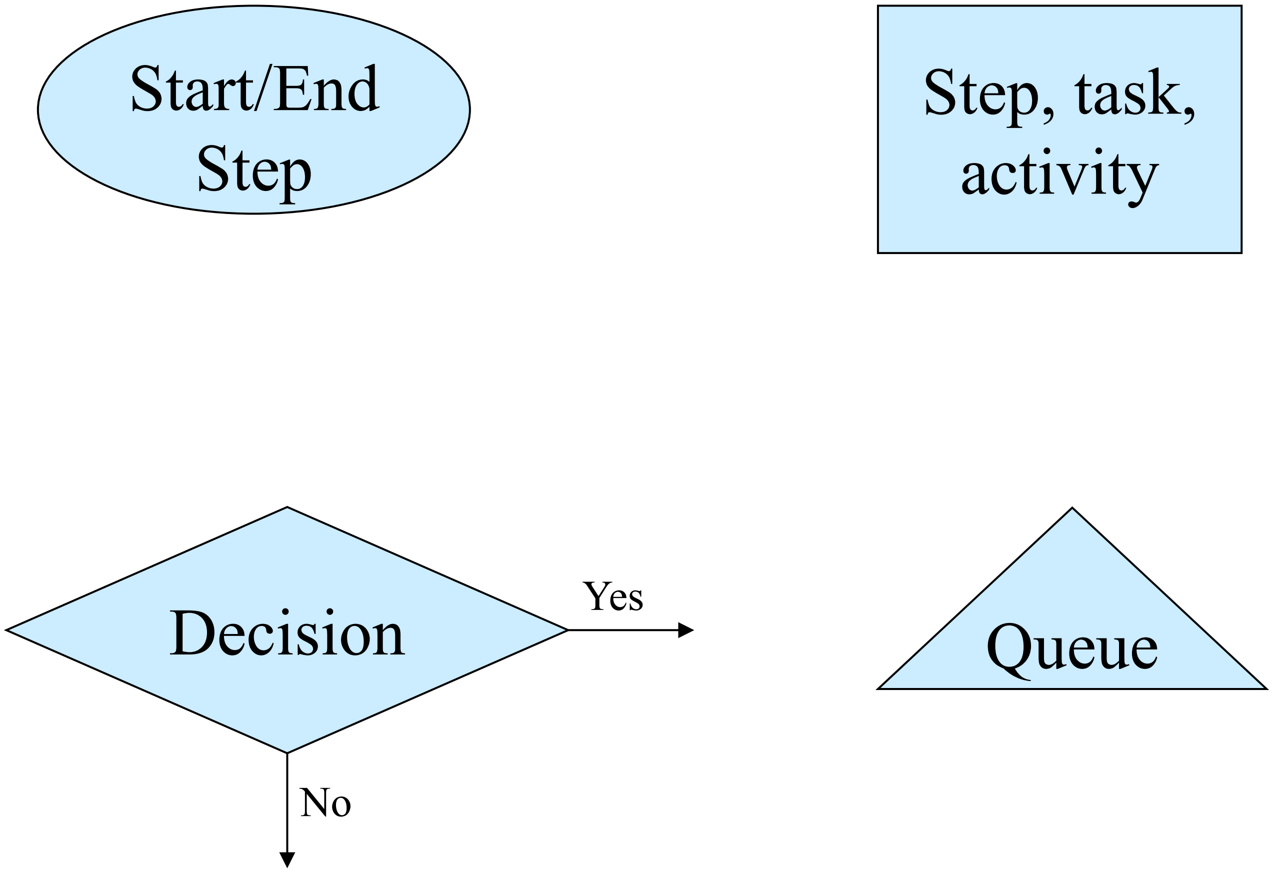
Basic process mapping (cont’d)

Often, we want to create detailed maps for some or all of the main steps given in the SIPOC



Operation 1
Operation 2
Operation 3
Operation 4
Operation 5
Operation 6
Operation 7

Standard (basic) process mapping symbols



Mapping as a team activity

Suspend your disbelief	Map the process the way it really is, not the way you think it should be.
Don’t make assumptions	If you don’t know what happens at a certain point, or can’t agree on what happens, put a question mark there. Then, go ask someone who does know.
Solicit feedback	Ask participants of the in scope workflow, and their internal customers, to review the map for accuracy and clarity.
Document your work	Use mapping software to create an electronic version of the map.

Writing good narrative

✓ Use active voice, not passive voice

- ☹ Order is entered
- ☺ Enter the order

✓ Use verb/object, not name of activity

- ☹ Order Entry
- ☺ Enter the order

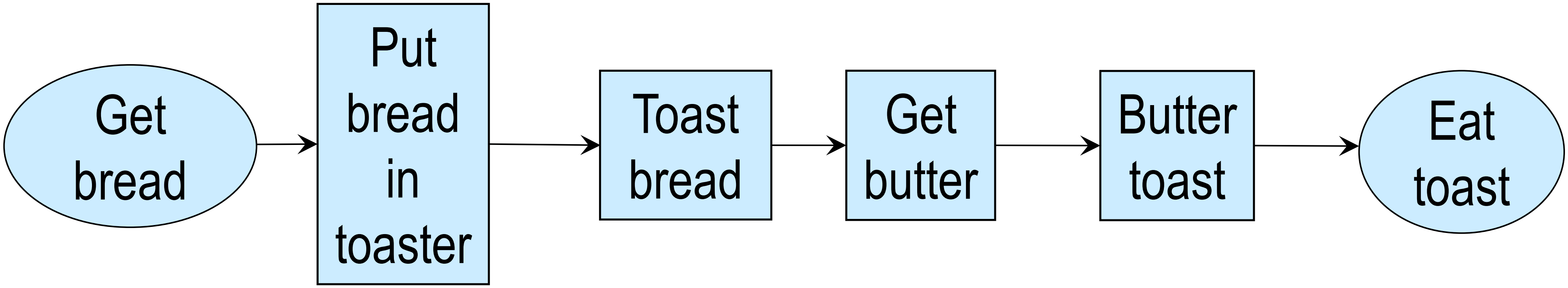
✓ Use short sentences with familiar words

- ☹ Twilight's last gleaming
- ☺ Dusk

✓ Use present tense

✓ Use logical, consistent layout

A high-level map for making toast



Get bread

Put bread in toaster

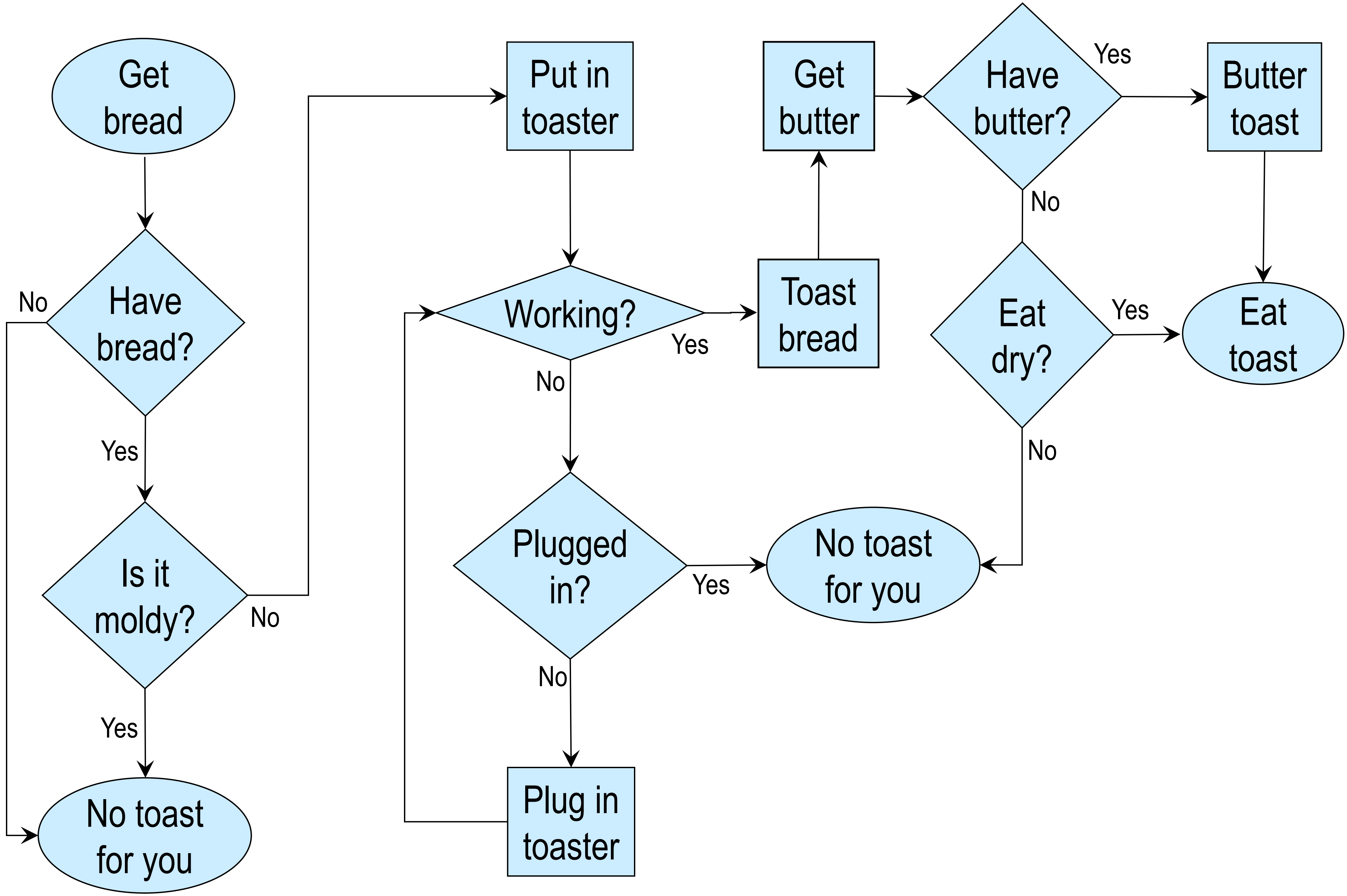
Toast bread

Get butter

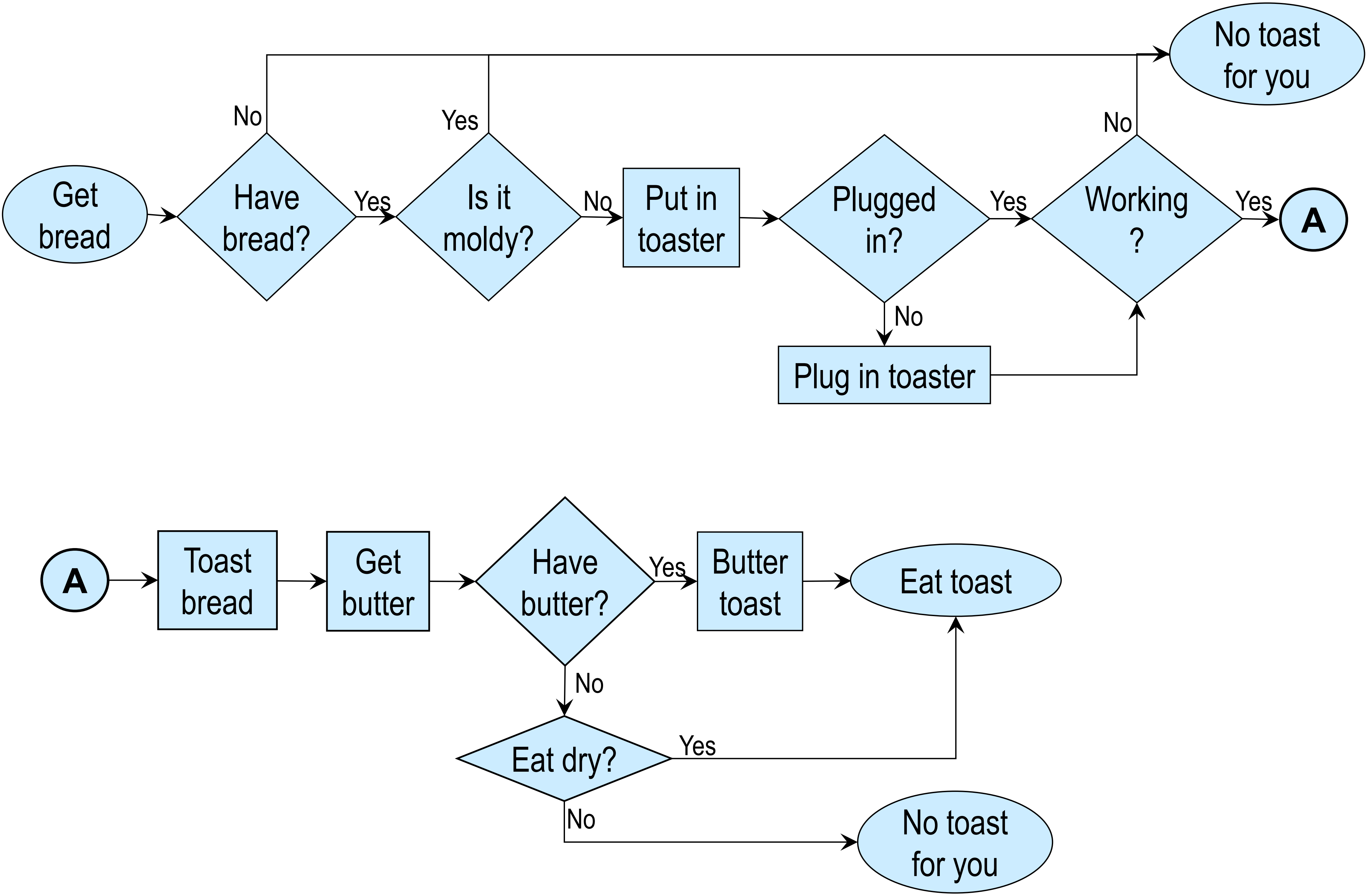
Butter toast

Eat toast

Decision steps show what really happens



Best practice: follow a qualitative timeline

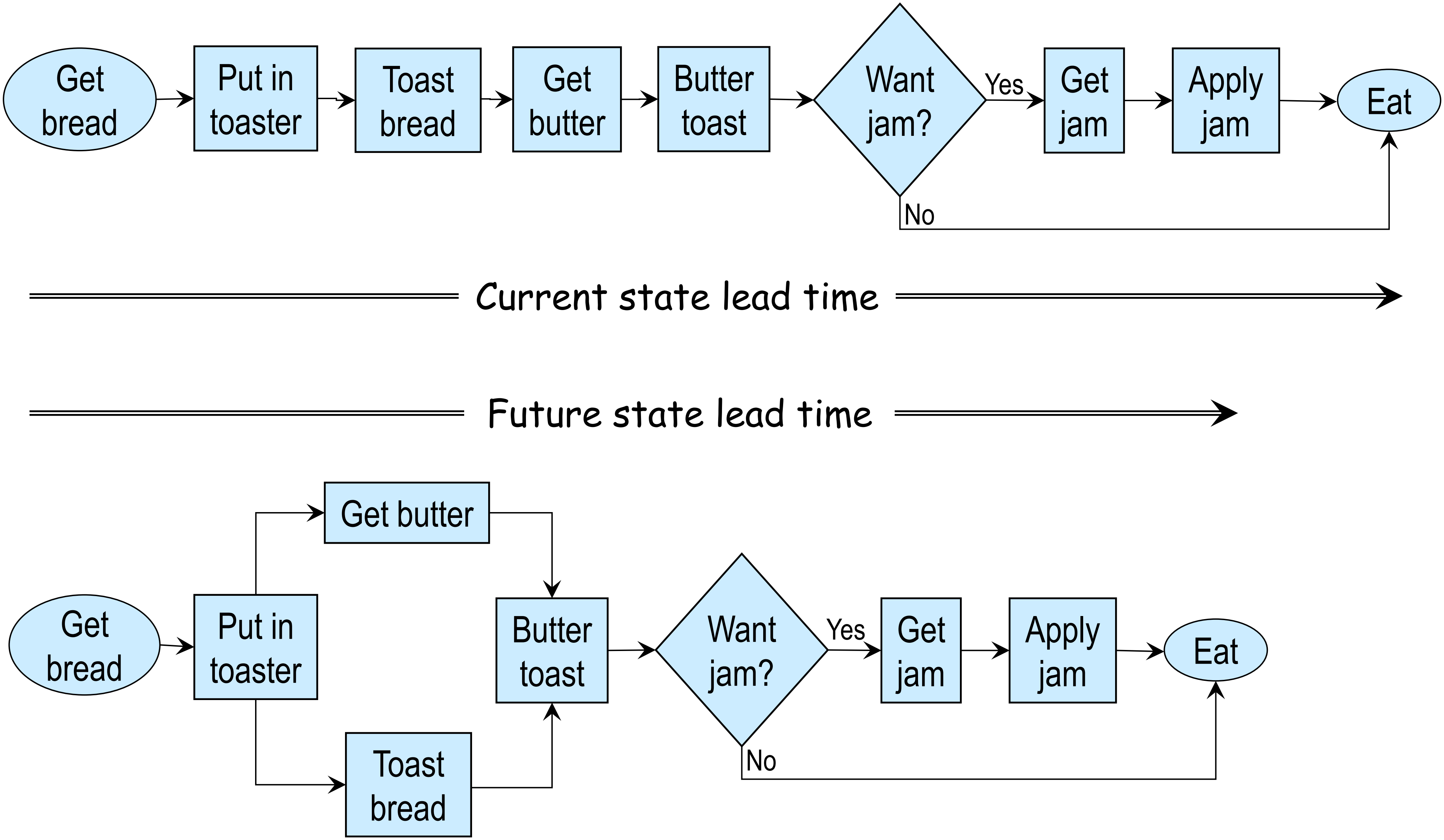


Get bread
Have bread?
No
Yes
Is it moldy?
Yes
No
No toast for you
Put in toaster
Plugged in?
Yes
No
Plug in toaster
Working ?
No
Yes
A

A
Toast bread
Get butter
Have butter?
Yes
Butter toast
Eat toast
No
Eat dry?
Yes
No
No toast for you

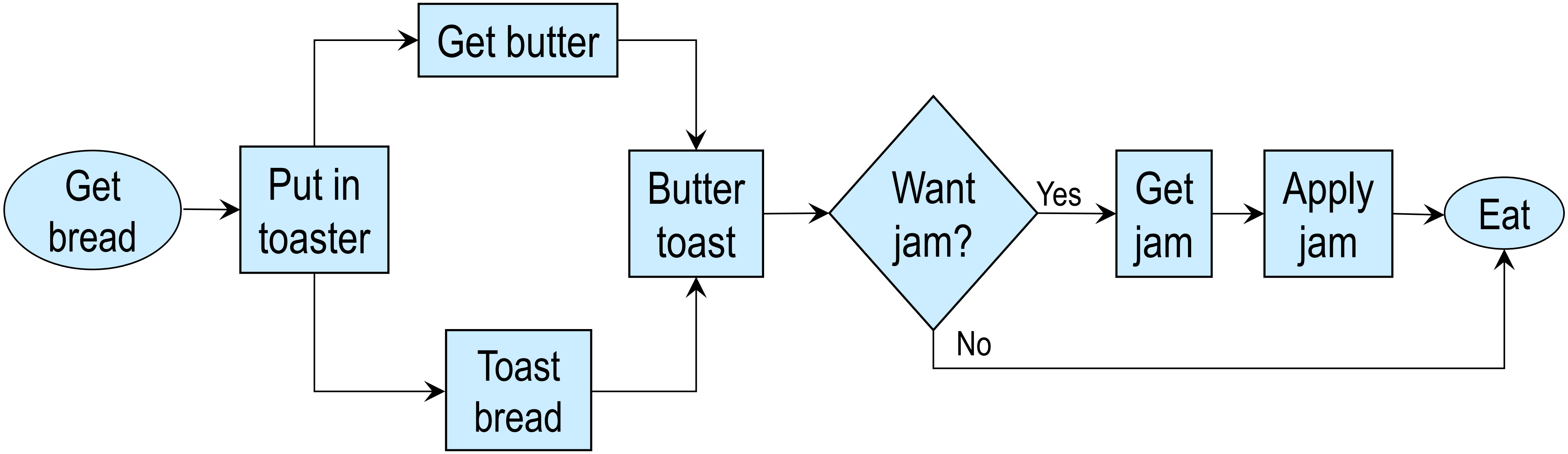
Parallel activities

Common technique for reducing lead time: convert *serial* to *parallel*



Exercise 6.1

How would you modify the toast-making process to further reduce the lead time?



Exercise 6.2

You are to create a process map based on the information given on the slide below. It will be beneficial to work on this in small groups.

This is not *your* process. Someone else is describing *their* process to you. Do not make unwarranted assumptions!

Use a separate sheet of paper to draw your map. Use a qualitative timeline!

Exercise 6.2 (cont’d)

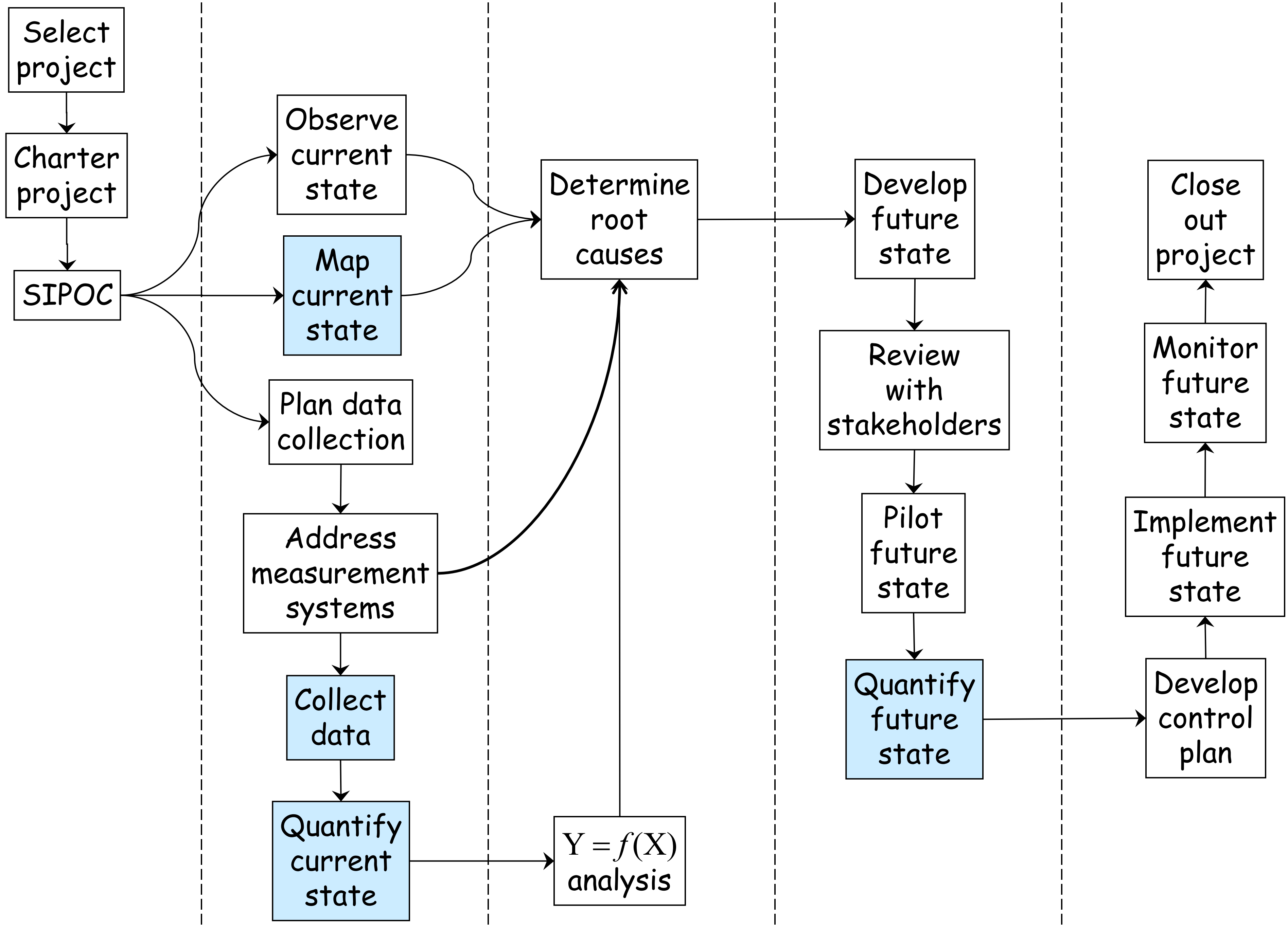
There are two types of material, A and B. The material must be processed before it can be used. There are two steps in this process. For Process 1, the A and B materials must be processed in separate Type 1 machines. If two Type 1 machines are available, load the A material into one machine, the B material into the other, and run the two machines at the same time. If there is only one Type 1 machine available, run the two loads sequentially in that machine.

When Process 1 is completed, unload the material, and move on to Process 2. Process 2 requires Type 2 machines. If two Type 2 machines are available, load the A material into one machine, the B material into another, and run the two machines at the same time.

Unlike the Type 1 machines, the A and B material can be processed together in the same Type 2 machine. If there is only one Type 2 machine available, load both the A and B material into that machine for processing. This will take longer than processing the A and B materials in separate machines, but not as long as running two loads sequentially.

When Process 2 is completed, unload the material, separate the A and B materials if necessary, then store them for subsequent use.

7 Value Stream Mapping



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

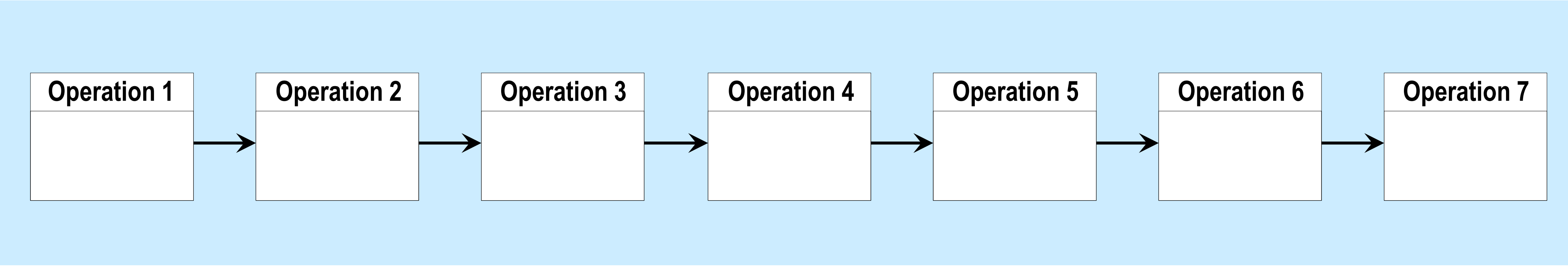
The nature of Value Stream Mapping

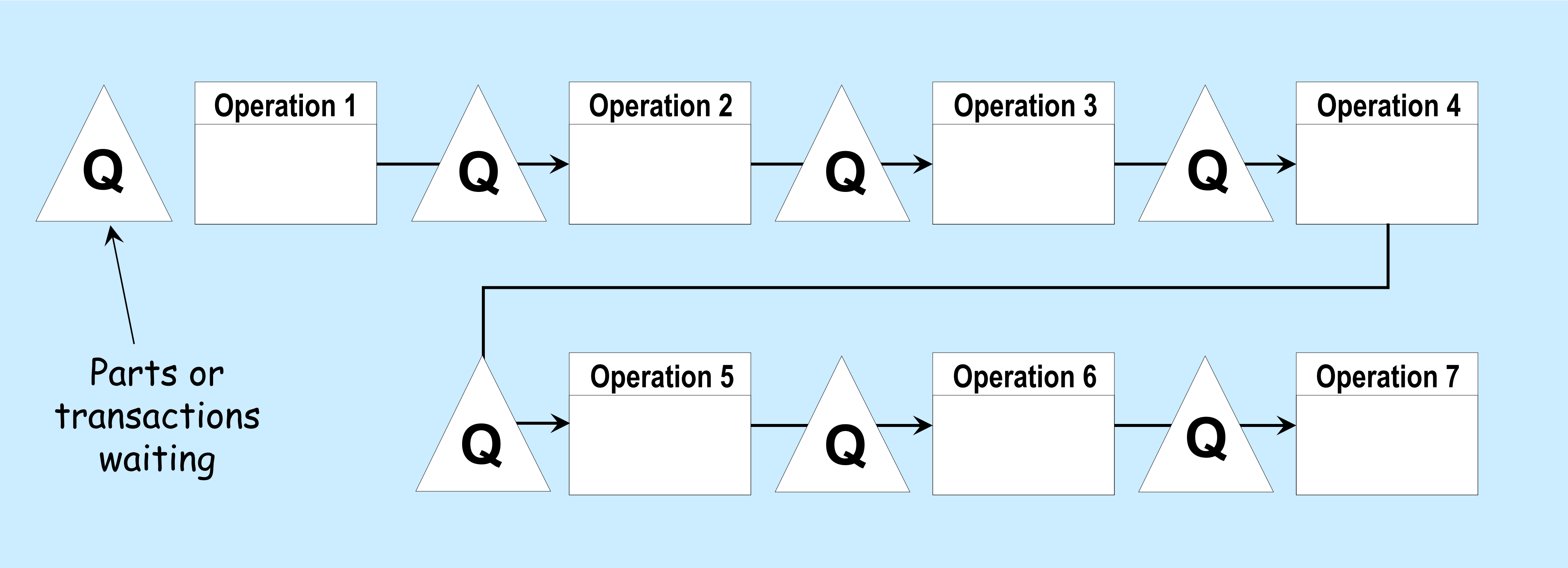
- Value stream mapping (VSM) combines several things:
    - ✓ Visualization of the current state
    - ✓ Documentation of the current state
    - ✓ Certain types of data collection and analysis

- VSM is an effective way to identify improvement opportunities
    - ✓ Especially in projects involving WIP, capacity, and lead time reduction
    - ✓ Also used to document the future state

From SIPOC to VSM

High-level map from SIPOC



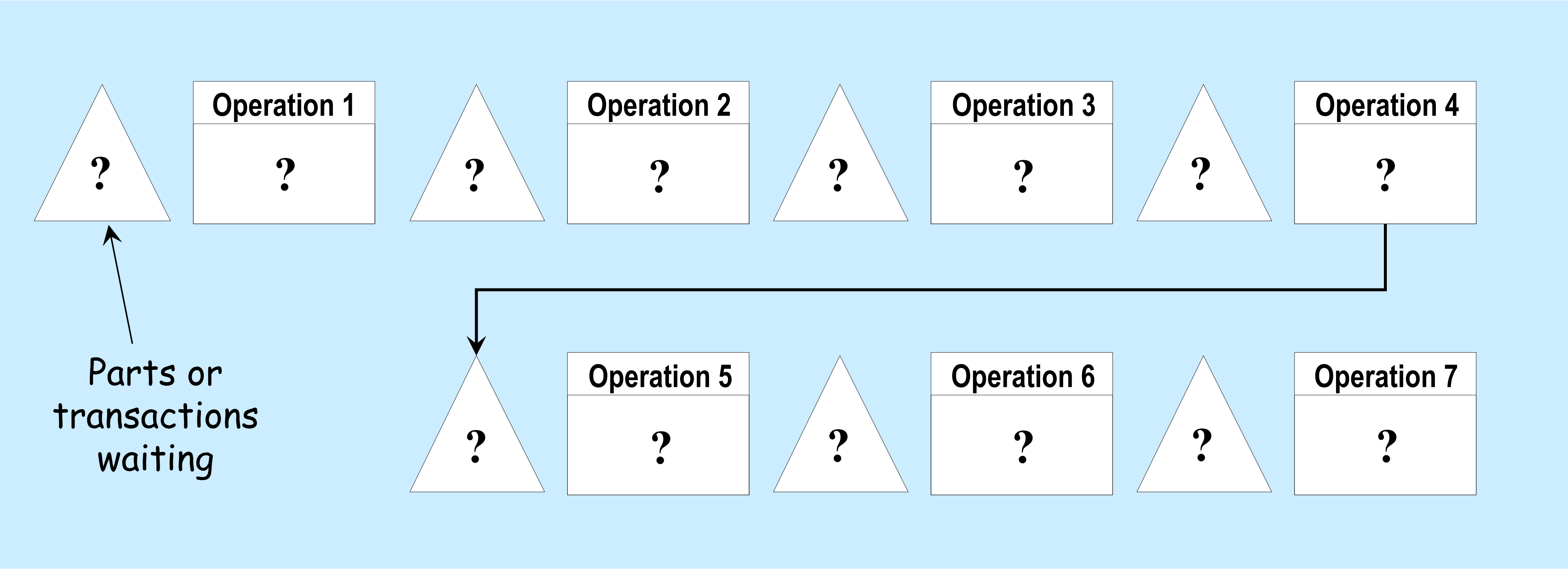


VSM, no data yet

What is the average lead time?

How much time is spent in each box or triangle?

How do we get this information?



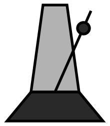
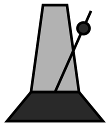
Definitions

Available Working Time (AWT)	• The time a process is available to conduct work • AWT excludes time when work isn't occurring such as time for breaks, meetings, lunch, preventative maintenance, estimates of unplanned downtime, change overs, etc.
Throughput (Tput)	• The average number of good parts or transactions completed over a period of time • Typically measured as average over at least several days • Throughput, lead time, and WIP are related through Little's Law

Definitions (cont'd)

Lead time (LT)	• The total elapsed time to produce one defect free product or transaction • The time difference between when a part or transaction enters and leaves a process
Customer Demand Rate (CDR)	• The number of parts or transactions that the customer desires over a period of time (usually a day, week, or month)

Definitions (cont'd)

Takt time (TT)	• The pace at which an operation should complete products or transactions in order to meet customer demand during the Available Working Time.  • Available working time during a period divided by the number of products or transactions *required* during that same period
Cycle time (CT)	• The fastest repeatable time between part or transaction completions using the current processes and resources  • Shows how a process is capable of performing • Combines with AWT to determine capacity

Definitions (cont'd)

Process Cycle Efficiency (PCE)	• The percentage of time that WIP is being transformed by VA activities. In other words, the percentage of lead time that is value added.
Work In Progress (WIP)	• Includes items waiting to be worked on and items actively being worked on. WIP includes all of the inventory in the production system.

Example 1

Available Working Time per day = 480 min – 90 min breaks, lunch, meetings

= 390 min

Avg. daily Customer Demand Rate = 32 units

$$\text{Takt time} = \frac{390 \text{ minutes}}{32 \text{ units}} = 12.2 \text{ mins}$$

During a study of this process, parts were completed at the following times:

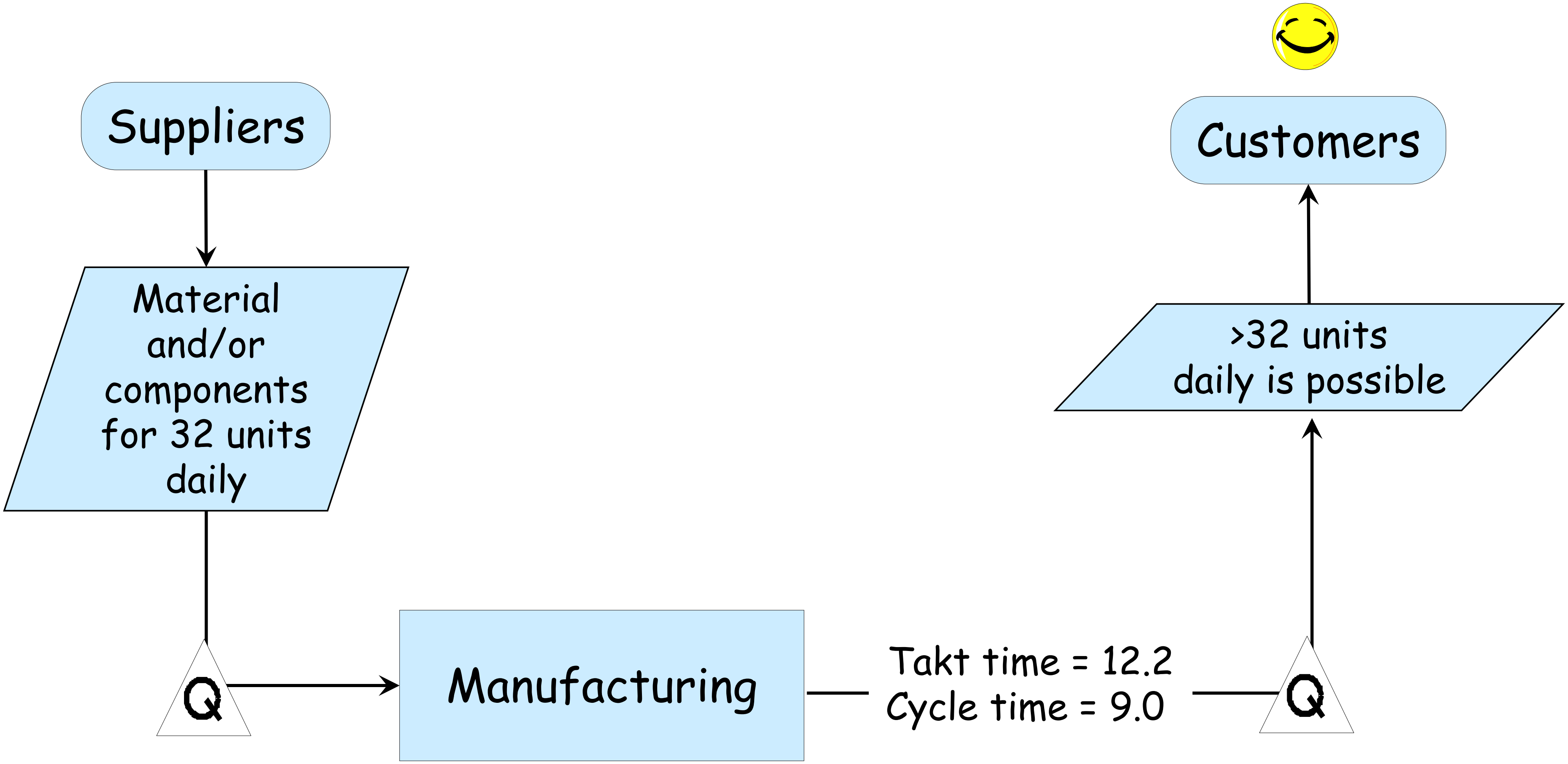
9:00, 9:09, 9:17, 9:28, 9:37, 9:46, 9:58, 10:07, 10:16, 10:24, 10:33, 10:42

Based on this, the elapsed time in minutes between completed units was:

9, 8, 11, 9, 9, 12, 9, 9, 8, 9, 9

Cycle Time = 9 minutes (the fastest repeatable value)

Example 1 (cont'd)



Suppliers

Material and/or components for 32 units daily

Q

Manufacturing

Takt time = 12.2
Cycle time = 9.0

Q

>32 units daily is possible

Customers

Getting used to takt time and cycle time

- Units of takt and cycle time: time divided by quantity
  - Shorter cycle time → more output
  - Longer cycle time → less output

- Cycle time *longer* than takt time
  - **Cannot** meet customer demand with current processes and resources

- Cycle time *shorter* than takt time
  - **Can** meet customer demand with current processes and resources, but may need to eliminate process variation

We may not want to operate as fast as possible

- Takt time longer than cycle time
- Downstream operations constrained to cycle time of upstream bottleneck
- Upstream operations pace themselves to cycle time of downstream bottleneck (pull system)

Exercise 7.1

Using the information provided in Example 1, consider the scenario where the customer wants to increase their purchases from 32 to 42 units per day.

a) What is the new takt time?

b) What is the cycle time and is the new takt time faster or slower than the cycle time?

c) Can you accommodate this demand increase?

d) What problems might need to be solved?

e) Why should cycle time measurements not typically be taken from process output data in an ERP system?

How do we get lead time data?

Method	Drawbacks
Download accurate, time stamped records from database	• The best scenario, if such data exists • Make sure WIP time is accounted for properly
Shadow parts or transactions	• Tedious • Logistically difficult • Time consuming for team members
Tag documentation	• Anything identified as "special" is likely to be expedited • Data will not represent reality
Enter "file cabinet data" into Excel	• Tedious and time consuming • Likelihood of data entry errors • May not exist
Little's Law	• Allows calculation of LT from WIP and T'put

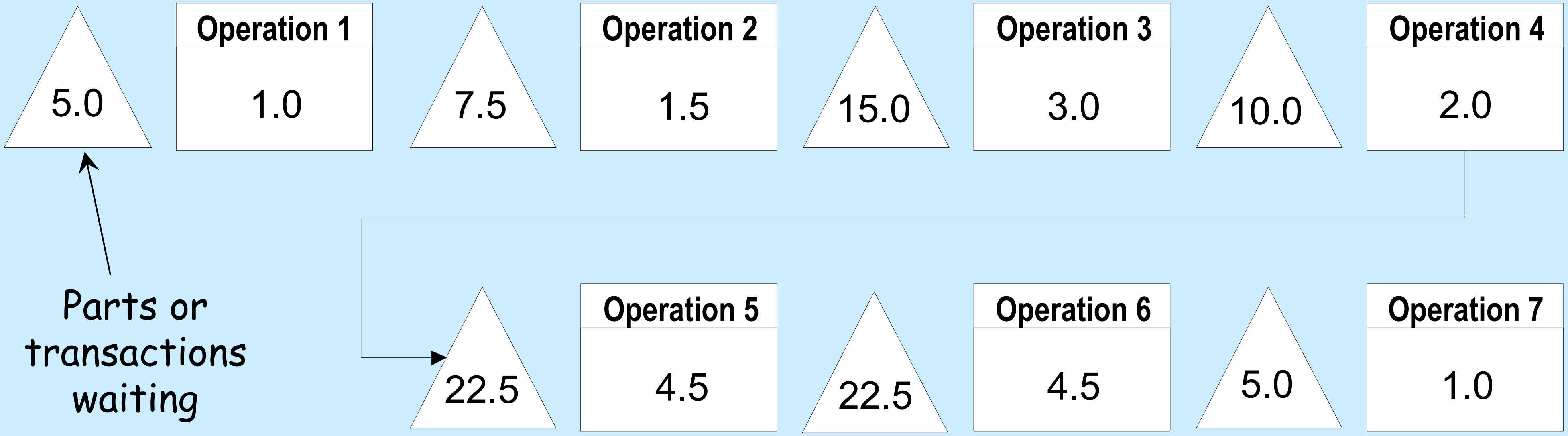
Little's law

Lead Time = (WIP) / (Throughput)

- WIP is easy to count during process observation
- If WIP varies, count multiple times and use average or min/max to show range in lead time
- Throughput is the quantity completed during an observation period. Period should be at least several days.
- Lead time = amount of time that passes between when a piece enters and leaves a process or processes
- These values can be calculated for individual processes or for an entire production process chain

VSM with WIP data

Average WIP for each box and triangle during an observation period



5.0

Operation 1
1.0

7.5

Operation 2
1.5

15.0

Operation 3
3.0

10.0

Operation 4
2.0

22.5

Operation 5
4.5

22.5

Operation 6
4.5

5.0

Operation 7
1.0

Parts or transactions waiting

- Suppose in the system shown above, each operation has a throughput of 6 pieces per hour, so the entire production process is also making 6 pieces per hour
- We can use Little’s Law to calculate the overall lead time for the process, for individual processes, or for subsets of processes

Applying Little's Law

	Avg. WIP
Queue 1	5.0
Operation 1	1.0
Queue 2	7.5
Operation 2	1.5
Queue 3	15.0
Operation 3	3.0
Queue 4	10.0
Operation 4	2.0
Queue 5	22.5
Operation 5	4.5
Queue 6	22.5
Operation 6	4.5
Queue 7	5.0
Operation 7	1.0
Total	**105.0**

The previously described process was studied and the average WIP counts are shown here. They are measured as follows:

- Queue WIP is the average pieces waiting to be processed. For example, Queue 1 WIP is the typical amount of work waiting to be processed by Operation 1.
- Operation WIP is the average pieces actively being processed. For example, Operation 1 is typically processing one piece.
- The Total WIP in the process is the sum of all of the Queue and Operation WIPs

Applying Little's Law

	Avg. WIP
Queue 1	5.0
Operation 1	1.0
Queue 2	7.5
Operation 2	1.5
Queue 3	15.0
Operation 3	3.0
Queue 4	10.0
Operation 4	2.0
Queue 5	22.5
Operation 5	4.5
Queue 6	22.5
Operation 6	4.5
Queue 7	5.0
Operation 7	1.0
Total	**105.0**

We can apply Little's Law to the entire process, an individual process, or a subset of processes. Remember:

Lead Time = (WIP) / (Throughput)

Since each operation, and therefore the entire process sequence, averages 6 pieces per hour, Little's Law lets us calculate lead times as follows:

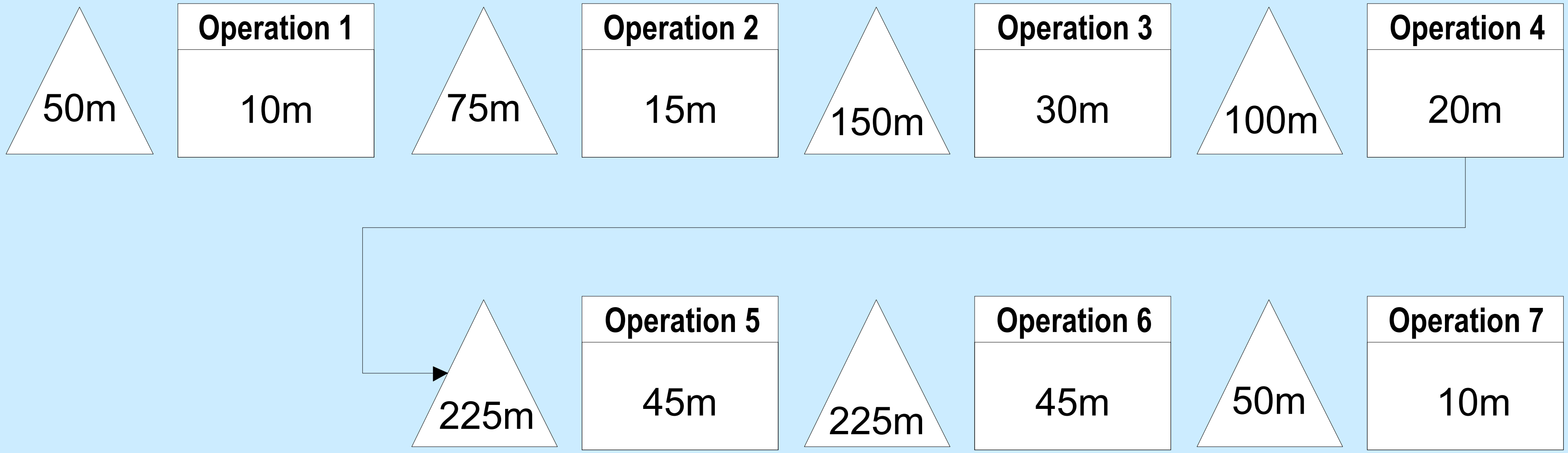
- For the entire process:

Lead Time = 105 pieces / 6 pieces per hour
= 17.5 hours or 1050 minutes

- For Queue 1 and Operation 1:

Lead Time = 6 pieces / 6 pieces per hour
= 1 hour or 60 minutes

VSM with waiting and process times



Lead time = 1050 minutes or 17.5 hours

Waiting time = Sum of time in queue
= 50 + 75 + 150 + 100 + 225 + 225 + 50 + 10 = 875 minutes

Process time = Sum of time the pieces are being worked on
= 10 + 15 + 30 + 20 + 45 + 45 + 10 = 175 minutes

Process Cycle Efficiency = The percent of lead time that a part is being worked on
= (175 / 1050)*100 = 16.7%

Exercise 7.2

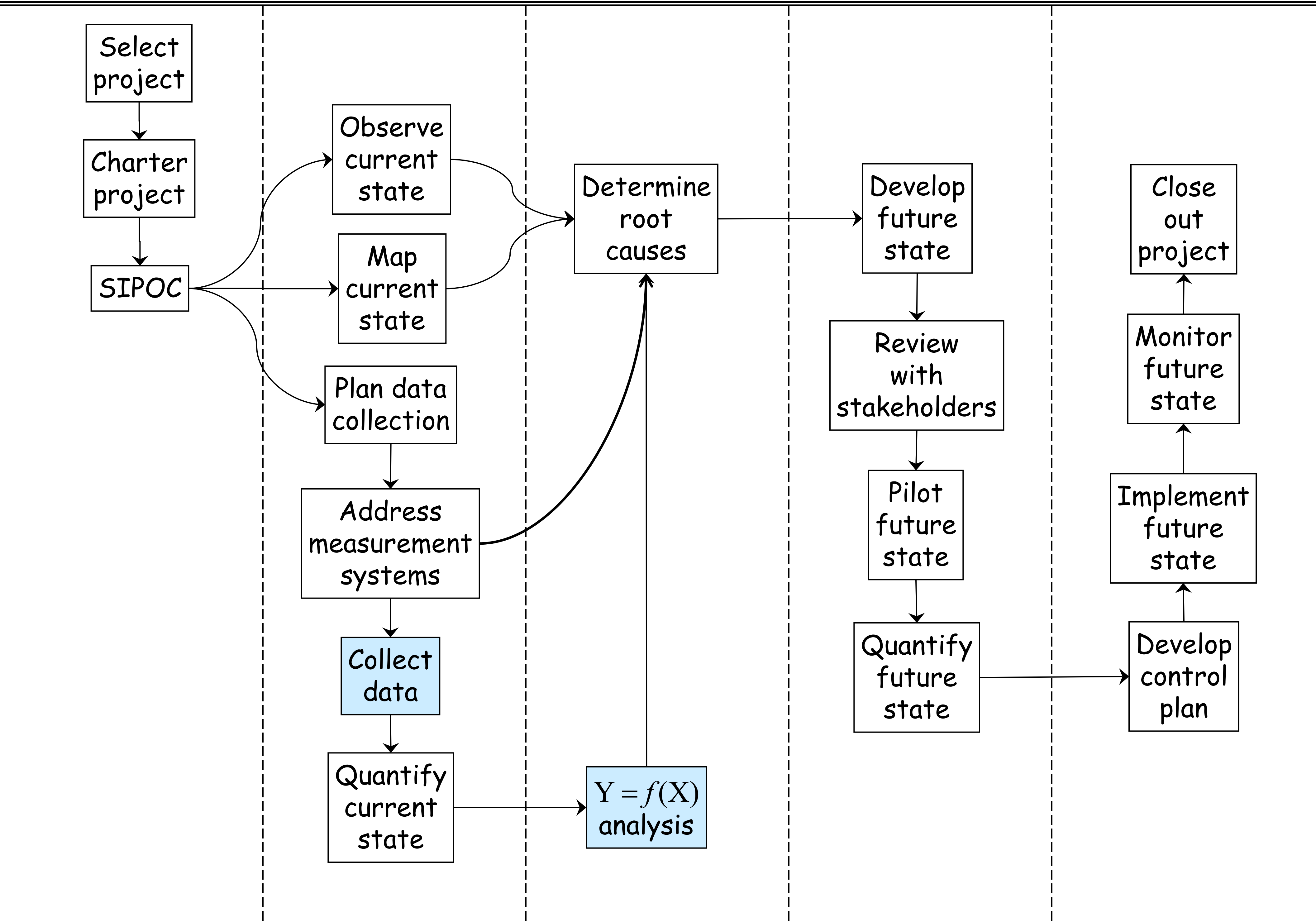
a) A manufacturing process completes an average of 45 defect-free parts each day. The average WIP is 15 parts. Calculate the average lead time in hours.

b) Supposing in the example above, the company works one 8-hour shift per day. Under what conditions would this impact the lead time calculations and when would it not?

c) A manufacturing operation runs 365 days a year. They produce about 416 defect-free units of a particular product per year. The average WIP for this product is 40. Calculate the average lead time in days.

d) Should raw materials be counted as WIP?

8 X and Y Variables



Select project

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Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

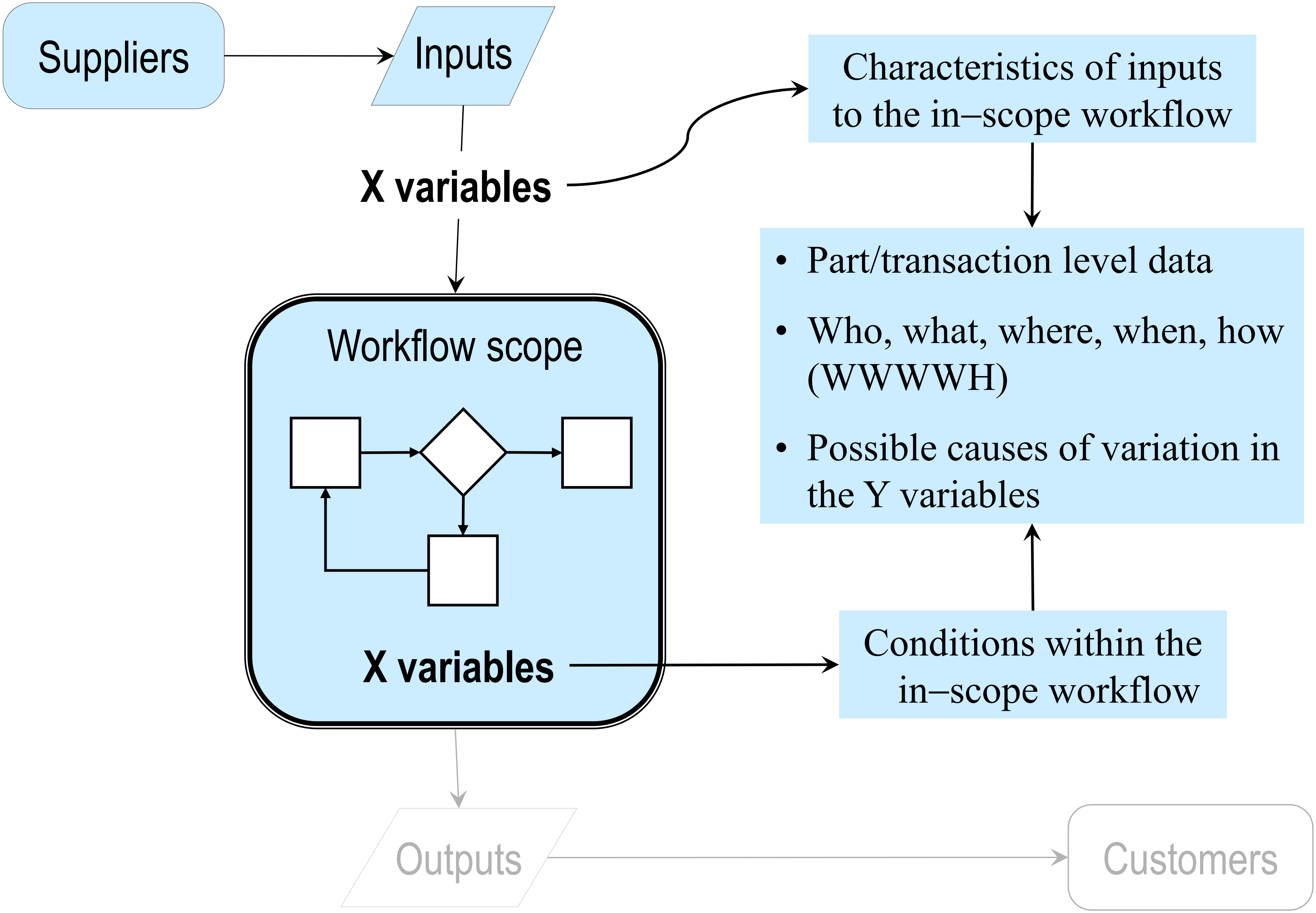
Monitor future state

Close out project

Topics

- X variables
- Fishbone Diagram
- Prioritizing X variables
- Y variables
- Operational definitions for data variables
- “Big Y” and “little y”

X variables



Suppliers

Inputs

X variables

Characteristics of inputs to the in–scope workflow

- Part/transaction level data
- Who, what, where, when, how (WWWWH)
- Possible causes of variation in the Y variables

Workflow scope

X variables

Conditions within the in–scope workflow

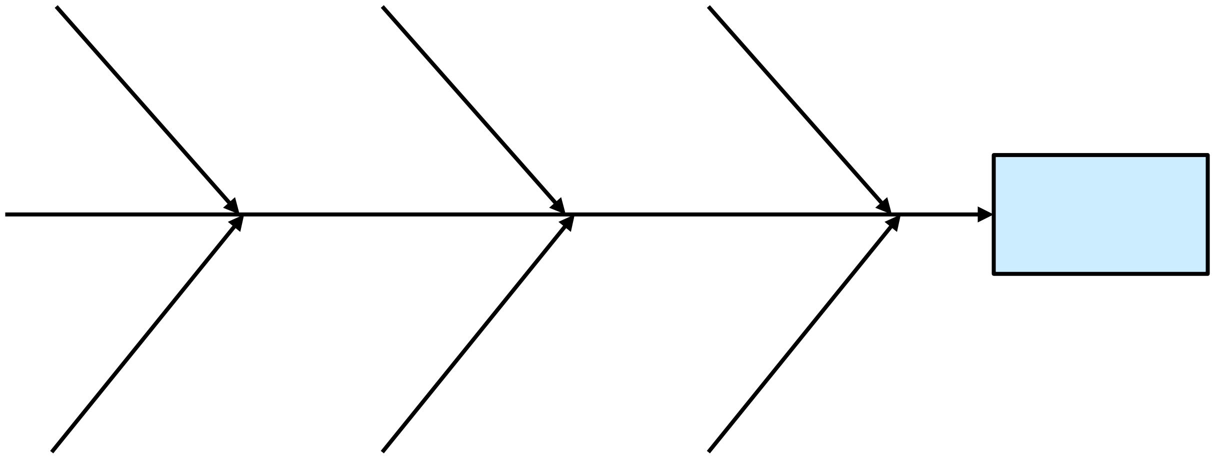
Outputs

Customers

Fishbone Diagram

The Fishbone Diagram is:

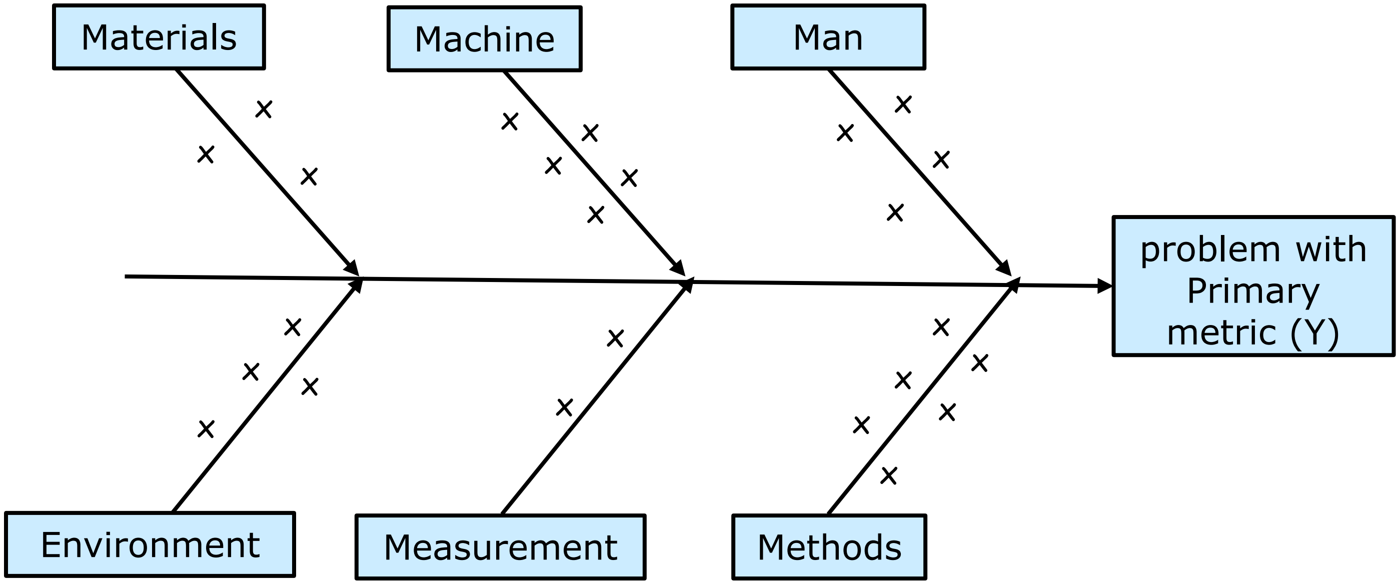
- used to identify all potential causes (X's or inputs) of the effect (output or problem of interest), usually the primary metric.
- part of identifying process inputs during the Measure Phase
- most often associated with root cause analysis
- also known as Cause-and-Effect Diagram and Ishikawa Diagram



Fishbone Diagram (cont.)

The Fishbone Diagram is created with the project team.

- It focuses the team on the particular effect, shown in the "head of the fish"
- All ideas for potential causes (critical x's) are collected using brainstorming
- Categories on the main "bones" help trigger ideas
  - Standard categories are Man, Machine, Materials, Methods, Measurement and Environment ("5 M's and an E")
  - The team can choose to use different categories
  - Standard categories (with minor modifications) are recommended for your first uses



Materials

Machine

Man

Environment

Measurement

Methods

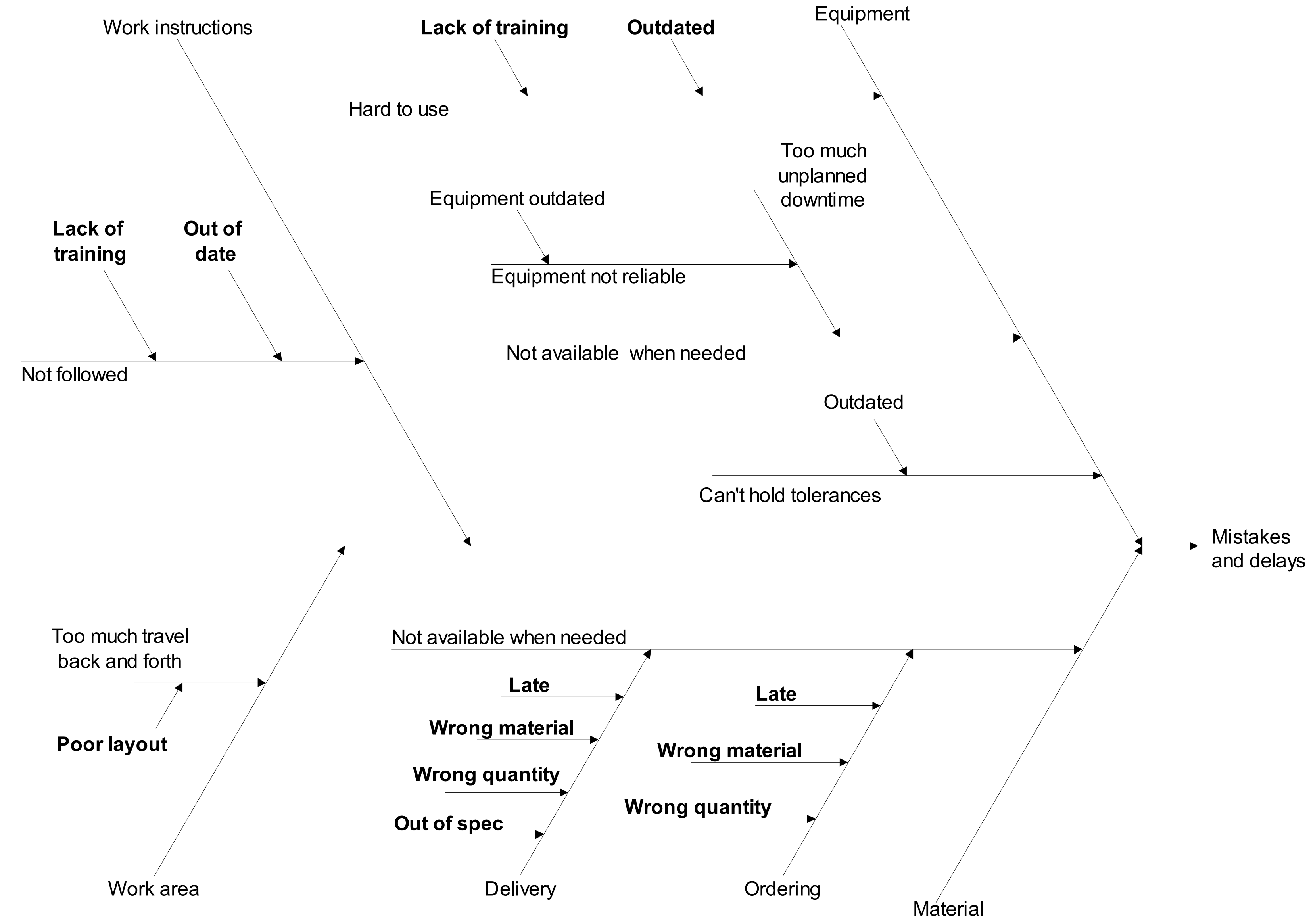
problem with Primary metric (Y)

Steps for Creating a Fishbone Diagram

The Fishbone Diagram must be visible to the entire team during the brainstorming (creation) session.

1. Put output of interest (usually primary metric) in the “head of the fish.”
2. Choose categories for “bones”
   - Standard Categories: Man, Machine, Materials, Methods, Measurement, Environment
   - The team can choose to use other categories
3. Brainstorm all possible inputs (x’s) that could cause the problem seen in the output (primary metric—Y)
   - Rules for Brainstorming: Accept all stated ideas and add to diagram; No ideas are evaluated or rejected during the brainstorming session
4. Break broad categorical x’s into more useful, more measurable features
   - Measurable features can be verified as causes of performance issues in the primary metric during the Analyze Phase
   - We can act upon them to improve the process
   - They need to be identified early in the project
   - Example: Work instructions not followed—out of date; lack of training
5. Highlight those x’s deemed most important by the team

Fishbone Diagram Example (non-standard categories)



Exercise 8.1

A project has been launched to improve the mounting bracket development process (MBDP) in a company that makes mounting brackets. Background on the project and process may be found in the following files in the *Student Files* folder:

MBDP charter

MBDP description for process map

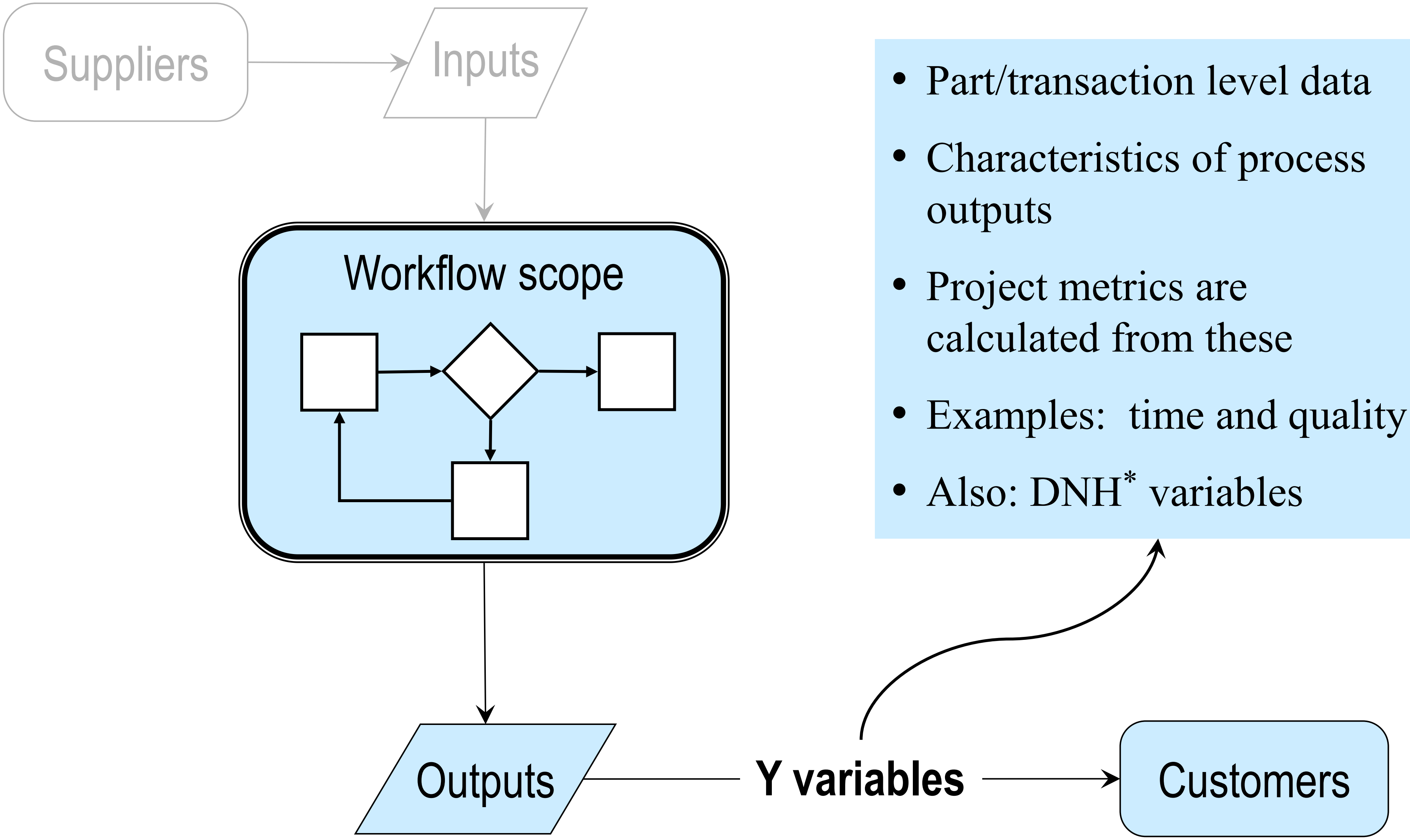
Based on the information in these documents and the process map you created earlier, create a Fishbone Diagram for this project.

Prioritizing X’s using Multi-voting

Another method for prioritizing X’s for data collection is to use multi-voting:

1. Count the number of X’s
2. Divide the total number of X’s by 3. Each team member gets that many “votes”
3. Each team member decides how they will apply their votes, giving one vote to each X they think is a most likely main contributor to the problem
    - Give a marker to each team member and have them write their votes on the fishbone diagram or list
    - Use a *secret ballot* if there are concerns of undo influence among team members
4. Focus data collection on those X’s that rise to the top

Y variables



- Part/transaction level data
- Characteristics of process outputs
- Project metrics are calculated from these
- Examples: time and quality
- Also: DNH[*] variables

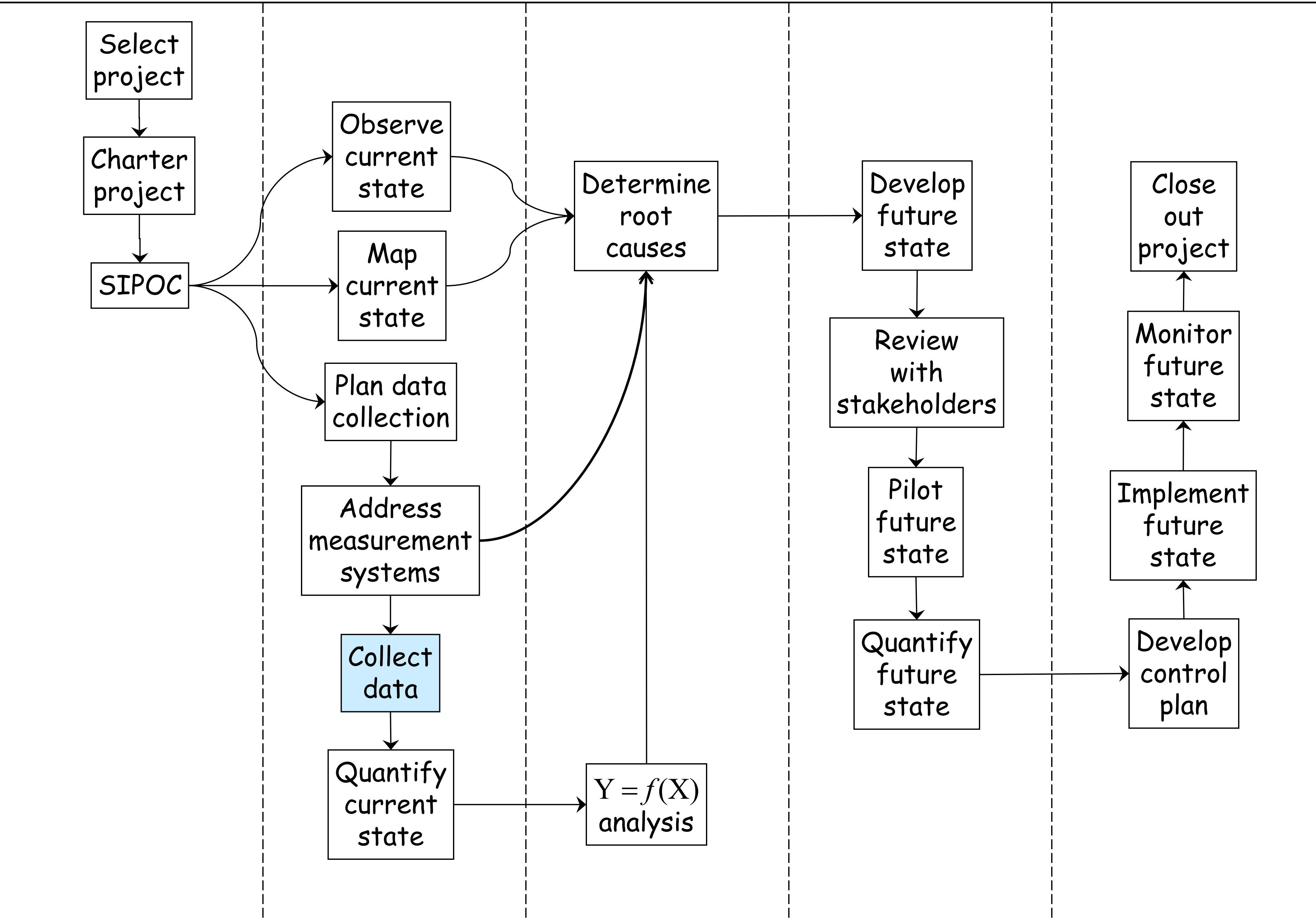
---

[*] Do No Harm — not trying to improve them, just don't want to make them worse.
These are your secondary project metrics.

Operational definition for a Y variable

Examples of questions to be answered

- How, and from what basic quantities, will Y be calculated?
- What measurement system will be used?
- If Y is a lead time, what are the starting and stopping points?
- If Y is pass/fail, what are the possible defects?
- If you are going to count defects per opportunity, how are the opportunities defined?
- If Y is unplanned downtime, how will you record your data: hourly/daily/weekly summaries or event log?
- If there is existing data, can you use it with minor modifications to your operational definition(s)? (Data readily available will jump start your project. Use it whenever possible, even if minor adjustments to the project scope are needed.)



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Purposes of data collection

- Calculate project metrics for the current state
- Pareto analysis of defect types, error types, failure reasons, etc.
- Comparisons within the current state (stratification analysis)
- Correlation of X and Y variables
- Use analysis results to help identify root causes

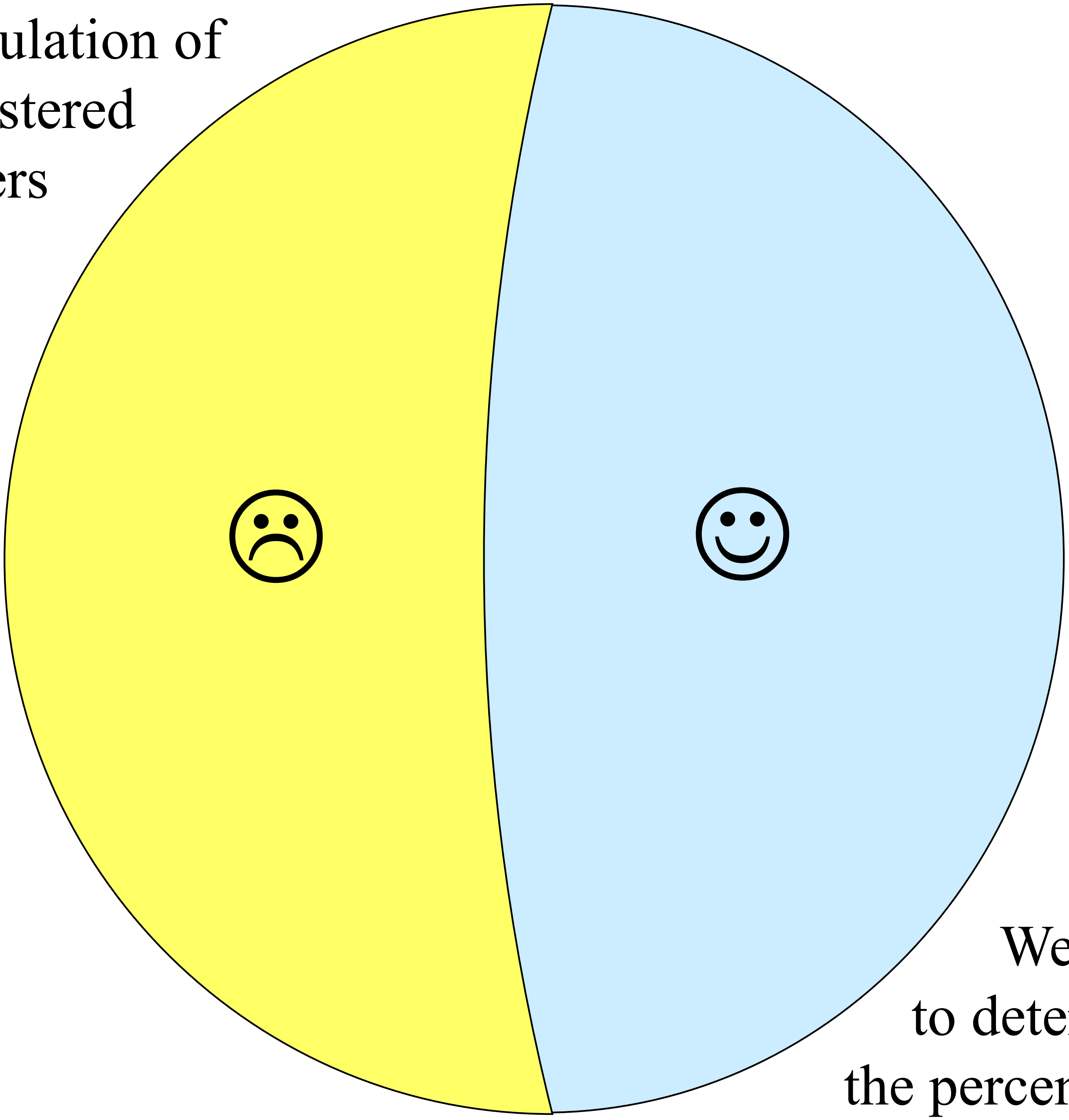
Population sampling

Population	• A specified collection of people or things
Sample	• A subset of a population • Usually relatively small • Intended to represent the population

Example: opinion poll

Population of
registered
voters

“Do you support
the President’s
policy on _____ ?”



We want
to determine
the percentages

The sample must be representative

"Do you support the President's policy on _____?"

Representative sampling (cont'd)

- Examples of obvious biases: sample includes only
  - ✓ Democrats
  - ✓ Republicans
  - ✓ Men
  - ✓ Women
  - ✓ Residents of Wyoming
  - ✓ Convicted white collar criminals
  - ✓ Relatives of elected government officials

- Standard survey sampling technique
  - ✓ All counties are categorized into something like 30 groups ("strata") according to population density
  - ✓ Each stratum (group of counties with similar population density) is randomly sampled in proportion to its population

- This is an example of *stratified random sampling*

Exercise 9.1

Decide whether the proposed sample in each case below will be representative of the population. If not, note obvious or possible biases on the slide below.

Population	Purpose	Proposed sample
(a) Former Enron employees	Opinion on culpability of top Enron executives	Those with the largest retirement accounts, comprising 85% of lost value
(b) A year, make, and model of car	Surreptitiously determine % with a given defect	Offer a free ____ until 100 cars have been inspected at each US dealership
(c) ER patients at a hospital last year	Customer satisfaction survey	Those whose last names begin with the letter M
(d) Lambs born in New Zealand last year	Determine % with "mad lamb" disease	Random sample of each ranch in NZ, proportional to # of lambs
(e) Registered voters	Opinion on presidential candidate	Generate telephone numbers at random, call those people

Exercise 9.1 (cont'd)

(a)

(b)

(c)

(d)

(e)

Incorrect interpretation of survey data

“Do you support
the President’s
policy on _____?”

☐ 51% of the people responding to the survey say “yes”

Infotainment Nightly “News”

“According to a recent survey, the majority of registered voters support the President’s policy.”

Interpretation of survey data (cont'd)

- Suppose the sampling plan was perfectly representative of the population

- Still, we cannot say that what is true in the sample is true in the population

- The sample data does *not* prove that 51% of registered voters agree with the President's policy

Must quantify the uncertainty

"Do you support the President's policy on ____?"

Rational Public Radio

"51% of sampled voters supported the President's policy. The margin of error is ±3 percentage points, so the survey is inconclusive."

Quantifying uncertainty (cont'd)

- "Margin of error" (MOE) is how we quantify our uncertainty about the population in light of the sample data
- The most we can say: "The percentage of registered voters agreeing with the President's policy is between 48% and 54%"
- The data fails to demonstrate a majority on *either* side of the question

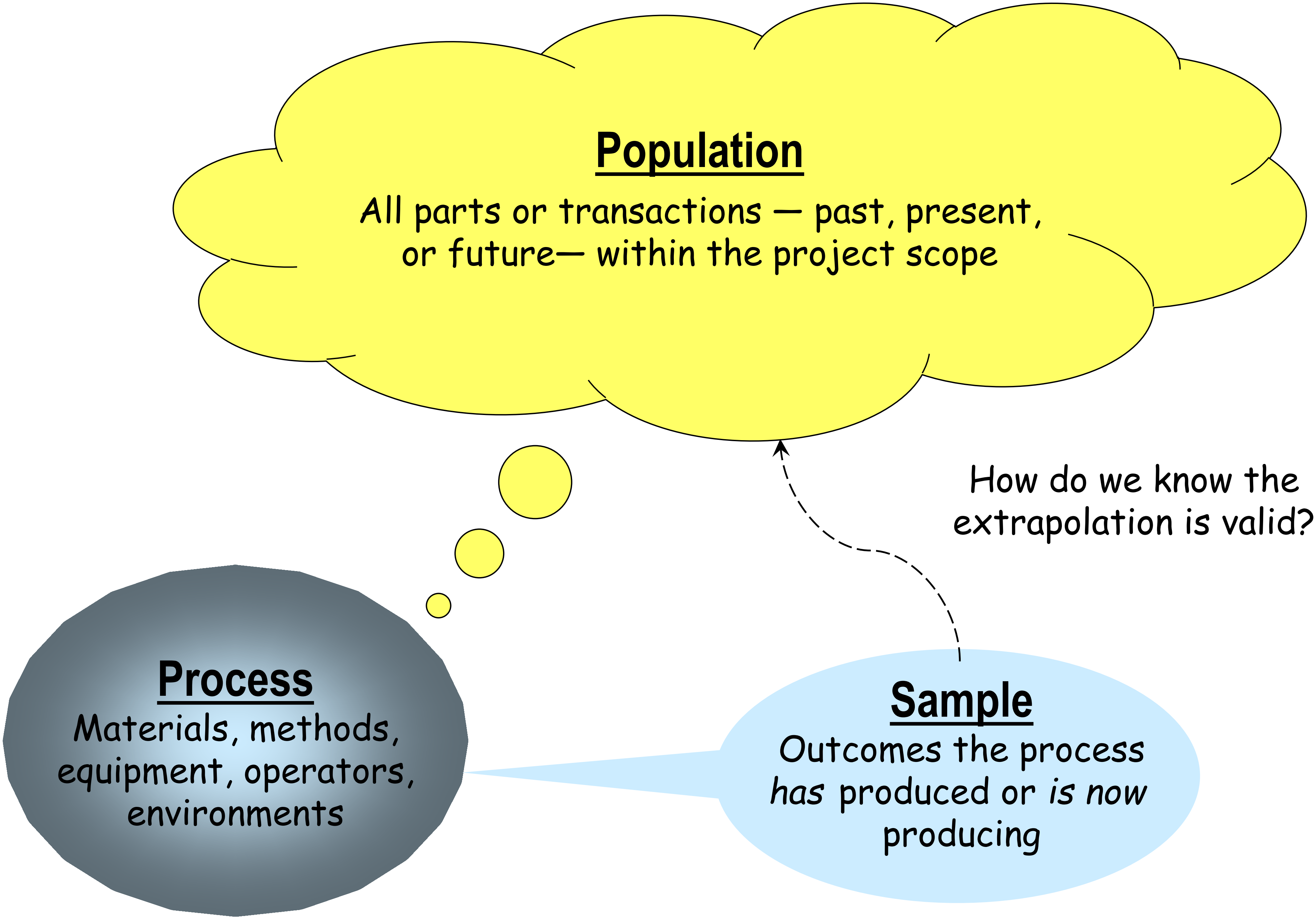
Process sampling

Process A predetermined sequence of actions and decisions intended to produce a desired outcome. (A way of doing something.)

- ✓ Manufacturing process
- ✓ Service process
- ✓ Business process
- ✓ Transactional process
- ✓ Decision process
- ✓ Design process

For any process, there is an associated *population*

Process sampling (cont’d)



Population

All parts or transactions — past, present, or future— within the project scope

How do we know the extrapolation is valid?

Process

Materials, methods, equipment, operators, environments

Sample

Outcomes the process *has* produced or *is now* producing

Process sampling for LSS projects

- 100% sampling for a period of time, is the most common method
- What are some situations where 100% sampling is not possible?
- The sample must cover a representative time period
- The sample must capture all *typical sources of variation* (see slide below)

Typical sources of variation

Process participants

“Identical” pieces of equipment

Time of day, week or month

Batches or lots of raw material

Different suppliers

Production lots, work orders, . . .

Different locations

Changing environmental conditions

Multiple measurement systems

⋮

“Less than 100%” sampling methods

Random	Items are selected by a random number generator
Systematic	Items are selected at regular intervals
Stratified random[*]	Items are sampled from homogeneous subpopulations, in proportion to subpopulation size
Judgment	Items are selected using knowledge of the process
Convenience	Items are selected based on cost or ease of access

[*] Usually considered to be the most representative sampling method.

Exercise 9.2

Check the sampling methods that apply in each case based on the given information.

	Random	Systematic	Stratified	Judgment	Convenience
Pulled 10 parts off the high-volume production line at the top of each hour					
Reviewed Enron electricity trades during periods of highest demand					
Used random numbers to select 10% of patient charts for the past year					
Monitored every 1000th customer service call					
Downloaded invoices with numbers ending in 0 or 5					
Inspected the first 3 parts from each production lot					
Took a sample from the top of each barrel on the top layer of the stack					

Sample size

- Amount of data: more is better than less
- Time period: longer is better than shorter*
- Capturing all typical sources of variation usually gives an adequate sample size
- You should do a sample size calculation just to make sure

---

*But beware of old data that is no longer relevant to your current state.

Sample size calculation: opinion poll example

ϕ	The fraction (proportion) of people in the population who would say yes to the survey question if asked. We don't know, and will never know, the exact value of ϕ. However, we can get an accurate estimate of ϕ if we collect enough data.
Sample	The people who respond to the survey. Usually, this is a very small subset of the population.
ϕ_{sample}	The fraction (proportion) of the respondents who say yes to the survey question. This is our estimate of ϕ. We don't know this now, but we will after we get the data.
MOE	Margin of error: the amount by which ϕ_{sample} could differ from ϕ, based on an established statistical standard of evidence. The most common standard of evidence is called "95% confidence."
N	The number of people who respond to the survey — the *sample size*. The required sample size depends on ϕ_{sample} and the desired MOE.

Sample size (cont'd)

In most opinion polls, ϕ_{sample} is assumed to be close to 0.5 when determining sample size. This gives the largest sample size needed to achieve the desired margin of error (MOE). If ϕ_{sample} is not 0.5, the MOE will be smaller, which is desirable. The approximate formula for the MOE (with 95% confidence) is:

$$\text{MOE} = 1.96\sqrt{\frac{\phi_{\text{sample}}\left(1 - \phi_{\text{sample}}\right)}{N}} = 1.96\sqrt{\frac{0.5\,(0.5)}{N}} = \frac{0.98}{\sqrt{N}}$$

We can solve this equation for N:

$$N = (0.98 / \text{MOE})^2$$

MOE	**N**
0.05	384
0.04	600
0.03	1067
0.02	2401
0.01	9604

Sample size calculation: process applications

- In process applications, ϕ represents the fraction defective

- In this case, the margin of error on the high side is of greatest interest:

$$\phi_{\text{sample}} + \text{MOE}_{\text{upper}} = \text{Upper bound on } \phi \text{ (with 95\% confidence)}$$

- To do a sample size calculation, we must provide two inputs:

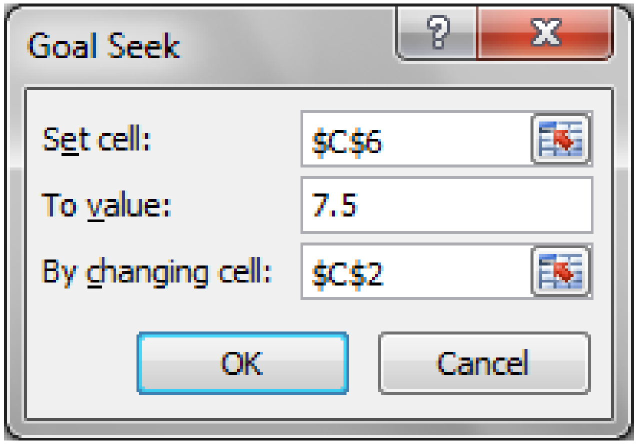
  a) A guess for ϕ_{sample}

  b) An acceptable upper bound on ϕ (giving the desired MOE, which is the difference between this upper bound and ϕ_{sample})

- Open *Student Files* → *calculator - sample size* → *% Defective*

Example

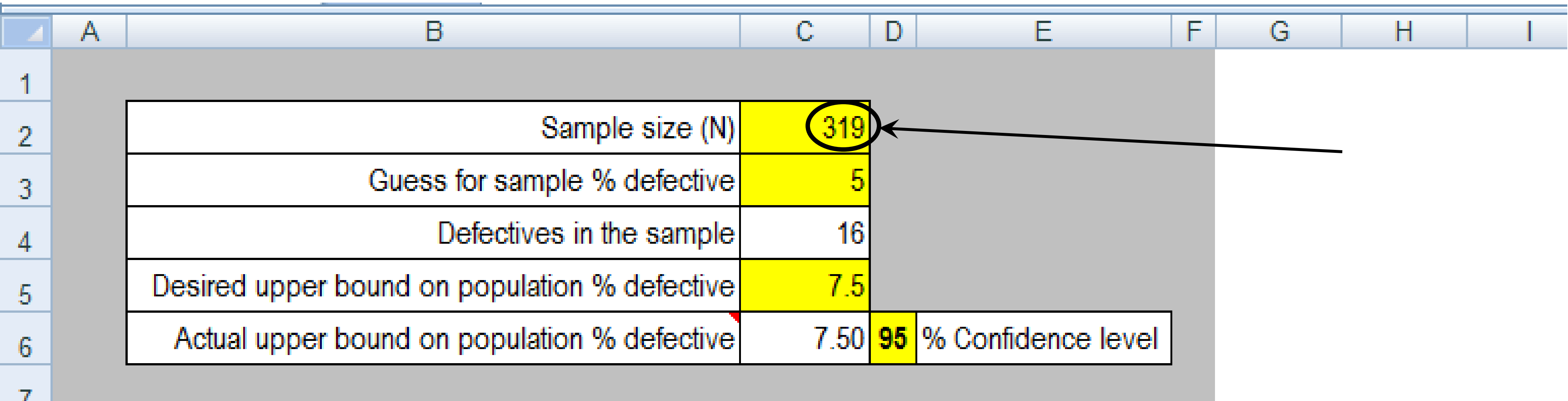
- We think ϕ_{sample} will be close to 0.05 (5% defective)
- If this turns out to be true, we want to be able to say (with 95% confidence) that ϕ is no larger than 0.075 (7.5% defective)
- Enter 1 in cell C2, 5 in C3, and 7.5 in C5
- We want to set cell C6 to 7.5 by changing cell C2
- Select *Data* → *What If Analysis* → *Goal Seek* → set up as shown to the right → click OK



Set cell: $C$6

To value: 7.5

By changing cell: $C$2



Sample size (N)	319		
Guess for sample % defective	5		
Defectives in the sample	16		
Desired upper bound on population % defective	7.5		
Actual upper bound on population % defective	7.50	95	% Confidence level

Exercise 9.3

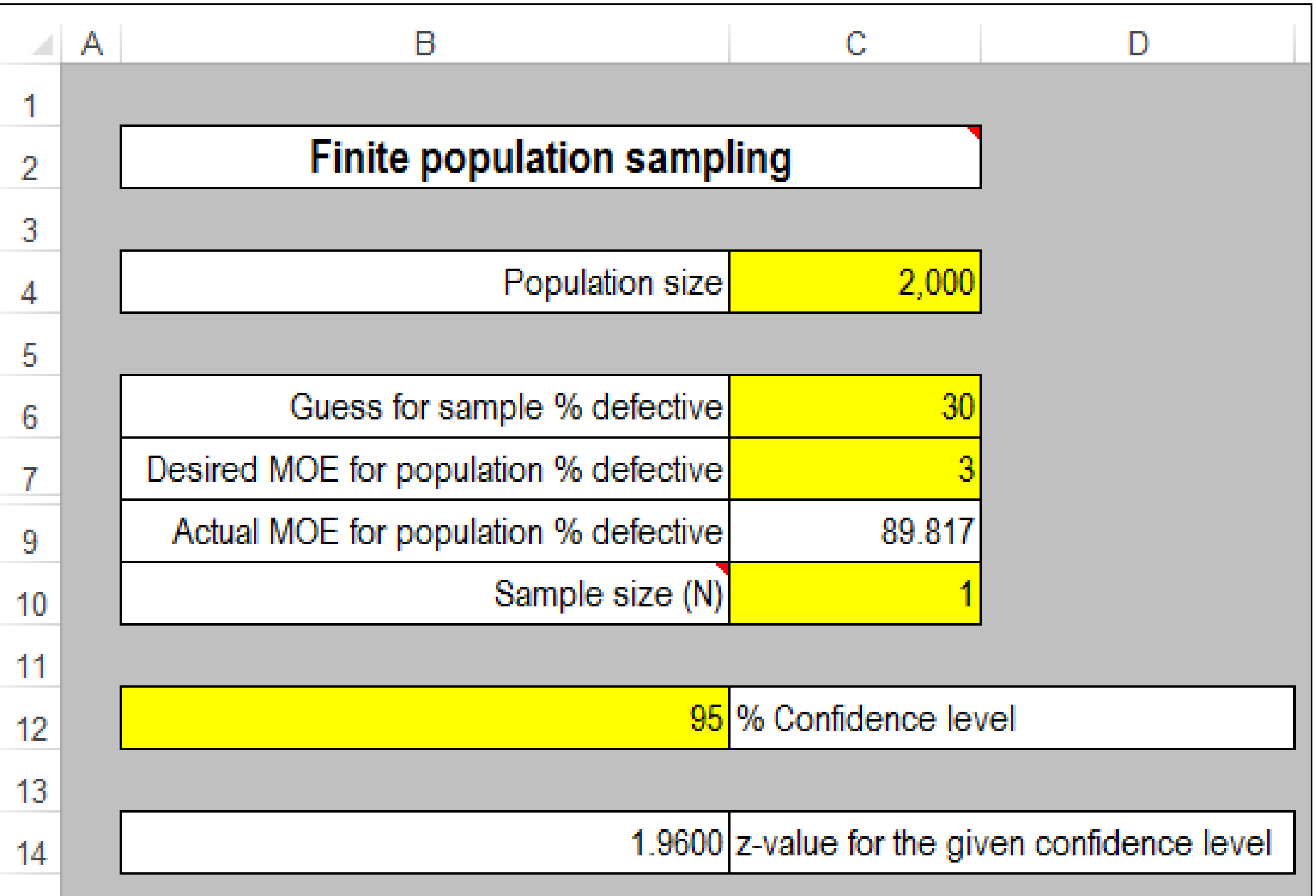
We want to get an accurate estimate of the population % defective. Find the required sample size in the following scenarios.

	Guess for sample % defective	Desired upper bound on population % defective	Sample size
(a)	10	20	
(b)	10	15	
(c)	10	13	
(d)	1	4	
(e)	1	3	
(f)	1	2	

Finite population sampling

Open *Student Files → calculator - sample size → Finite population sampling*

- We want to determine the % defective in a finite population of size 2000
- Enter the values shown below in cells C4, C6, and C7
- We want to set cell C9 to 3 by changing C10



	A	B	C	D
1				
2		**Finite population sampling**		
3				
4		Population size	2,000	
5				
6		Guess for sample % defective	30	
7		Desired MOE for population % defective	3	
9		Actual MOE for population % defective	89.817	
10		Sample size (N)	1	
11				
12		95	% Confidence level	
13				
14		1.9600	z-value for the given confidence level	

Data

↓

What If Analysis

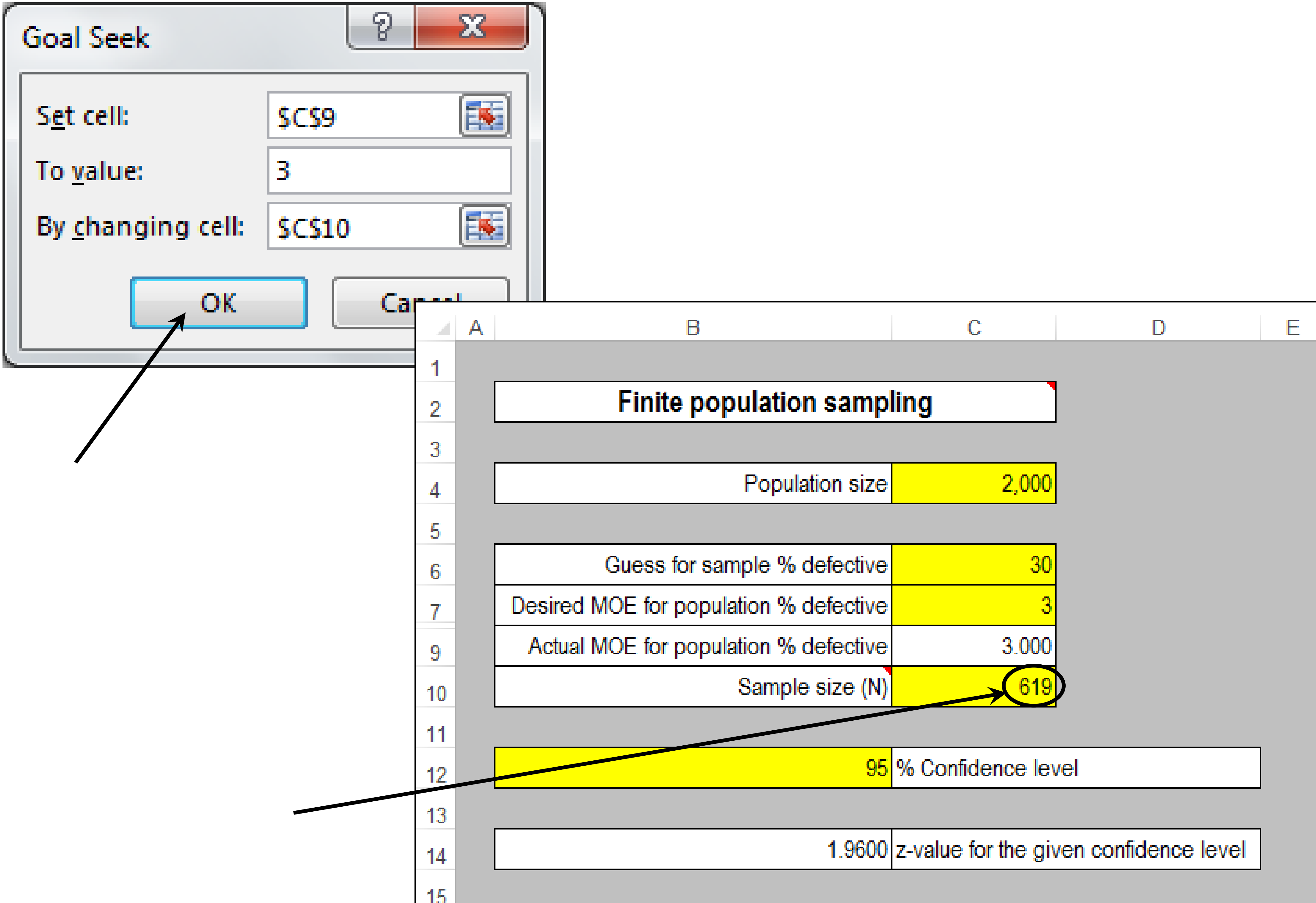
↓

Goal Seek

↓

Set up as shown on the next slide

Finite population sampling (cont'd)



Set cell: $C$9

To value: 3

By changing cell: $C$10

	A	B	C	D	E
1					
2		**Finite population sampling**			
3					
4		Population size	2,000		
5					
6		Guess for sample % defective	30		
7		Desired MOE for population % defective	3		
9		Actual MOE for population % defective	3.000		
10		Sample size (N)	619		
11					
12		95	% Confidence level		
13					
14		1.9600	z-value for the given confidence level		
15					

Sample size for estimating a population mean

- This requires an estimate of the standard deviation

- Common practice:
    - ✓ Collect a small amount of data, calculate the standard deviation
    - ✓ Do a sample size calculation to see how much more you need
    - ✓ You can also get a rough estimate of the mean from this data

- Suppose our rough estimates are $\mu = 50.4$ and $\sigma = 9.8$

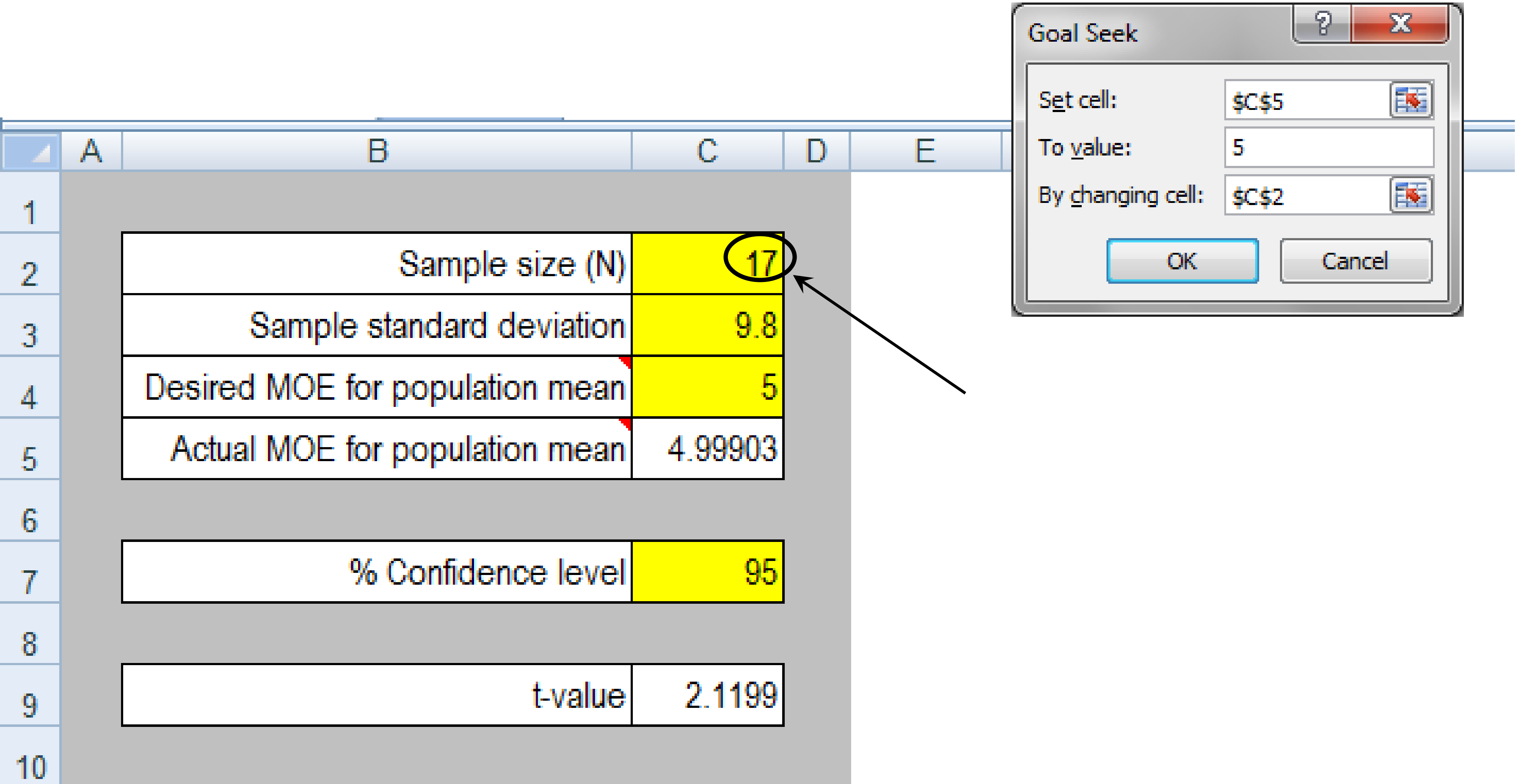
- We want our MOE to be 10% of the mean → MOE = .1 * 50.4 = 5

- Go to the sheet *Pop. mean for quant. Y* → enter the value 2 in cell C2, 9.8 in C3, and 5 in C4

- Select *Data* → *What If Analysis* → *Goal Seek*

Sample size for population mean (cont'd)

- We want to set cell C5 to 5 by changing cell C2
- Set *Goal Seek* up as shown here, click OK



Sample size (N)	17
Sample standard deviation	9.8
Desired MOE for population mean	5
Actual MOE for population mean	4.99903
% Confidence level	95
t-value	2.1199

Goal Seek

Set cell: $C$5

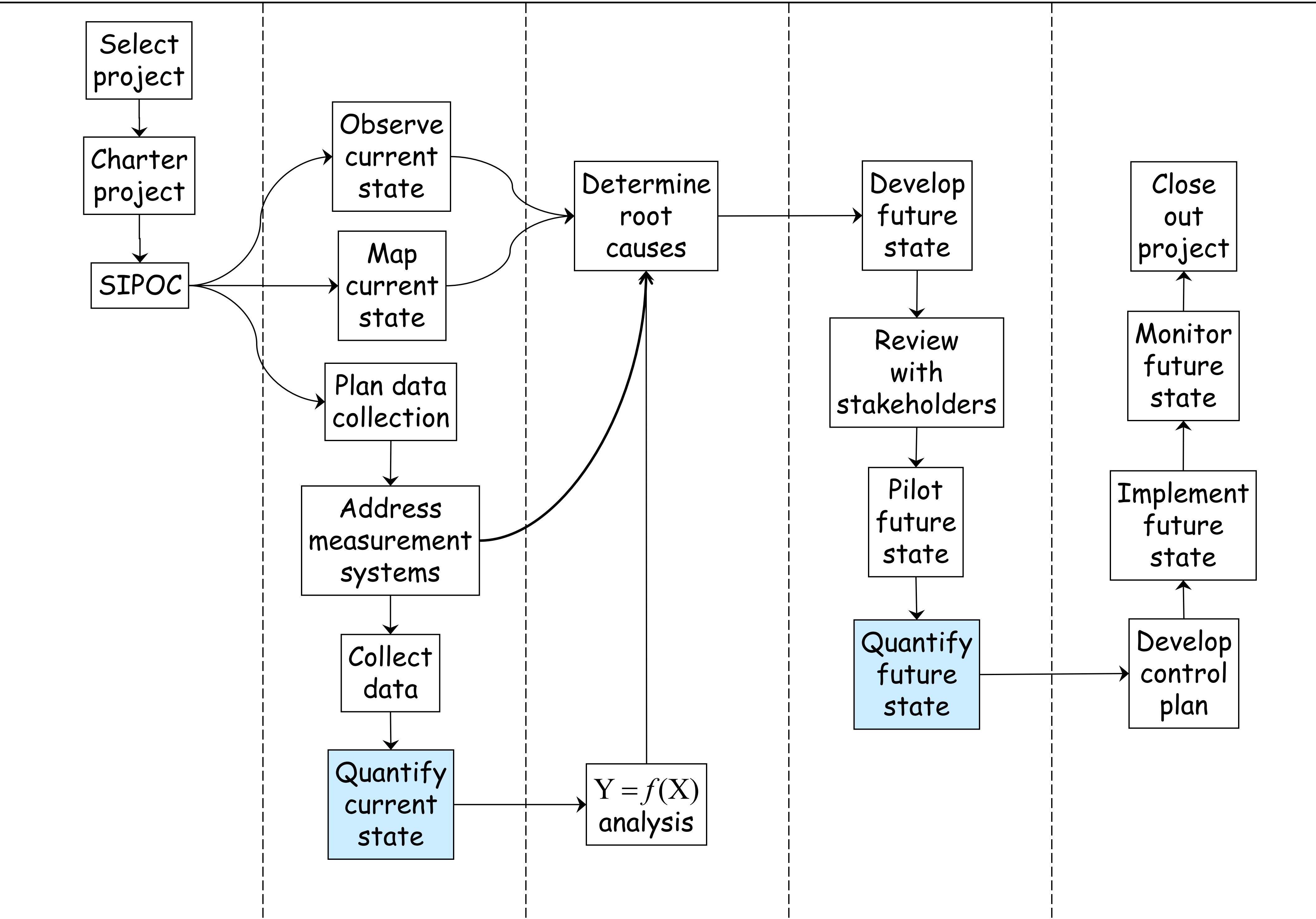
To value: 5

By changing cell: $C$2

Exercise 9.4

a) For the previous example, calculate the sample size assuming we want our MOE to be 5% of the mean instead of 10%.

b) Calculate the sample size assuming we want MOE to be 1% of the mean.


Select project
Charter project
SIPOC
Observe current state
Map current state
Plan data collection
Address measurement systems
Collect data
Quantify current state
Determine root causes
Y = f(X) analysis
Develop future state
Review with stakeholders
Pilot future state
Quantify future state
Close out project
Monitor future state
Implement future state
Develop control plan

Basic statistic summary for continuous (quantitative) data

$$\text{Average} = (\text{Sum of N numbers}) \big/ \text{N}$$

$$\text{Sample mean} = \text{Average of a sample from a population}$$

A set of numbers: 76, 80, 80, 81, 82, 82, 88, 92

$$\text{N} = 8$$

$$\begin{aligned} \text{Average} &= (76 + 80 + 80 + 81 + 82 + 82 + 88 + 92) \big/ 8 \\ &= 661/8 \\ &= 82.6 \end{aligned}$$

$$\text{Minimum} = 76$$

$$\text{Maximum} = 92$$

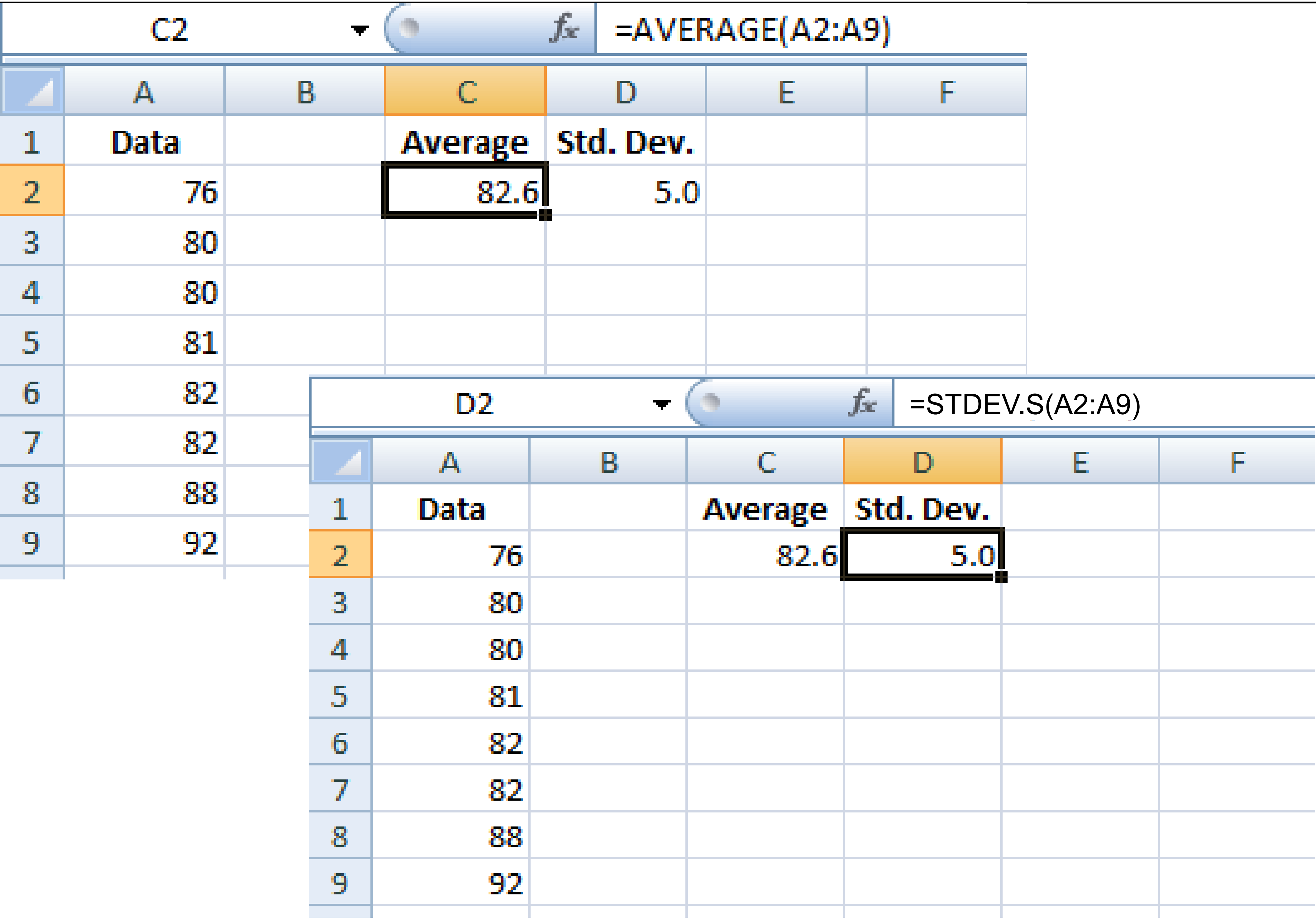
Basic statistics (cont'd)

Sample standard deviation $=$

$$\sqrt{\frac{\begin{array}{l}(76-82.6)^2+(80-82.6)^2+(80-82.6)^2+(81-82.6)^2\\ \qquad +(82-82.6)^2+(82-82.6)^2+(88-82.6)^2+(92-82.6)^2\end{array}}{7}}$$

$$= 5.04$$

Average and standard deviation in Excel



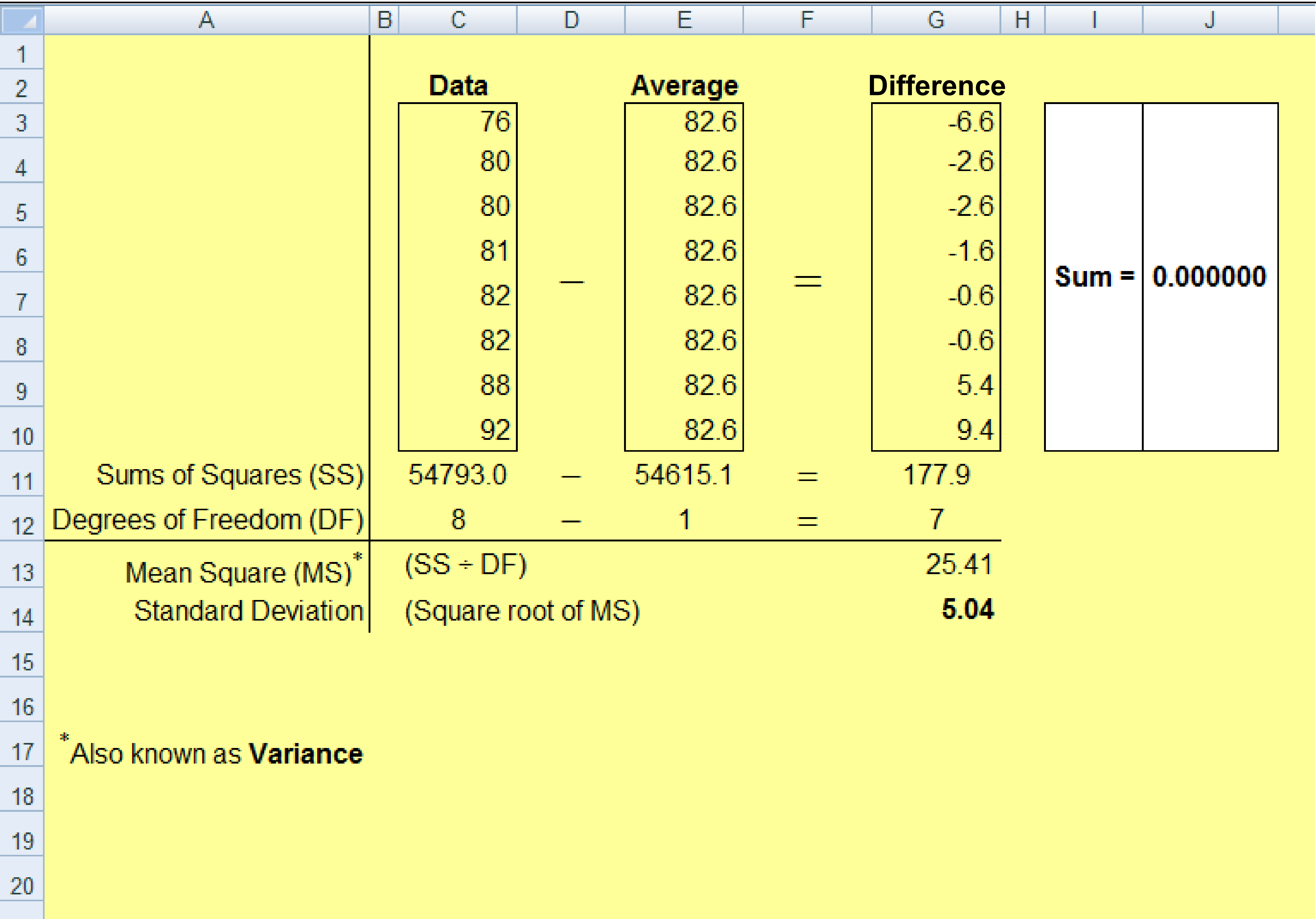
C2 =AVERAGE(A2:A9)

	A	B	C	D	E	F
1	**Data**		**Average**	**Std. Dev.**		
2	76		82.6	5.0		
3	80					
4	80					
5	81					
6	82					
7	82					
8	88					
9	92					

D2 =STDEV.S(A2:A9)

	A	B	C	D	E	F
1	**Data**		**Average**	**Std. Dev.**		
2	76		82.6	5.0		
3	80					
4	80					
5	81					
6	82					
7	82					
8	88					
9	92					

Open *Student Files* → *anatomy of STDEV*



	A	B	C	D	E	F	G	H	I	J
1										
2			**Data**		**Average**		**Difference**			
3			76	–	82.6	=	-6.6		**Sum =**	**0.000000**
4			80		82.6		-2.6			
5			80		82.6		-2.6			
6			81		82.6		-1.6			
7			82		82.6		-0.6			
8			82		82.6		-0.6			
9			88		82.6		5.4			
10			92		82.6		9.4			
11	Sums of Squares (SS)		54793.0	–	54615.1	=	177.9			
12	Degrees of Freedom (DF)		8	–	1	=	7			
13	Mean Square (MS)[*]		(SS ÷ DF)				25.41			
14	Standard Deviation		(Square root of MS)				**5.04**			
15										
16										
17	[*] Also known as **Variance**									
18										
19										
20										

Anatomy of STDEV (cont'd)

This sheet lays out the calculation of the sample standard deviation (the STDEV.S function in Excel).

The *Data* column contains 8 independent measurements (no constraints among them). We describe this by saying this column has 8 *degrees of freedom* (DFs).

The *Average* column contains a single value, repeated 8 times. We describe this by saying this column has 1 DF.

The *Difference* column is mathematically constrained to sum to 0, so it contains only 7 mathematically independent values. From any 7 values in this column, we can calculate the remaining value. (What is the formula?) We describe this by saying this column has 7 DFs.

This is why the sum of the squared differences is divided by 7 rather than 8. Dividing by 8 would bias it downwards.

Exercise 10.1

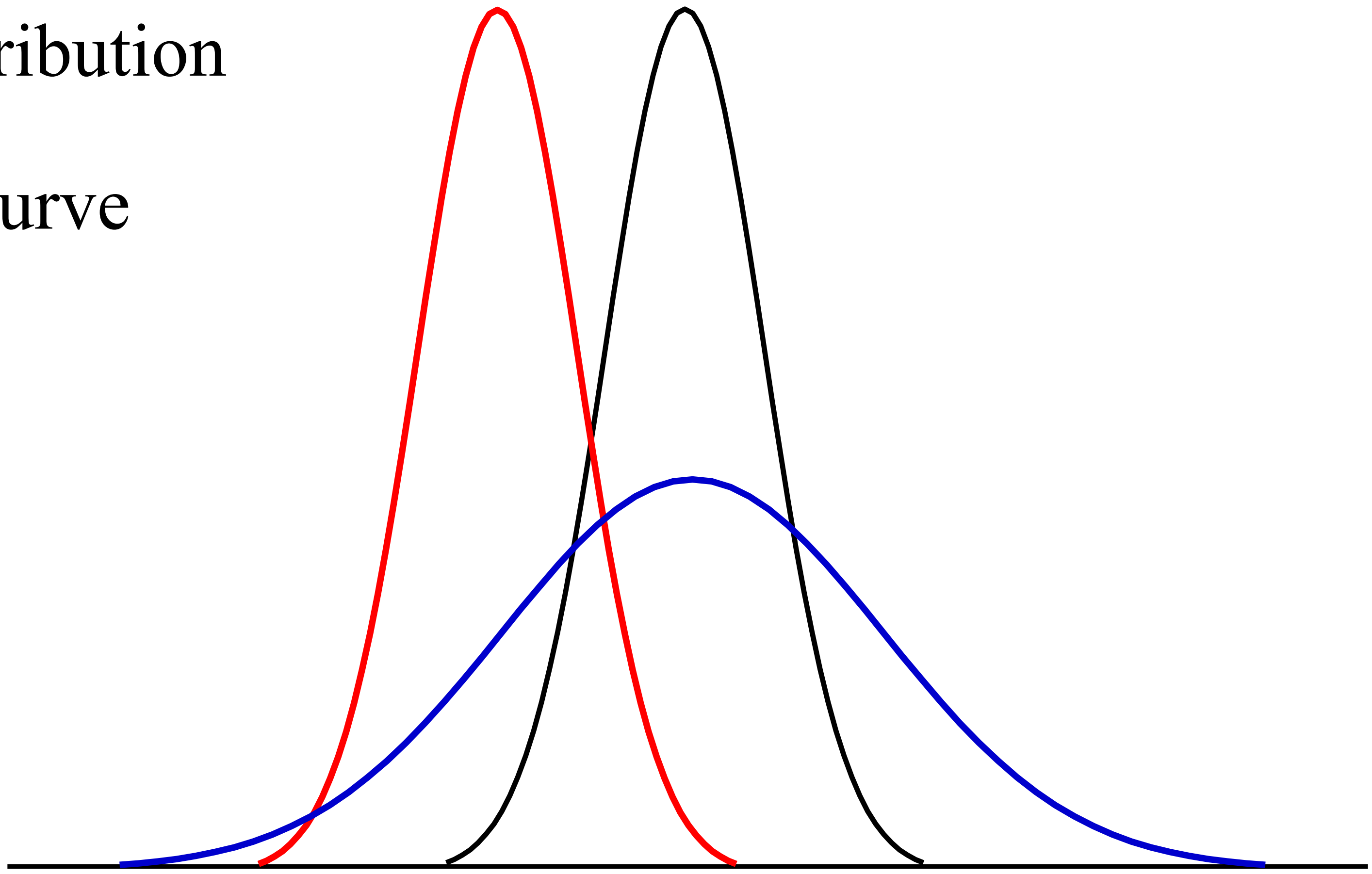
a) Open *Data Sets* → *solution properties*. Calculate the average and standard deviation for *Spec grav*. Save your work.

b) Open *Data Sets* → *ED patient visits*. Calculate the average and standard deviation of *Visits*. Save your work.

The Normal Distribution

Also known as

- Gaussian distribution
- Bell-shaped curve



Everyone believes in the Normal curve: experimenters think it is a mathematical theorem, mathematicians think it is an experimental fact. —G. Lippman

Normal distribution (cont’d)

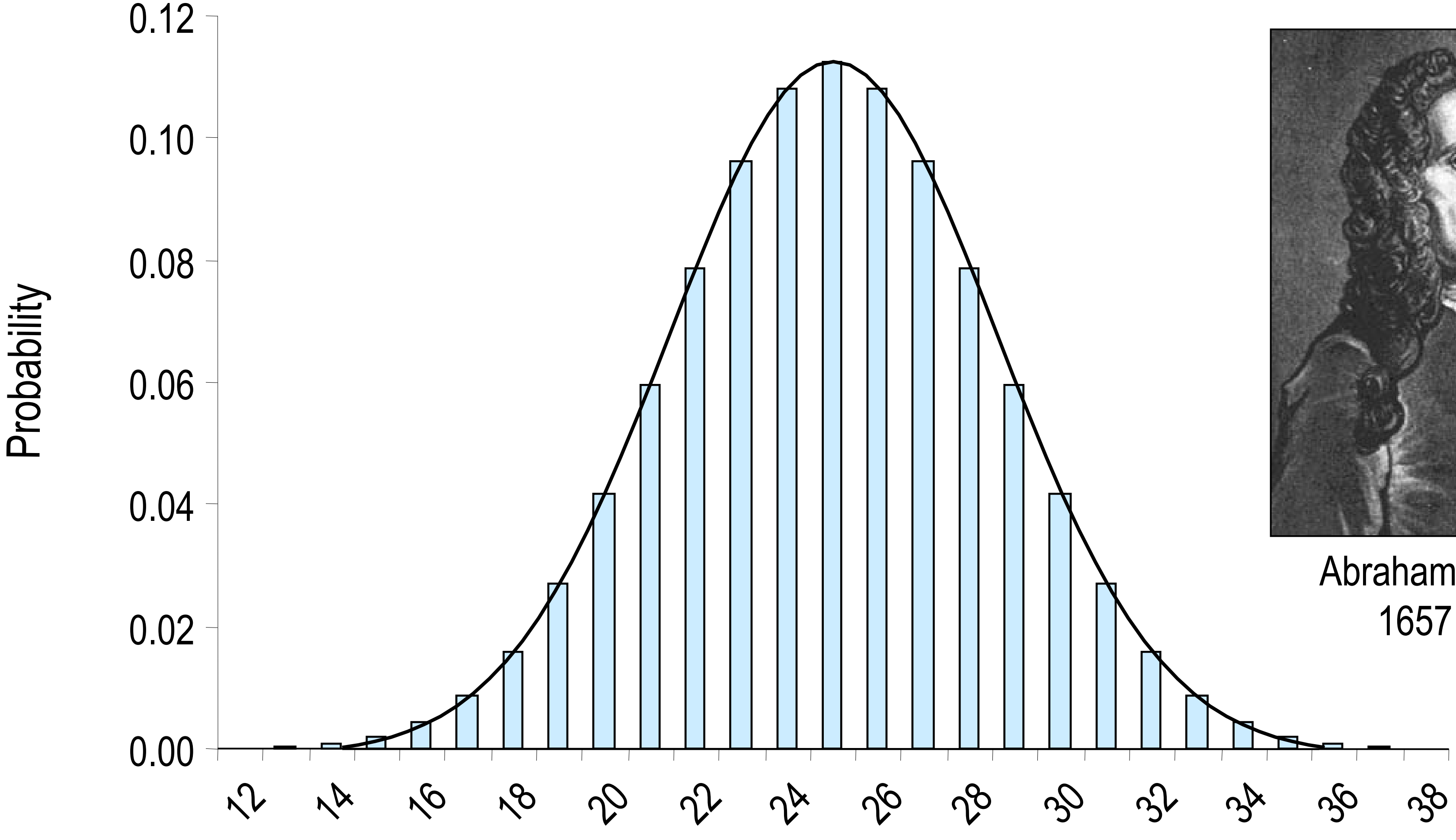
The Normal distribution is an abstraction, an idealization, a mathematical construct. At the same time, it has been a device of great practical value in Statistics.

It’s called the Gaussian distribution because the German mathematician Carl Friedrich Gauss made important early applications to astronomy in the 1820s. As we will see, it was actually discovered a century earlier by the French mathematician Abraham de Moivre.

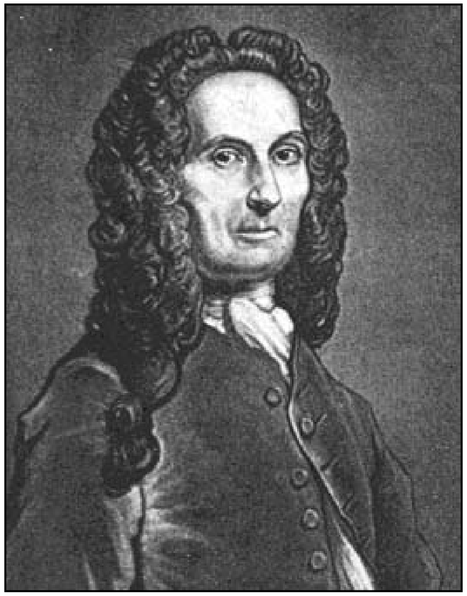
I guess life really isn’t fair.

Origin of the Normal distribution

As the number of tosses of a fair coin increases, the probability distribution of the number of heads approaches a bell shaped curve.



Number of heads in 50 tosses of a fair coin



Abraham de Moivre
1657 - 1754

Origin of Normal distribution (cont’d)

The statistical model for the number of heads in N tosses of a coin is called the Binomial distribution. In 1730, the French mathematician Abraham de Moivre discovered the bell-shaped curve as the limiting form approached by the Binomial distribution as the sample size N increases without bound. He never made any money on his discovery of the Normal distribution, and in fact died a pauper. To add insult to injury, it was eventually named after someone else (Gauss).

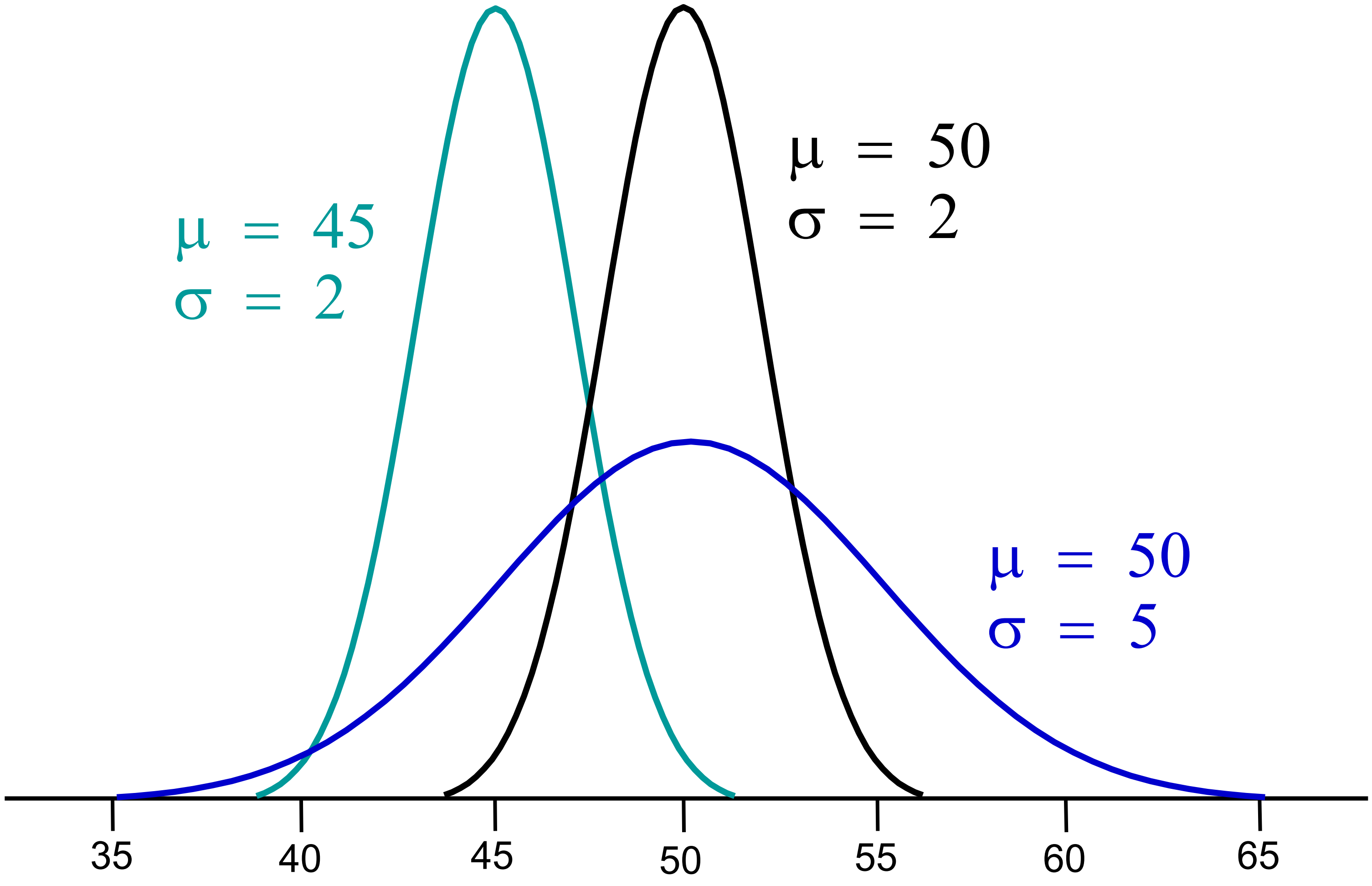
Over the next 200 years, de Moivre’s discovery was extended far beyond coin tossing. Today, we know that many quantitative measurements are sums of large numbers of small, independent, possibly unobservable contributing factors. Measurements of this type in a stable population will follow the Normal distribution, at least as a good approximation. Statisticians call this phenomenon the Central Limit Theorem.

The Normal distribution is the default population model for quantitative measurements.

The bell shaped curve

μ = Greek letter *mu* → Population mean

σ = Greek letter *sigma* → Population standard deviation



Bell-shaped curve (cont'd)

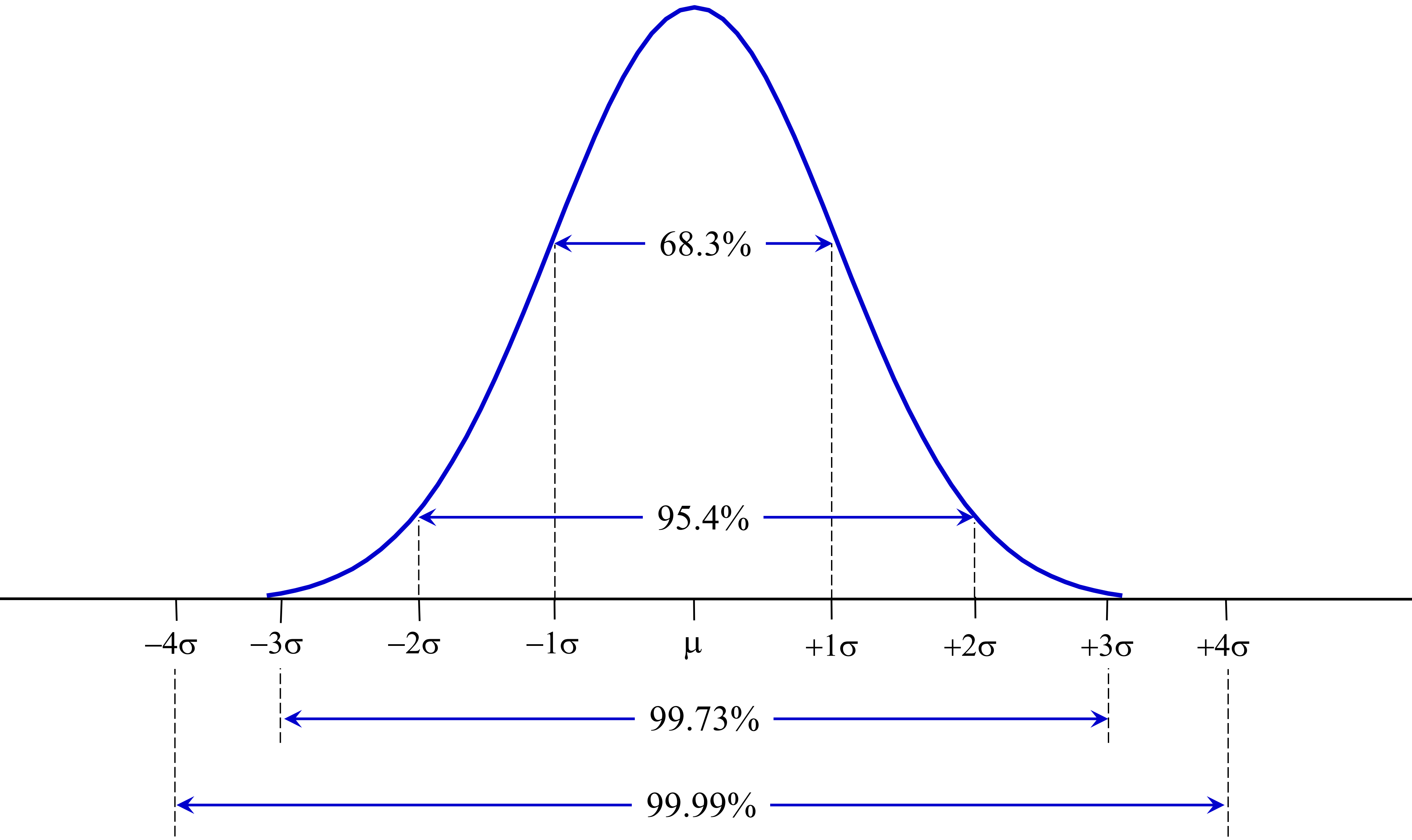
A population model is an equation that can be used to make predictions about a population. When we represent the mean and standard deviation by Greek letters, as above, we are thinking of the mean and standard deviation of the entire population, not just the numbers in our data set. It means we are thinking of the Normal distribution as a population model.

The formula for the bell shaped curve is given below. In this equation, *f*(*y*) is the height of the curve above the value *y* on the horizontal axis.

$$f(y) = \frac{1}{\sqrt{2\pi}} \frac{1}{\sigma} e^{-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2}$$

You may have been graded "on the curve" at some point in your academic career. Well, this is the curve.

Area under curve = % of population



Area under curve (cont'd)

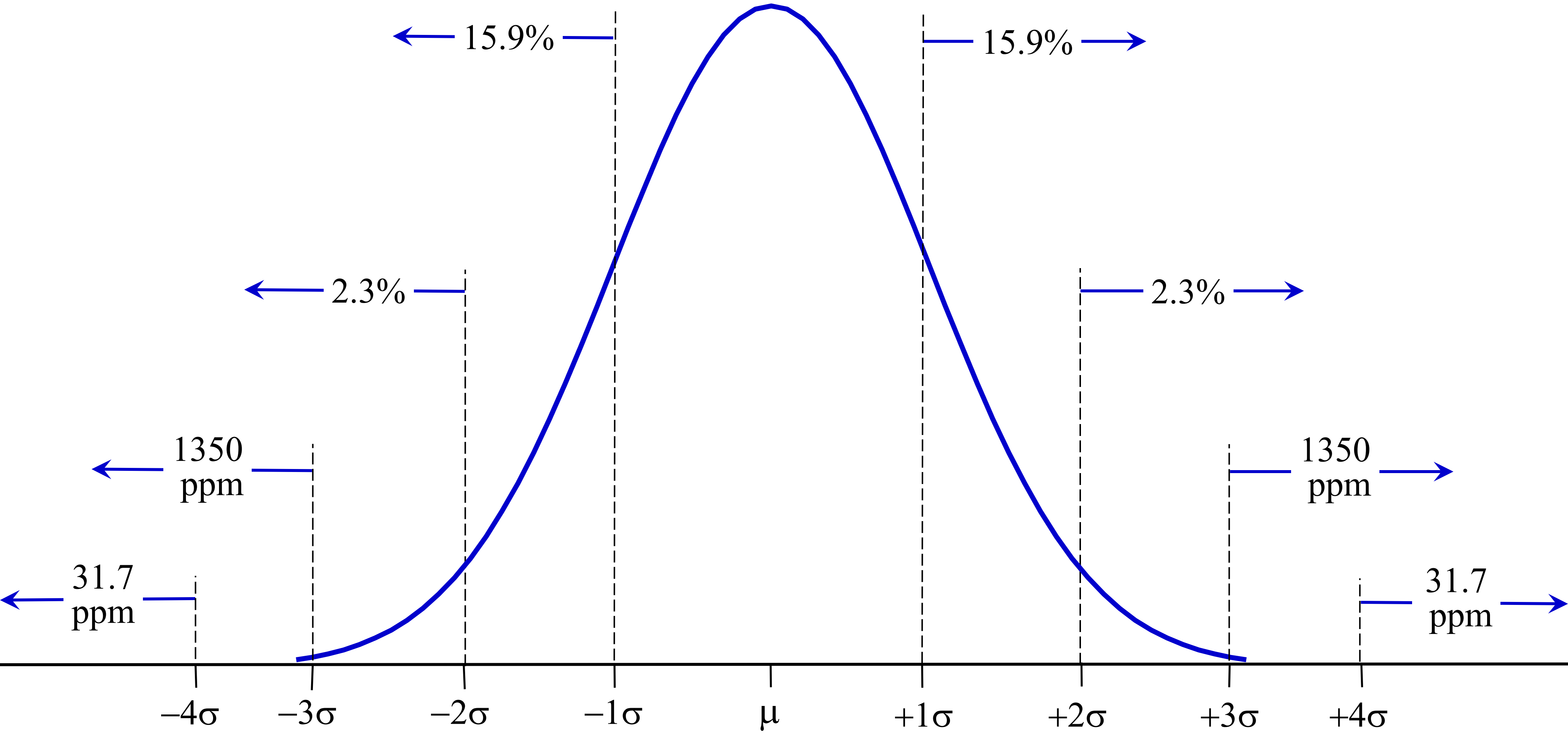
For a Normal population:

- The 1.960σ limits contain 95% of the population.
- The 2σ limits contain 95.45% of the population.

- The 2.576σ limits contain 99% of a Normal population
- The 3σ limits contain 99.73% of the population.

Area under curve = % of population

Usually we care mostly about % *beyond* certain points

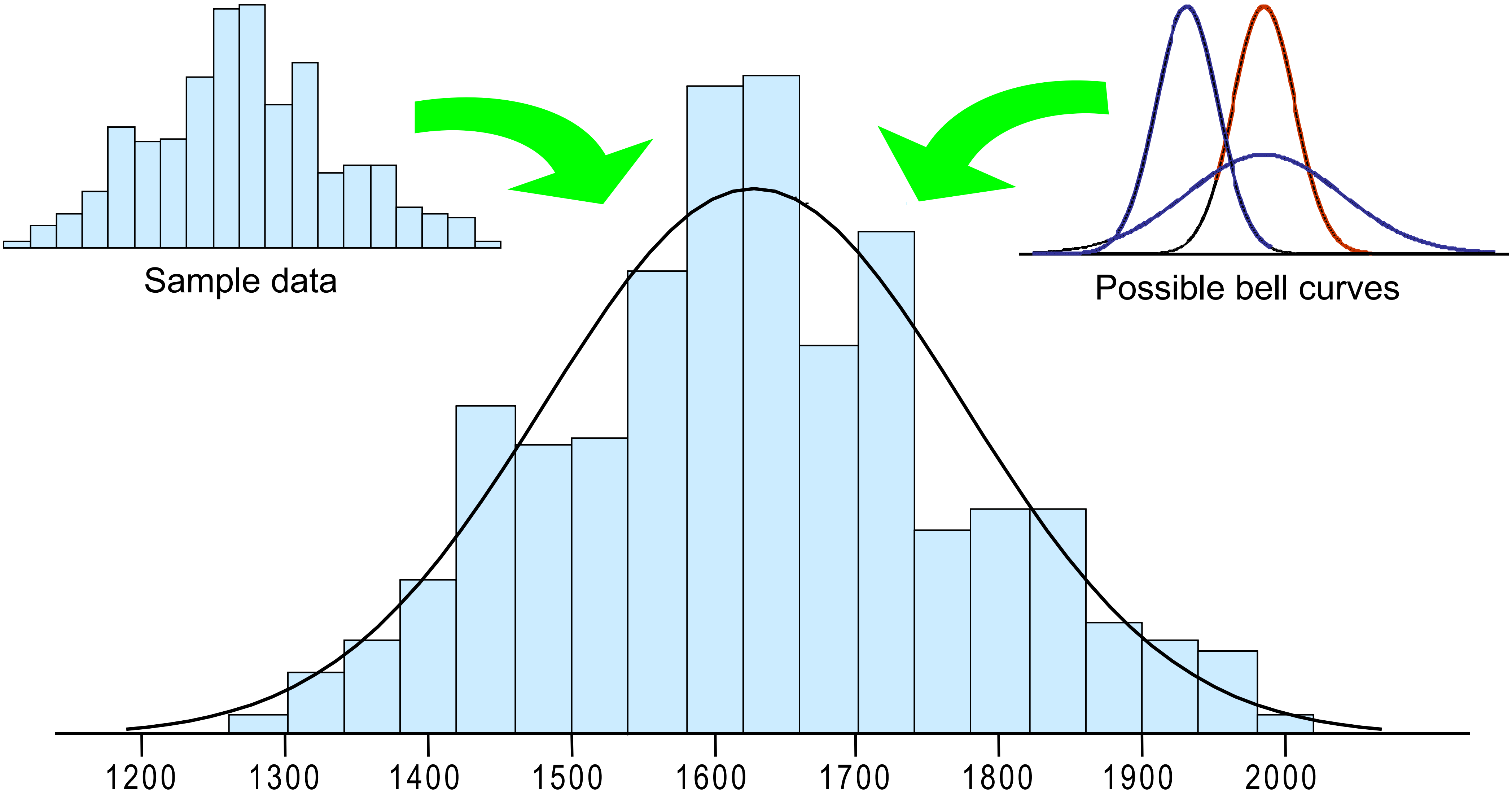


Fitting the bell curve to data

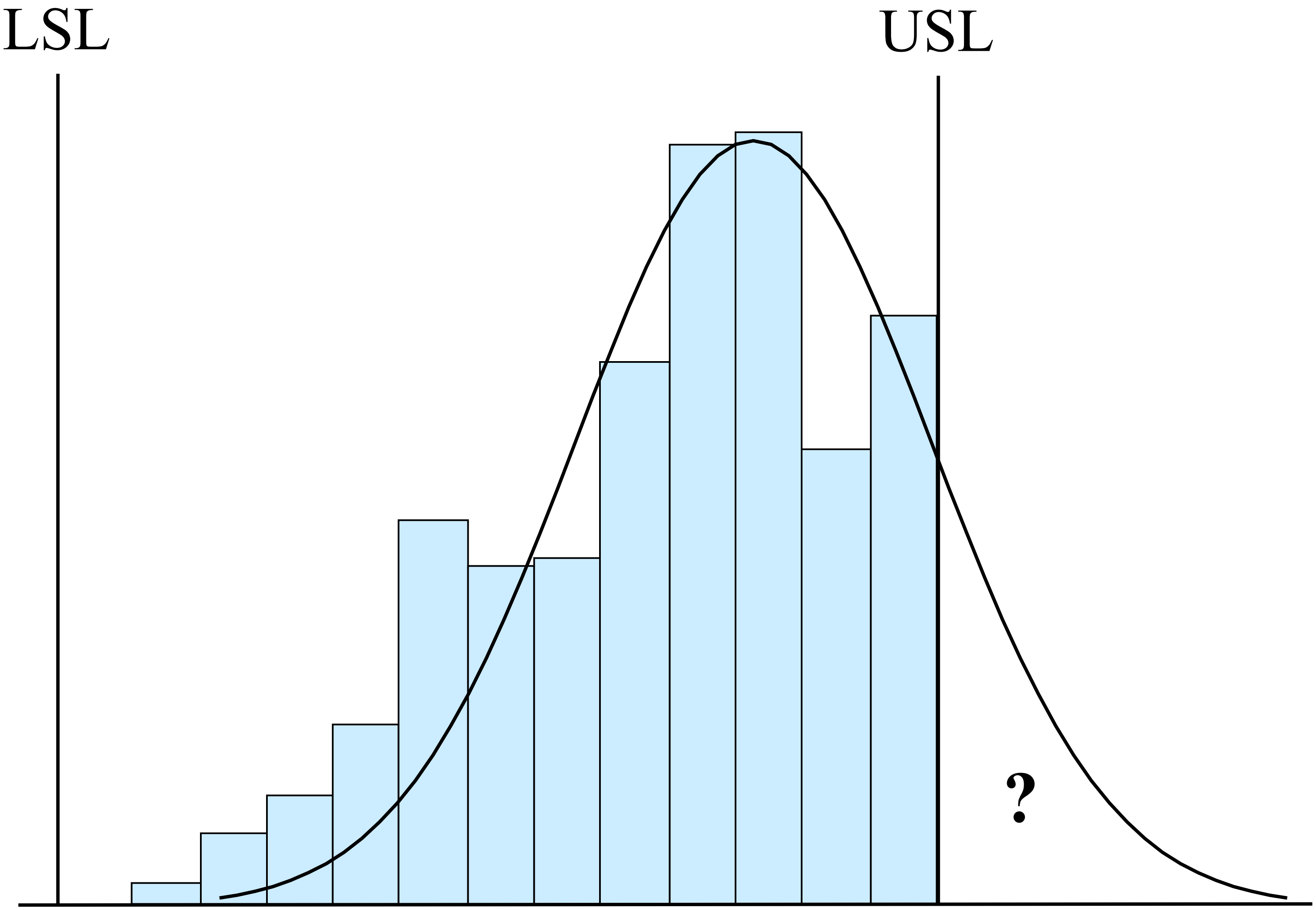
Sample mean (1632.1) → μ

Sample standard deviation (142.2) → σ

$$f(y)=\frac{1}{\sqrt{2\pi}}\frac{1}{\sigma}e^{-\frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^{2}}$$



Why use fitted distributions?



Why distributions? (cont'd)

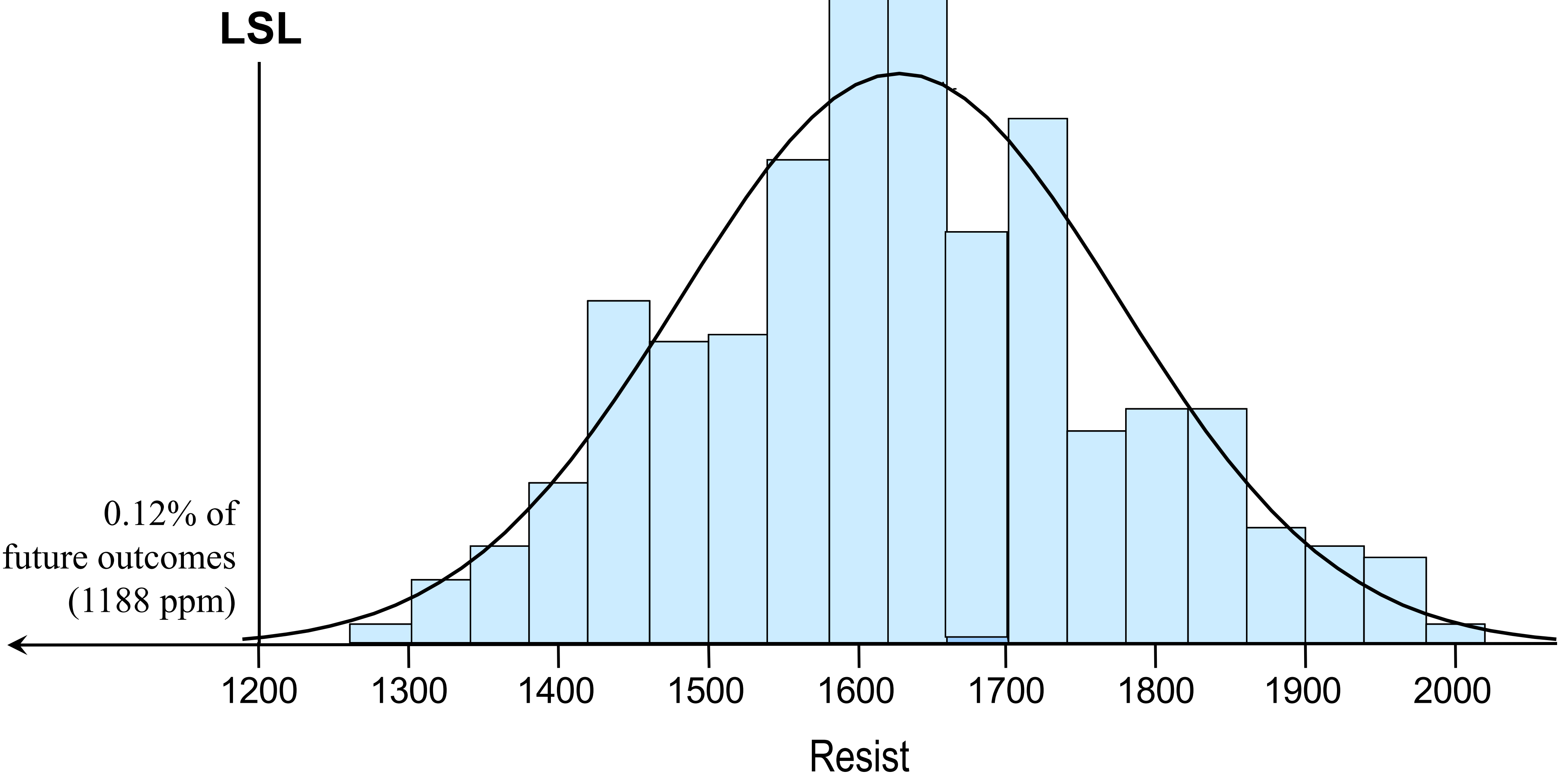
The practice of calculating % defective or DPPM by means of fitted distributions instead of raw data came about historically as a crude but effective way for customers in the aerospace and automotive supply chains to expose the "hidden factories" of their suppliers.

Suppliers would present final inspection data to customers to document their process capability. In the example shown above, the supplier claims 100% yield. When plotted as a histogram, the data mysteriously disappears right at the upper spec limit. This is because parts exceeding the upper limit are either scrapped or reworked to the limit. Often the rework is done by the inspector and not recorded as rework. In many cases, the first pass data is not recorded.

A distribution curve pays no attention to spec limits and will always produce a positive value for % defective or DPPM. This gives an estimate of the supplier's first pass yield. In the example shown above, it is obvious that the first pass yield is far below 100%.

Using the Normal curve to predict % defective or DPPM

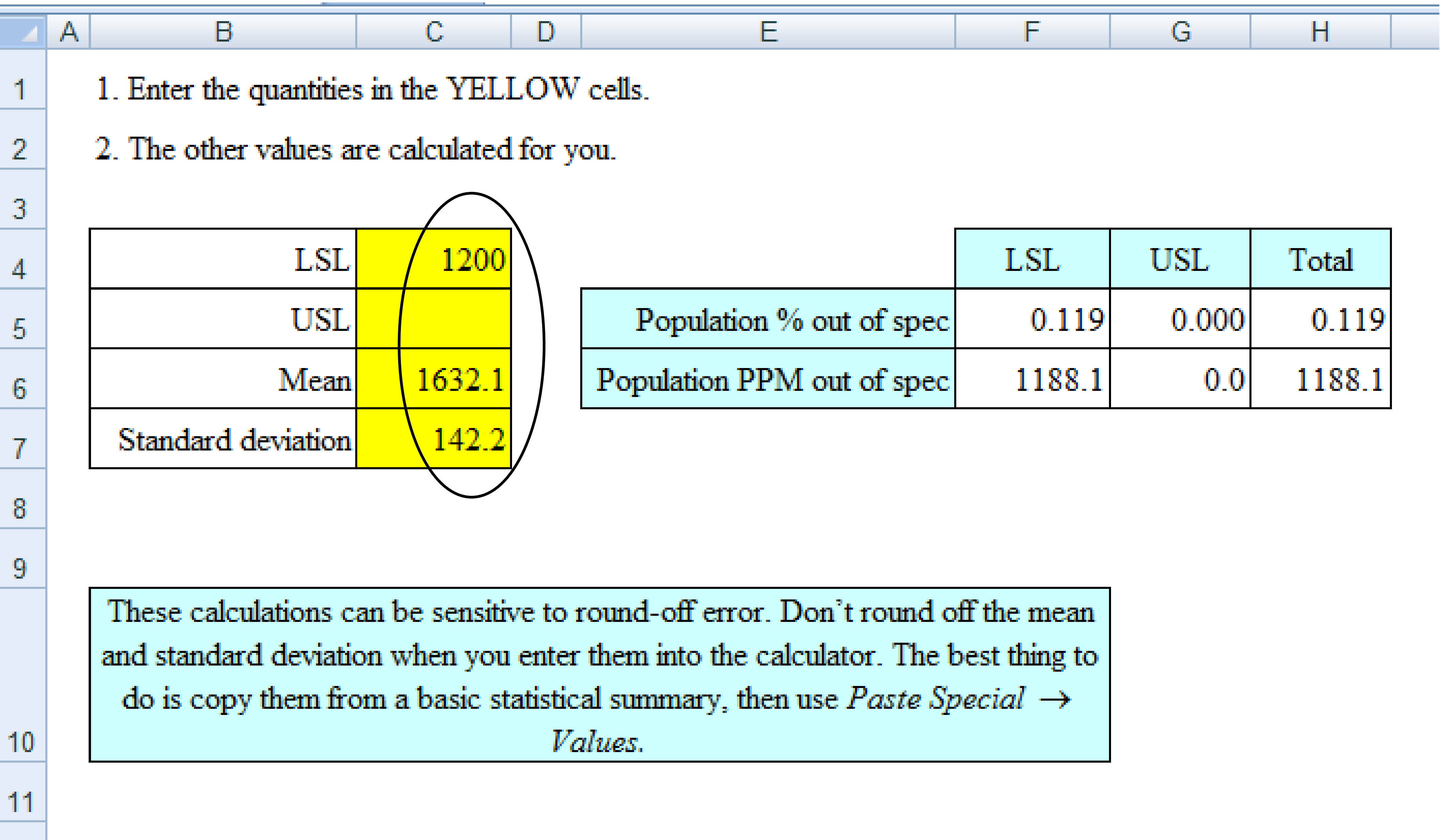
Allows extrapolation (😊 ☹)



0.12% of
future outcomes
(1188 ppm)

% below 1200

Student Files → calculator - Normal distribution



1. Enter the quantities in the YELLOW cells.

2. The other values are calculated for you.

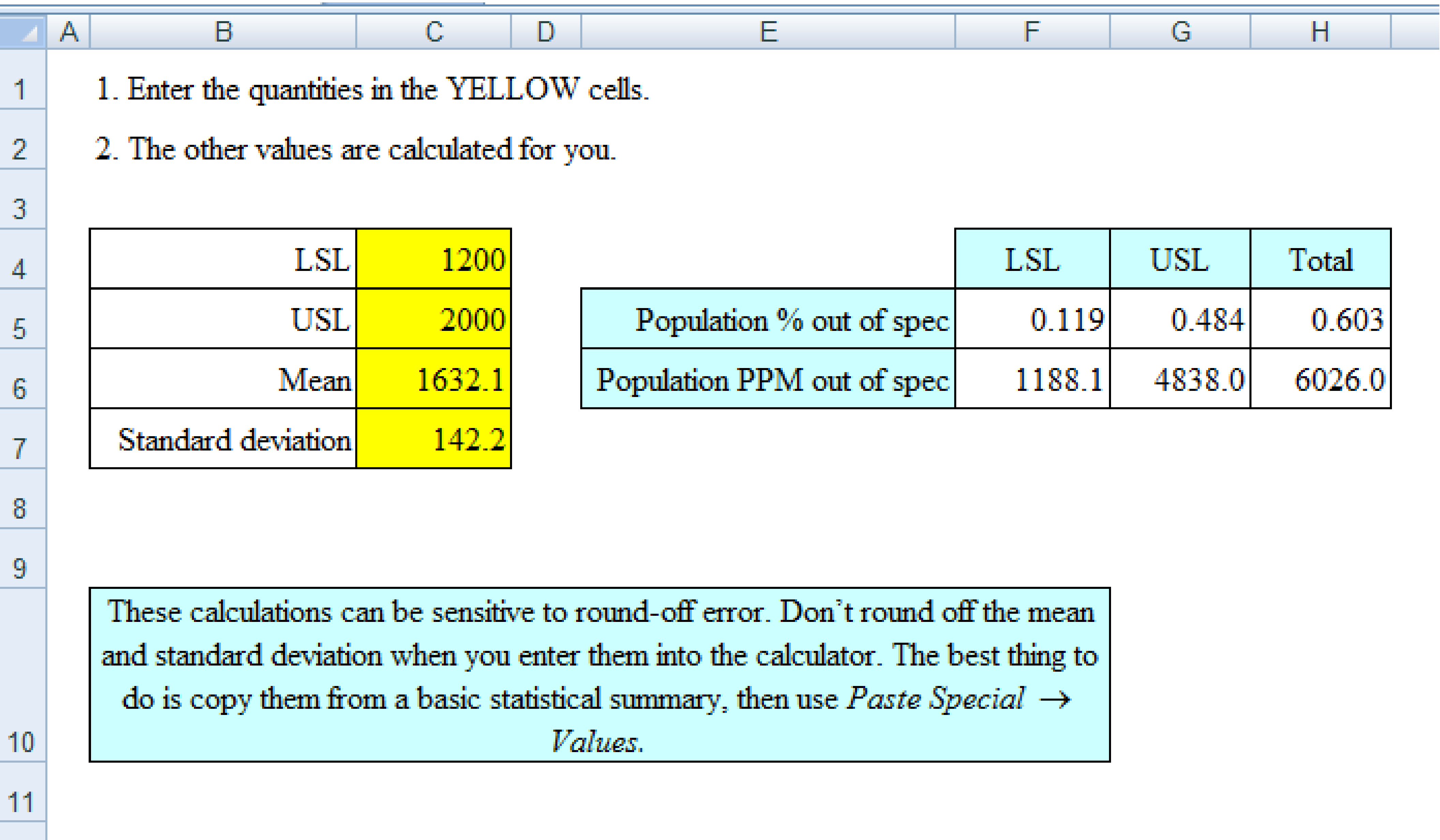
LSL	1200
USL	
Mean	1632.1
Standard deviation	142.2

	LSL	USL	Total
Population % out of spec	0.119	0.000	0.119
Population PPM out of spec	1188.1	0.0	1188.1

These calculations can be sensitive to round-off error. Don't round off the mean and standard deviation when you enter them into the calculator. The best thing to do is copy them from a basic statistical summary, then use *Paste Special → Values.*

% below 1200 **or** above 2000

Student Files → calculator - Normal distribution



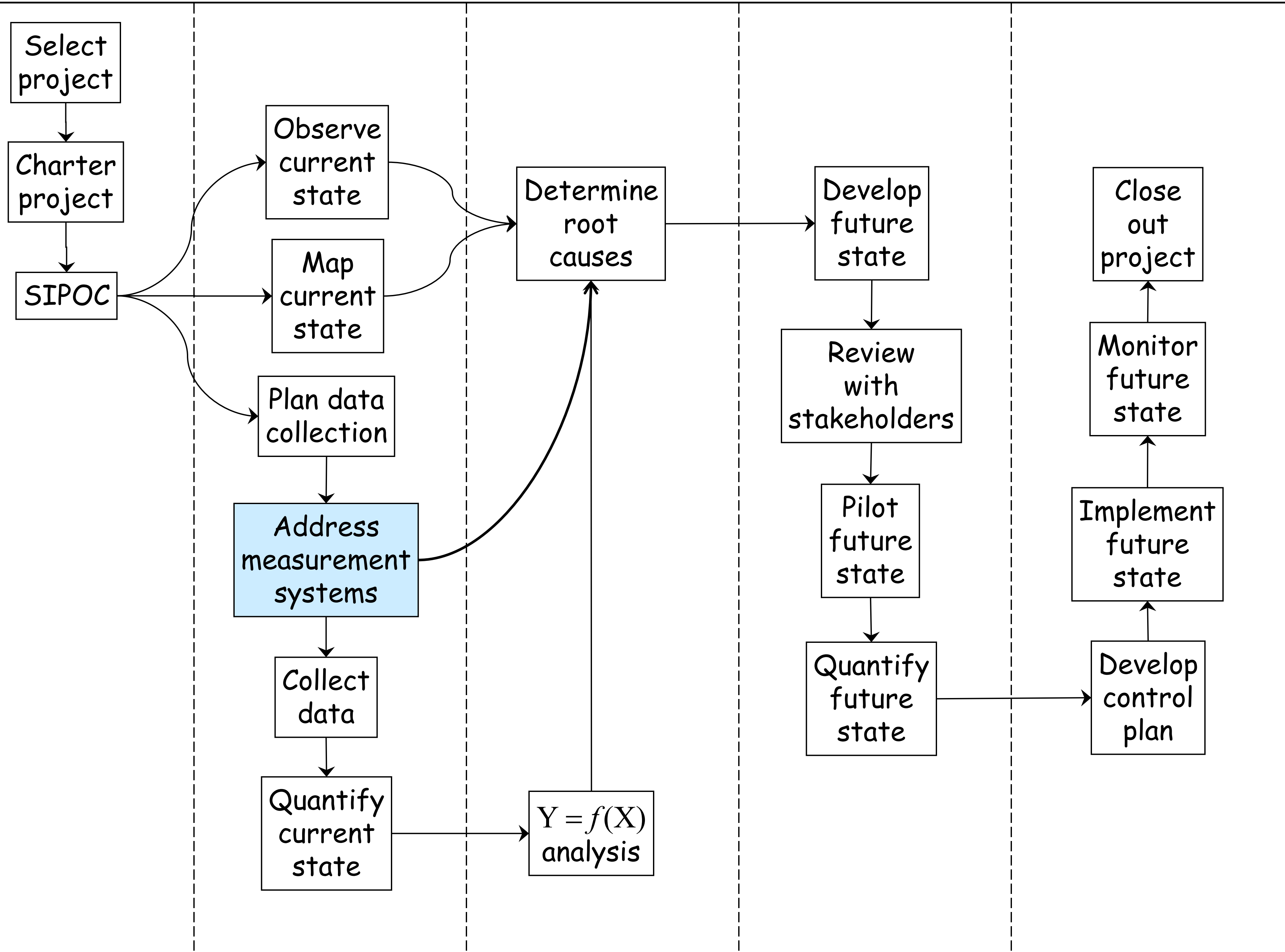
1. Enter the quantities in the YELLOW cells.

2. The other values are calculated for you.

LSL	1200
USL	2000
Mean	1632.1
Standard deviation	142.2

	LSL	USL	Total
Population % out of spec	0.119	0.484	0.603
Population PPM out of spec	1188.1	4838.0	6026.0

These calculations can be sensitive to round-off error. Don't round off the mean and standard deviation when you enter them into the calculator. The best thing to do is copy them from a basic statistical summary, then use *Paste Special → Values.*



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

Monitor future state

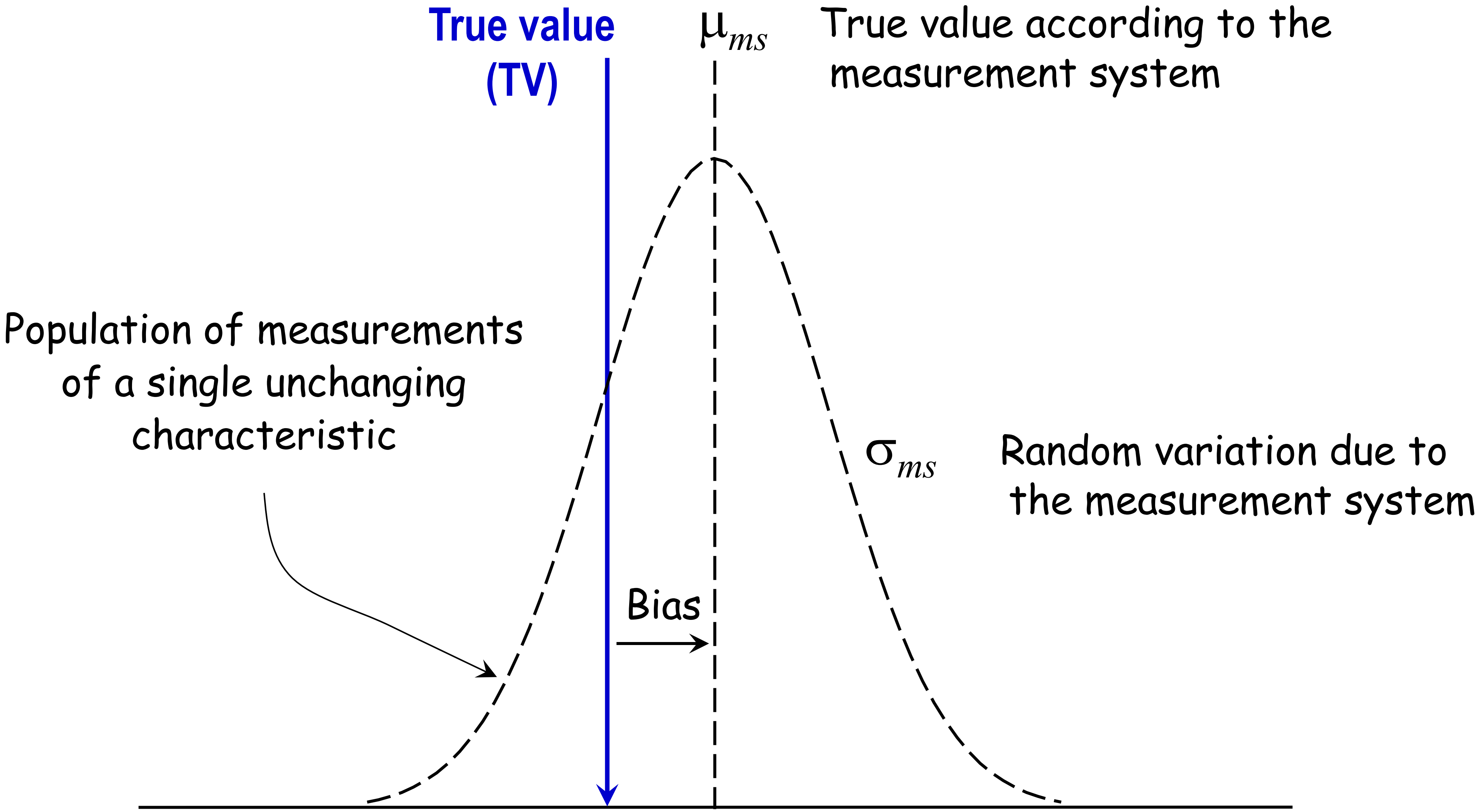
Close out project

Topics

- Population model for measurement variation
- How components of variation add up
- Calculating measurement variation*
- Degrees of freedom

*In the situation where there is only one appraiser.

Population model for measurement variation



True value (TV)

μ_{ms} True value according to the measurement system

Population of measurements of a single unchanging characteristic

σ_{ms} Random variation due to the measurement system

Bias

Measurement error = Systematic error (bias) + Random error

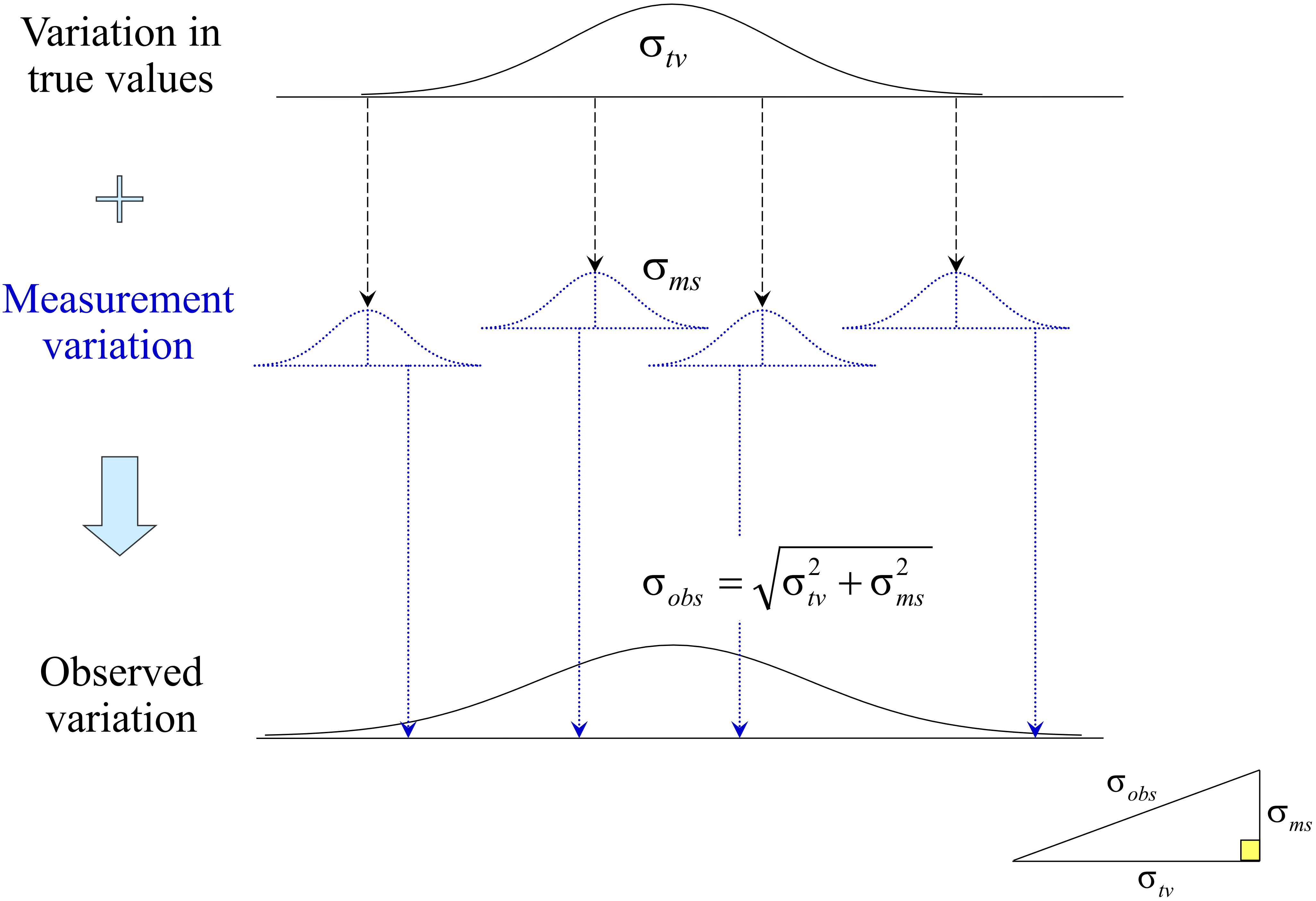
Population model (cont'd)

- The purpose of calibration is to eliminate gage bias
- Calibration requires standards (measurable items whose true values are known) or a calibrated second gage of higher accuracy
- The primary objective of quantitative measurement system analysis (MSA) is to determine the variation contributed by the measurement system, σ_{ms}, which is *more than gage bias*

To be clear, calibration is not enough!

- Quantitative MSA does not require standards
- If gage bias is constant during the MSA, the resulting σ_{ms} will be accurate
- If gage bias changes during the MSA, the resulting σ_{ms} will be biased upwards

How components of *variation* add up



Variation in true values

Measurement variation

Observed variation

$$\sigma_{obs} = \sqrt{\sigma_{tv}^2 + \sigma_{ms}^2}$$

Components of *measurement system variation*

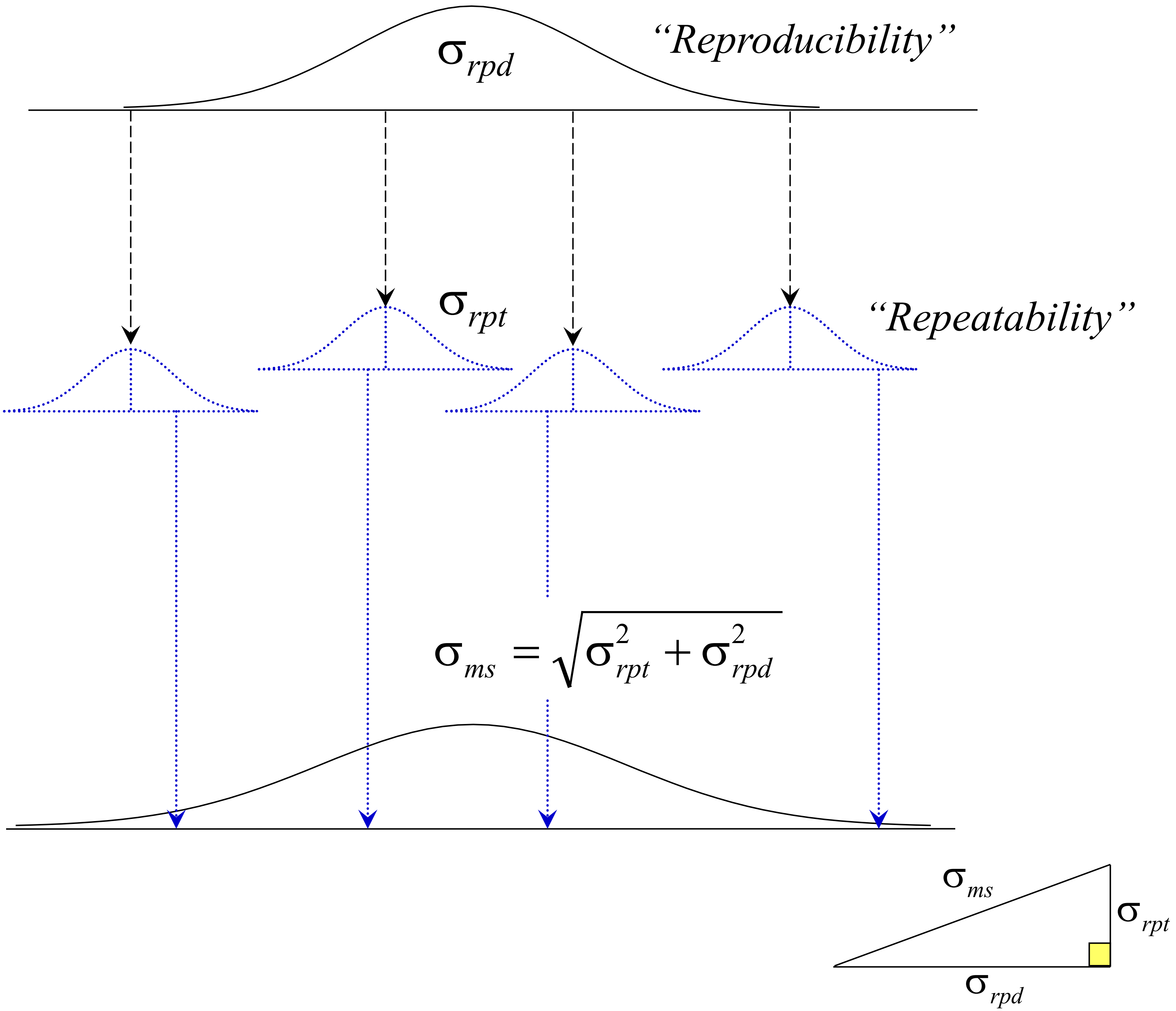
Appraisers not agreeing with each other

+

Appraisers not agreeing with themselves

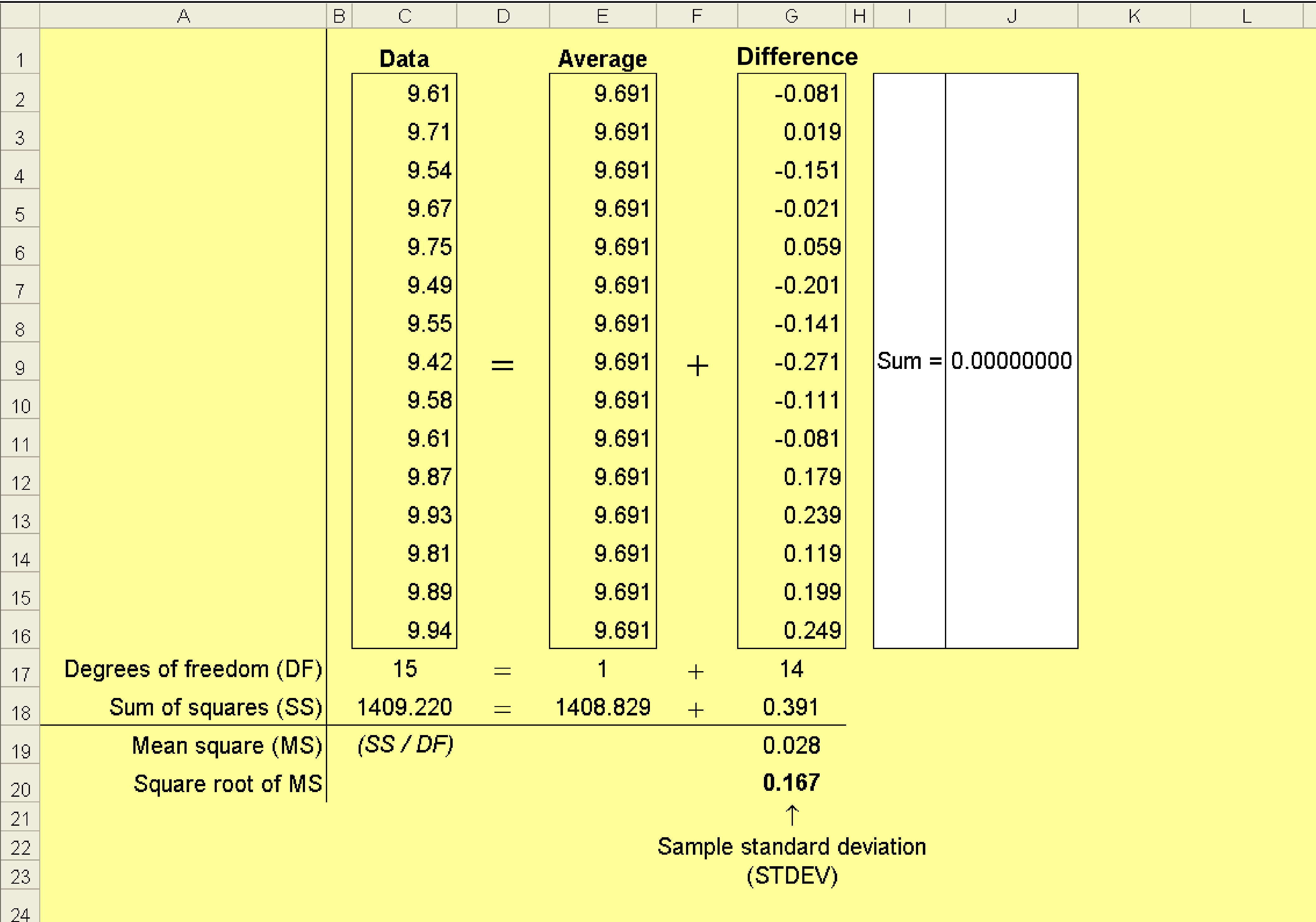
↓

Measurement system variation



$$\sigma_{ms} = \sqrt{\sigma_{rpt}^2 + \sigma_{rpd}^2}$$

STDEV revisited



	Data		Average		Difference		
	9.61		9.691		-0.081		
	9.71		9.691		0.019		
	9.54		9.691		-0.151		
	9.67		9.691		-0.021		
	9.75		9.691		0.059		
	9.49		9.691		-0.201		
	9.55		9.691		-0.141		
	9.42	=	9.691	+	-0.271	Sum =	0.00000000
	9.58		9.691		-0.111		
	9.61		9.691		-0.081		
	9.87		9.691		0.179		
	9.93		9.691		0.239		
	9.81		9.691		0.119		
	9.89		9.691		0.199		
	9.94		9.691		0.249		
Degrees of freedom (DF)	15	=	1	+	14		
Sum of squares (SS)	1409.220	=	1408.829	+	0.391		
Mean square (MS)	*(SS / DF)*				0.028		
Square root of MS					**0.167**		

↑

Sample standard deviation
(STDEV)

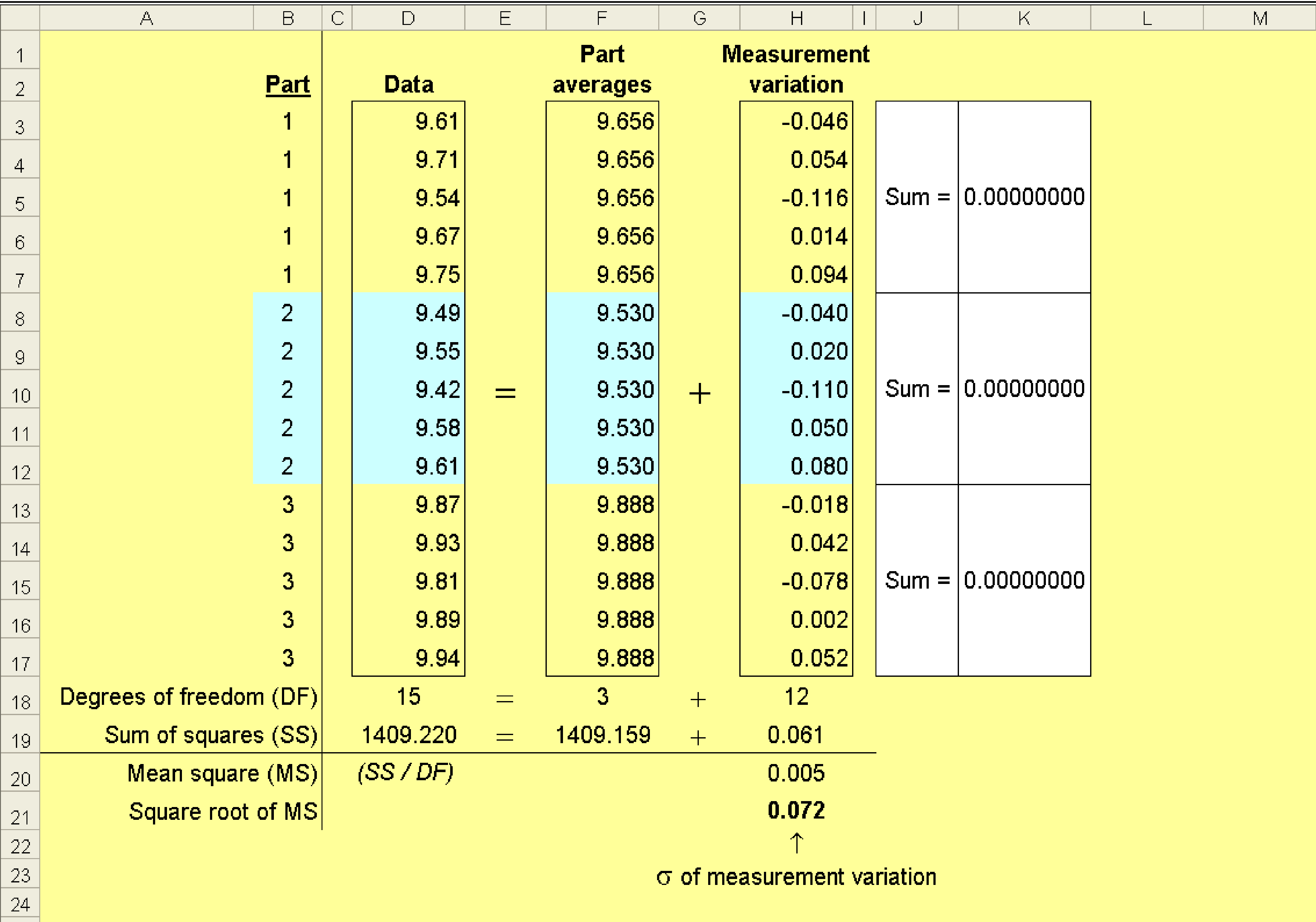
STDEV (cont'd)

The slide above is a screen shot of the worksheet *Observed variation* in *Student Files* → *MSA - one appraiser*. This sheet reviews the calculation of the sample standard deviation. In MSA, this is called the "observed variation." In other types of data analysis, it is called the "total variation."

Recap of *degrees of freedom* (DFs)

- The *Data* column has 15 DFs because it consists of 15 independent measurements.
- The *Average* column has 1 DF because it consists of a single value repeated 15 times.
- The *Difference* column is constrained to sum to 0, so it contains only 14 independent values, so it has 14 DFs.
- DFs have to add up. For example, 15 = 1 + 14.

MSA with one appraiser (cont'd)



	Part	Data		Part averages		Measurement variation		
	1	9.61		9.656		-0.046		
	1	9.71		9.656		0.054		
	1	9.54		9.656		-0.116	Sum =	0.00000000
	1	9.67		9.656		0.014		
	1	9.75		9.656		0.094		
	2	9.49		9.530		-0.040		
	2	9.55		9.530		0.020		
	2	9.42	=	9.530	+	-0.110	Sum =	0.00000000
	2	9.58		9.530		0.050		
	2	9.61		9.530		0.080		
	3	9.87		9.888		-0.018		
	3	9.93		9.888		0.042		
	3	9.81		9.888		-0.078	Sum =	0.00000000
	3	9.89		9.888		0.002		
	3	9.94		9.888		0.052		
Degrees of freedom (DF)		15	=	3	+	12		
Sum of squares (SS)		1409.220	=	1409.159	+	0.061		
Mean square (MS)		*(SS / DF)*				0.005		
Square root of MS						**0.072**		

↑

σ of measurement variation

MSA with one appraiser (cont'd)

The slide above is a screen shot of the sheet *Measurement variation*. It lays out the calculation of σ_{ms} when each of 3 parts is measured 5 times by one appraiser.

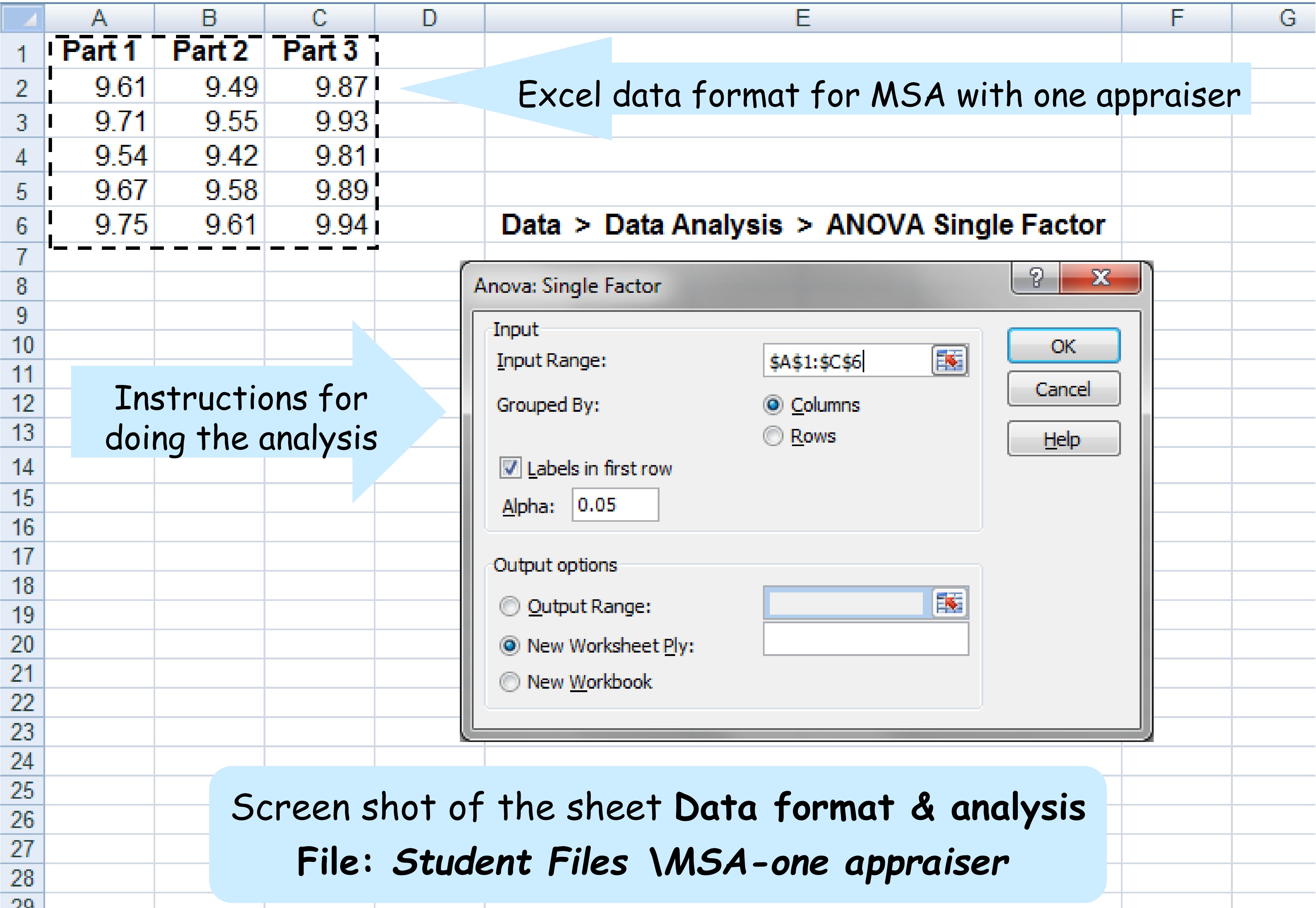
The *Part averages* column has 3 DFs because it consists of 3 independent values (the part averages).

In the *Measurement variation* column, the values for each part are constrained to sum to 0, so any 4 of them determine the remaining value. There are 3 parts, so there are only 3 × 4 = 12 independent values in this column, so it has 12 DFs.

Because the calculation of σ_{ms} involves only 12 independent values, we sometimes refer to σ_{ms} itself as having 12 DFs. The greater the DFs for σ_{ms}, the more accurate it is.

As before, DFs have to add up: $15 = 3 + 12$.

MSA with one appraiser (cont'd)



Part 1	Part 2	Part 3
9.61	9.49	9.87
9.71	9.55	9.93
9.54	9.42	9.81
9.67	9.58	9.89
9.75	9.61	9.94

Excel data format for MSA with one appraiser

Data > Data Analysis > ANOVA Single Factor

Instructions for doing the analysis

Anova: Single Factor

Input

Input Range: $A$1:$C$6

Grouped By: ● Columns ○ Rows

☑ Labels in first row

Alpha: 0.05

Output options

○ Output Range:

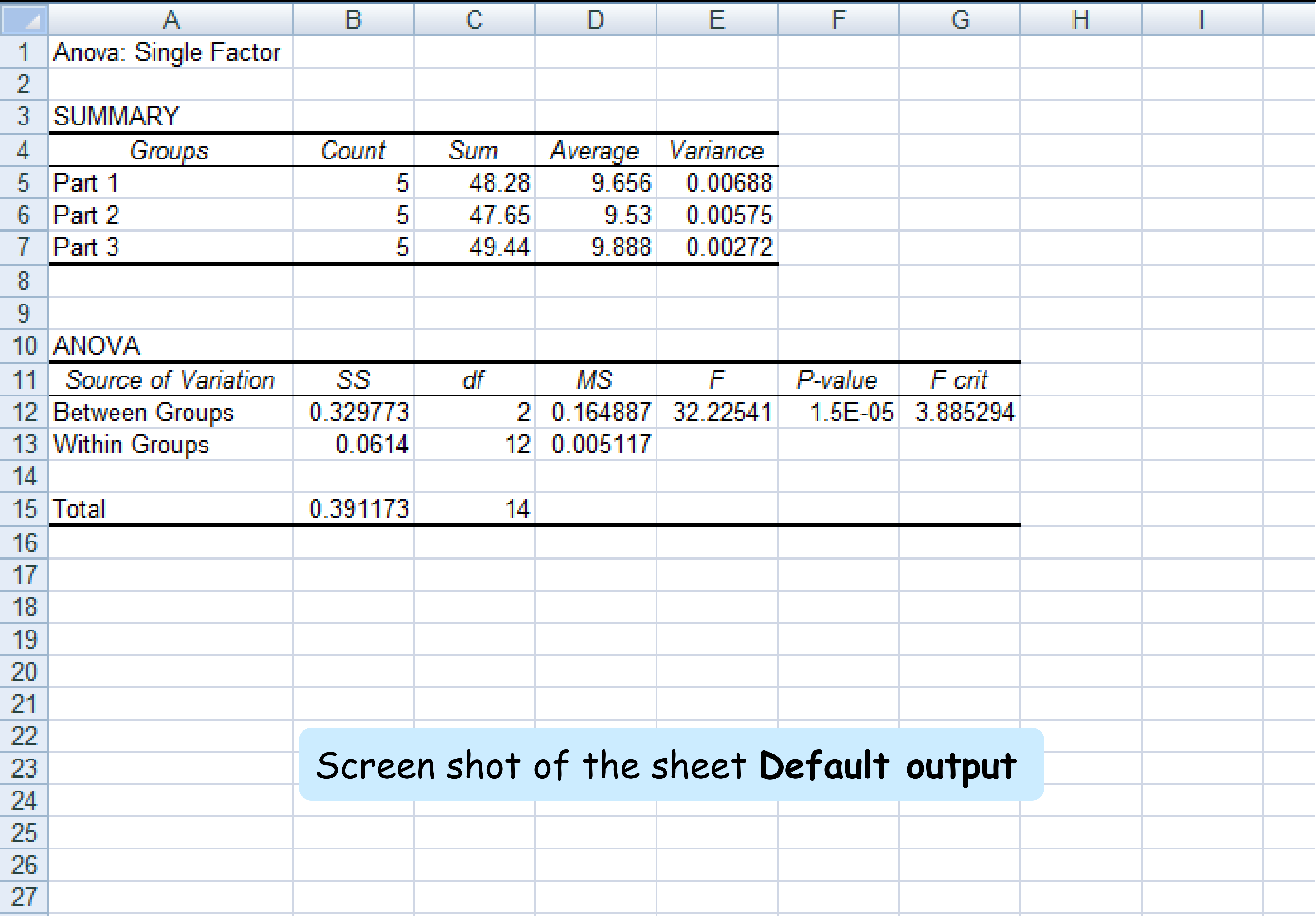
● New Worksheet Ply:

○ New Workbook

Screen shot of the sheet **Data format & analysis**

File: *Student Files \MSA-one appraiser*

MSA with one appraiser (cont'd)



Anova: Single Factor

SUMMARY

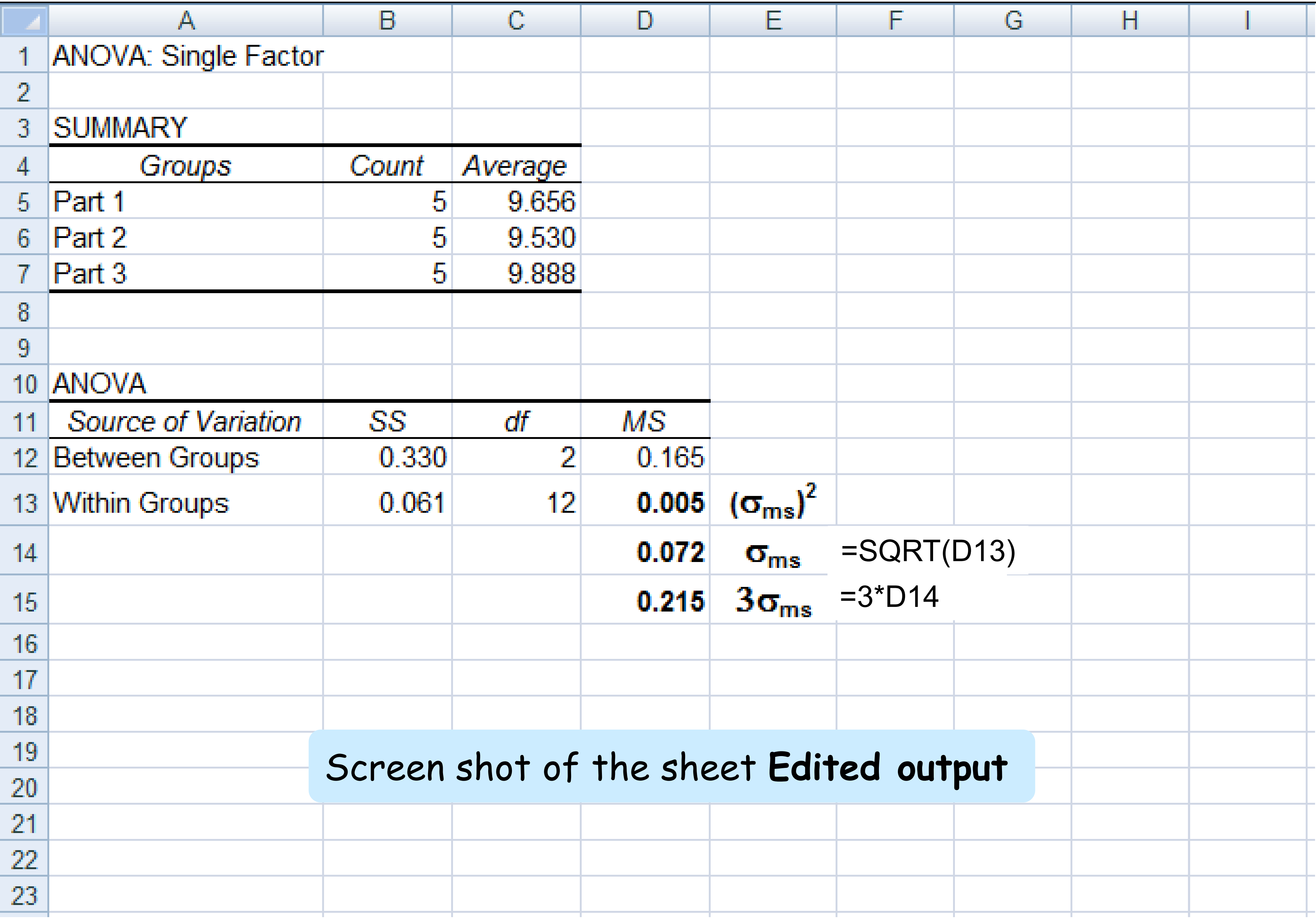
Groups	*Count*	*Sum*	*Average*	*Variance*
Part 1	5	48.28	9.656	0.00688
Part 2	5	47.65	9.53	0.00575
Part 3	5	49.44	9.888	0.00272

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.329773	2	0.164887	32.22541	1.5E-05	3.885294
Within Groups	0.0614	12	0.005117			
Total	0.391173	14				

Screen shot of the sheet **Default output**

MSA with one appraiser (cont'd)



	A	B	C	D	E	F	G	H	I
1	ANOVA: Single Factor								
2									
3	SUMMARY								
4	*Groups*	*Count*	*Average*						
5	Part 1	5	9.656						
6	Part 2	5	9.530						
7	Part 3	5	9.888						
8									
9									
10	ANOVA								
11	*Source of Variation*	*SS*	*df*	*MS*					
12	Between Groups	0.330	2	0.165					
13	Within Groups	0.061	12	**0.005**	$(\sigma_{ms})^2$				
14				**0.072**	σ_{ms}	=SQRT(D13)			
15				**0.215**	$3\sigma_{ms}$	=3*D14			
16									
17									
18									
19									
20									
21									
22									
23									

Screen shot of the sheet **Edited output**

Exercise 11.1

Open file *Student Files \ MSA-one appraiser*

Perform the analysis shown in the last three slides.

The value $3\sigma_{ms}$ is the *measurement error* — the amount by which a single measurement could vary (+ or -) from the true value.

Degrees of freedom for MSA with one appraiser

- Let: N = sample size of an MSA (total number of measurements)

  I = number of items in the MSA (parts, transactions, samples, . . .)

- DF for σ_{ms} = N – I

NOTE:
I, not 1 (one) !

- In the previous example: N = 15, I = 3

- DF for σ_{ms} = N – I = 15 – 3 = 12

Exercise 11.2

For each scenario below, give the total number of measurements and the degrees of freedom for σ_{ms}.

	N	DF
(a) 1 item is measured 15 times		
(b) Each of 15 items is measured 1 time		
(c) Each of 3 items is measured 5 times		
(d) Each of 3 items is measured 10 times		
(e) Each of 15 items is measured 2 times		
(f) Each of 4 items is measured 10 times		
(g) Each of 20 items is measured 2 times		
(h) Each of 8 items is measured 8 times		
(i) Each of 36 items is measured 2 times		

Degrees of freedom for MSA with multiple appraisers

- Let: N = sample size of an MSA (total number of measurements)

  I = number of items in the MSA (parts, transactions, whatever)

  A = number of appraisers

  S = number of *sessions* (measurements per item per appraiser)

- In general: DF for σ_{ms} . . . . N – I

  DF for σ_{rpt} (repeatability) . . . . . IA(S – 1)

  DF for σ_{rpd} (reproducibility) . . . . I(A – 1)

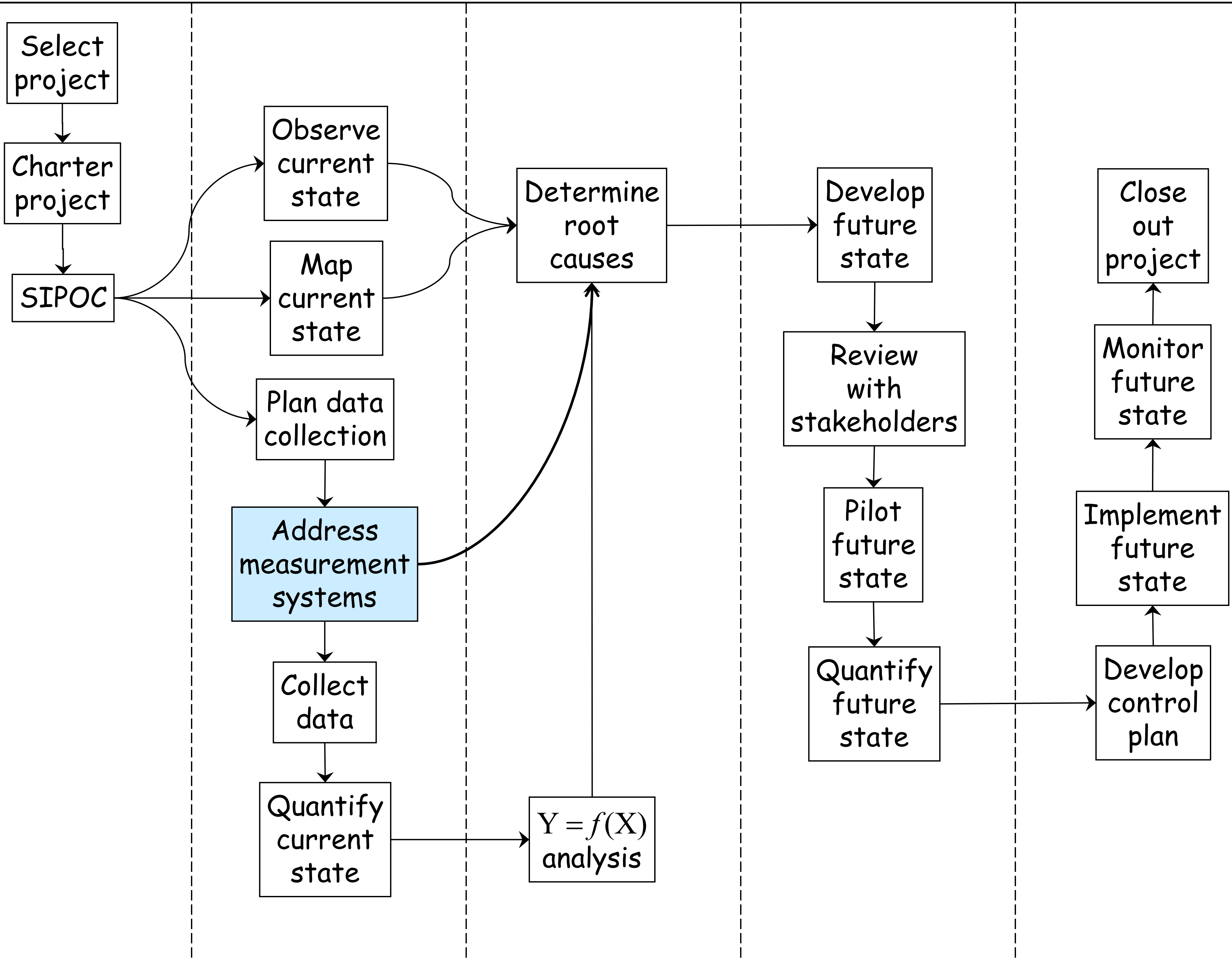
- Note that the DFs for σ_{rpt} and σ_{rpd} add up to the DF for σ_{ms} (because N = IAS)

Example

- 5 items, 7 appraisers, 2 sessions
- $N = (5)(7)(2) = 70$
- DF for $\sigma_{ms} = N - I = 70 - 5 = 65$
- DF for σ_{rpt} (repeatability) $= IA(S - 1) = 5(7)(1) = 35$
- DF for σ_{rpd} (reproducibility) $= I(A - 1) = 5(6) = 30$

Exercise 20.3

Repeat these calculations for 10 items, 3 appraisers, and 3 sessions.



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

Monitor future state

Close out project

Topics

- Gages
- Measurement systems
- Statistical model for measurement variation
- Impact of measurement variation
- Measurement system analysis (MSA)
- Basic assumption for MSA
- MSA for quantitative measurements

Gages

- A *gage* is a measurement device
- Gages can produce quantitative measurements or categorical classifications
- The people who use the gages are usually called *appraisers*, *inspectors*, or *operators*
- For visual inspections, the appraisers are themselves the gages, but they are not called that
- For automated measurement systems, the appraisers may not play a significant role in producing the results

Measurement system

- A set of gages used to measure defined characteristics of a defined class of objects or events
- The gages produce the same type of data
- For quantitative measurements, the gages provide the same data resolution (x.x, x.xx, x.xxx, xx.x, . . .)
- The appraisers are part of the system
- The methods and documentation are part of the system
- If there are standards, they are part of the system

Impact of measurement variation

		Action taken	
		Pass	**Fail**
True outcome	**Good**	☺	*“False alarm”*
	Bad	*“Escape”*	☺

Which type of error is more costly? For which is the cost easier to quantify?

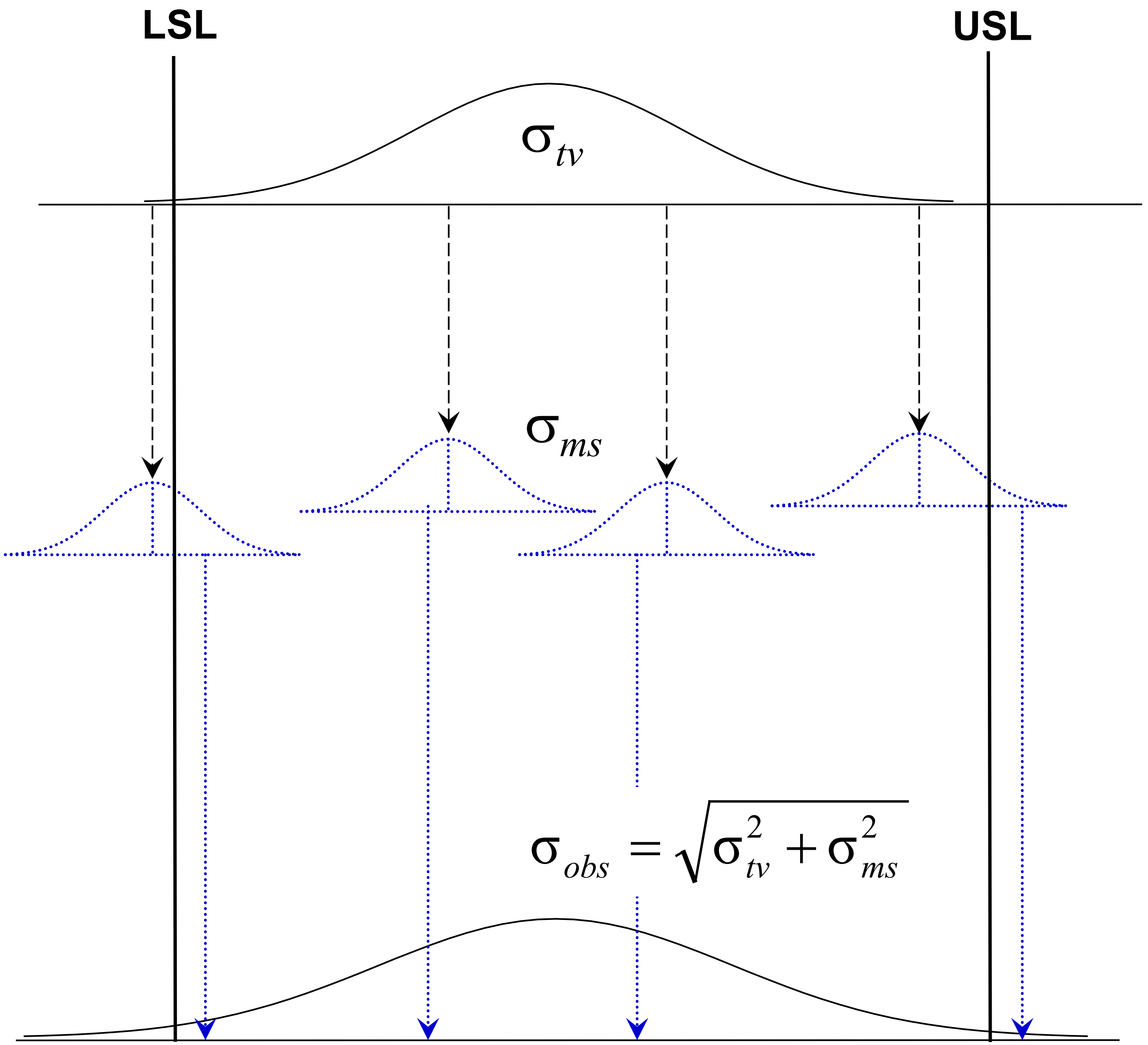
Impact of measurement variation (cont'd)

Variation in true values

+

Measurement variation

Variation in observed values



$$\sigma_{obs} = \sqrt{\sigma_{tv}^2 + \sigma_{ms}^2}$$

Passing bad items

Failing good items

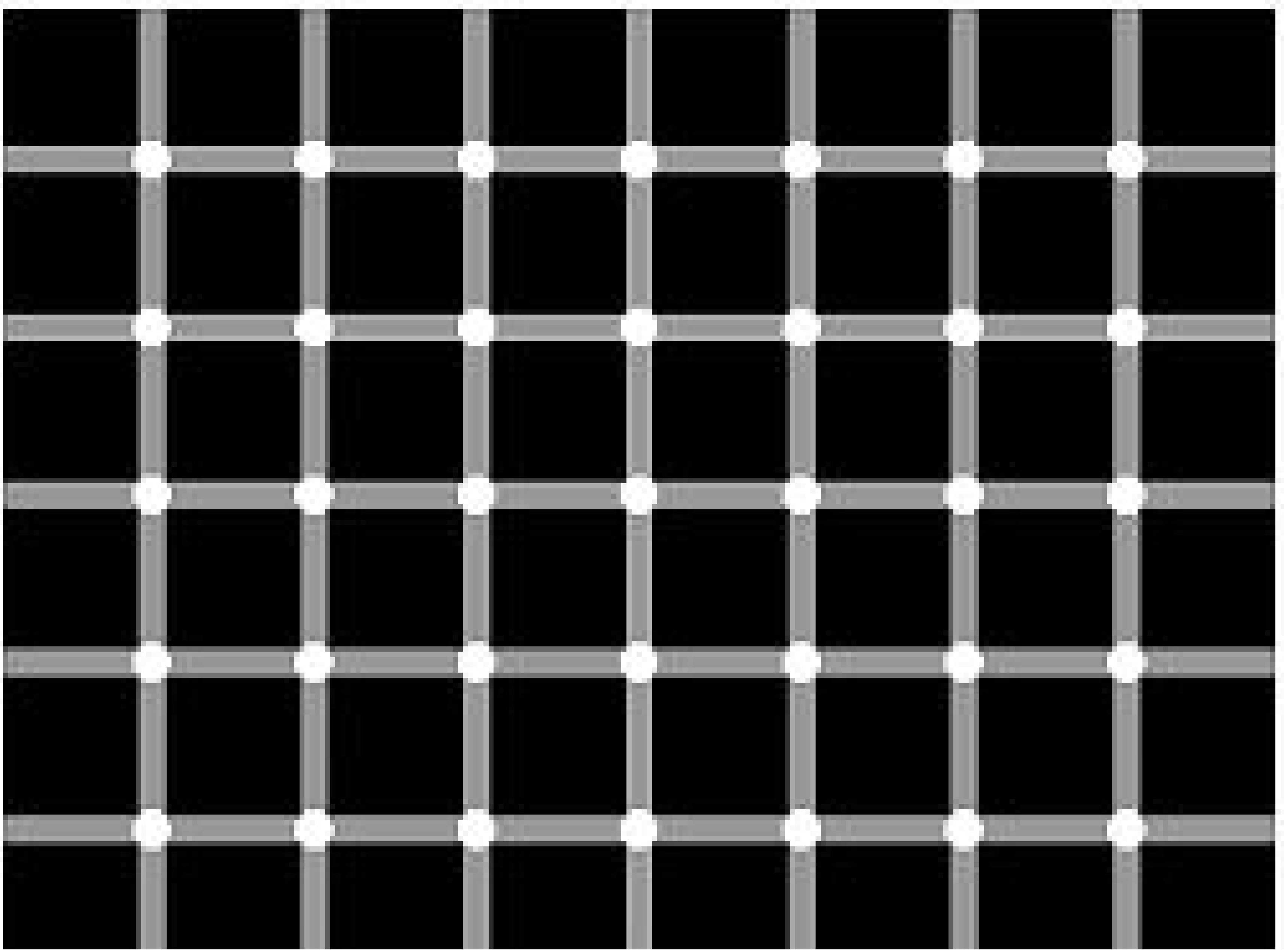
Measurement system analysis (MSA)

- Companies should make decisions based on data
- Bad data → bad decisions
- One large company estimated the annual cost impact of excessive measurement variation as $33M
- MSA quantifies and classifies measurement variation
- MSA → corrective action → reduced measurement variation → reduced cost

Common corrective actions

- Improving procedures and fixtures
- Improving gages
- Training appraisers
- Acquiring better gages

Exercise: count the black dots



Basic assumption for MSA

- MSA requires multiple measurements of "unchanging objects"

- This is not always possible
  - ✓ Measurement process may destroy measured items
  - ✓ Measurement process may change measured characteristics
  - ✓ Measured characteristics may change over time

- In such cases, ad hoc workarounds are used
  - ✓ Treat contiguous material samples as the same sample
  - ✓ Treat items categorized as "very similar" as the same item

- Workarounds bias σ_{ms} upwards
  - ✓ Measurement system looks worse than it really is

Capability metrics for quantitative MSA

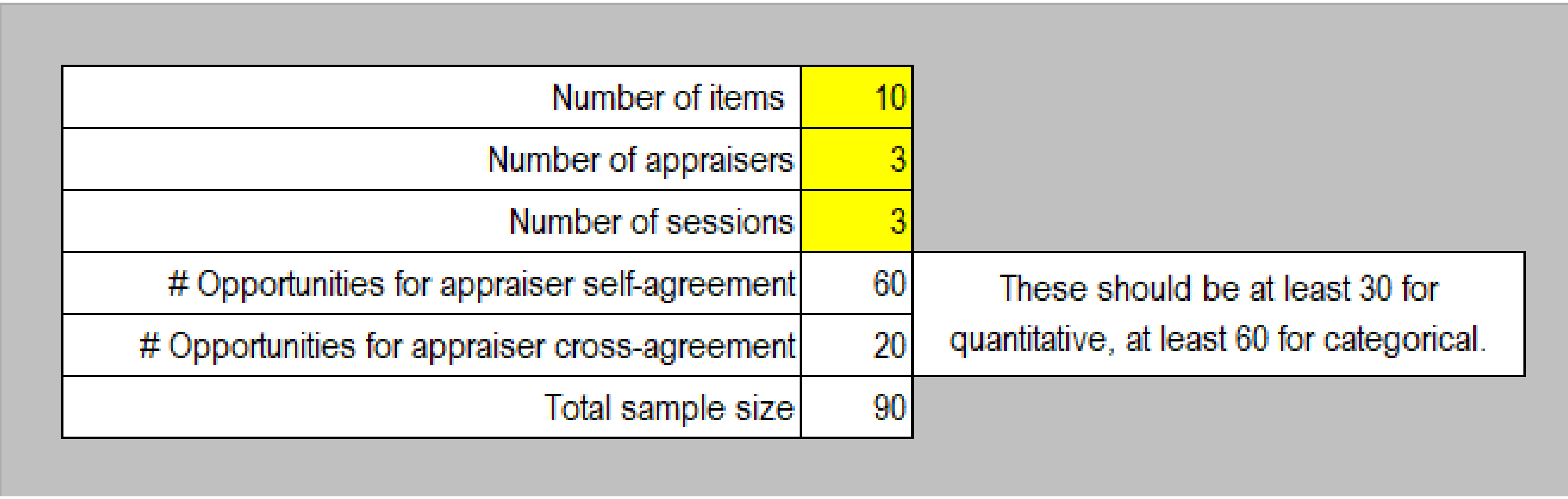
% Tolerance	$100 \times \dfrac{3\sigma_{ms}}{(\mathrm{USL} - \mathrm{LSL})/2}$	- Most common metric - Must have both LSL and USL (usually product or process specs)
% Tolerance LSL only	$100 \times \dfrac{3\sigma_{ms}}{\mu - LSL}$	- Use when there is only LSL - Process mean (μ) should be based on historical data, not the MSA data
% Tolerance USL only	$100 \times \dfrac{3\sigma_{ms}}{USL - \mu}$	- Use when there is only USL - Process mean (μ) should be based on historical data, not the MSA data
% Process	$100 \times \dfrac{\sigma_{\mathrm{ms}}}{\sigma_{\mathrm{obs}}}$	- Doesn't require spec limits - Process standard deviation (σ_{obs}) should be based on historical data, not the MSA data
Measurement error	$3\sigma_{ms}$	- Has units of the measured characteristic - Intrinsic capability, not relative to product or process requirements

Acceptability criteria for “percent” metrics

10% or less	Excellent
10-20%	Good
20-30%	Acceptable
Greater than 30%	Unacceptable

Examples of step 3

Open *Student Files* → *calculator - sample size* → *MSA* sheet

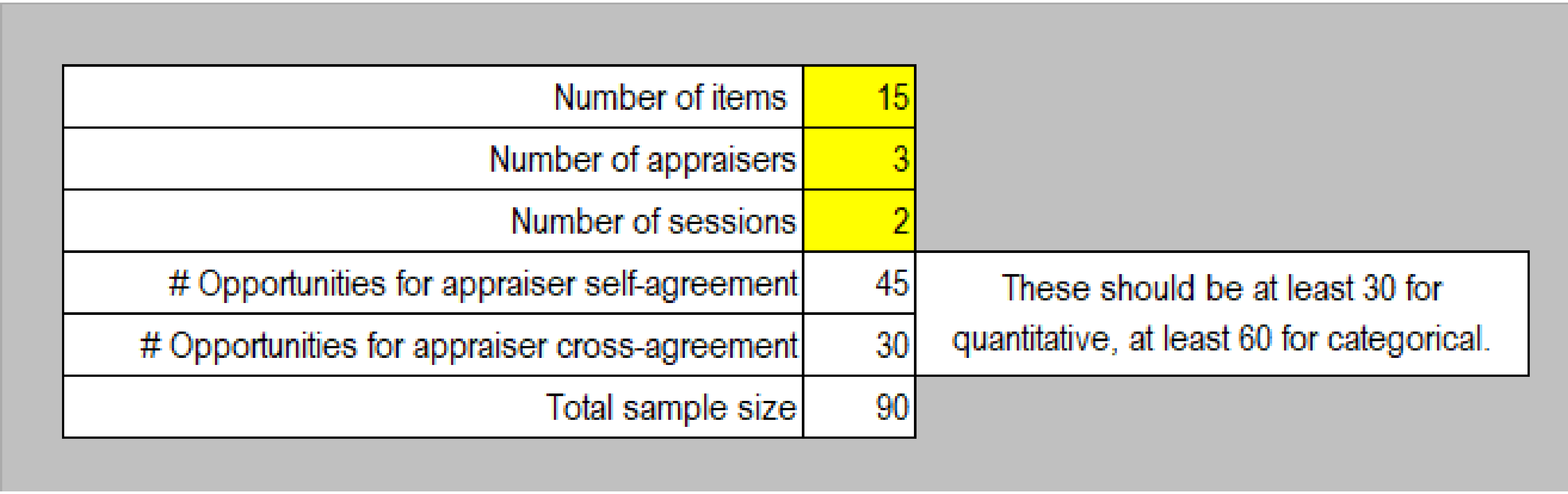


Number of items	10	
Number of appraisers	3	
Number of sessions	3	
# Opportunities for appraiser self-agreement	60	These should be at least 30 for quantitative, at least 60 for categorical.
# Opportunities for appraiser cross-agreement	20	
Total sample size	90	

- The standard automotive gage study (“10 3 3”)
- Not enough opportunities for appraiser cross agreement
- Unnecessarily many opportunities for appraiser self agreement

Examples of step 3

A better plan

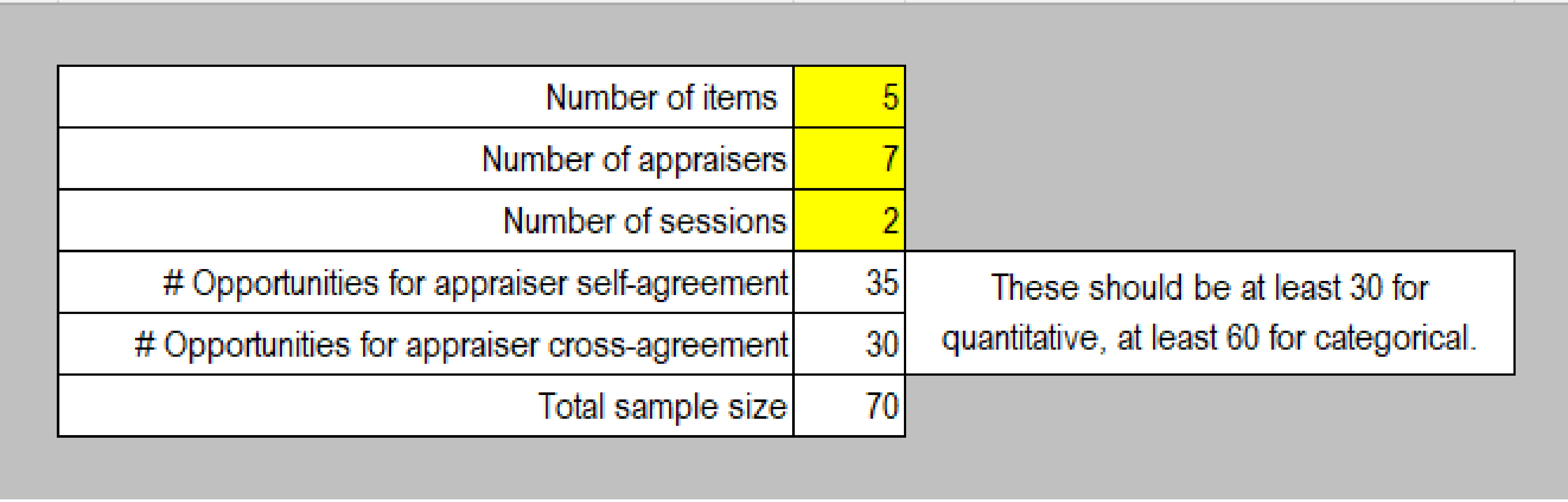


Number of items	15	
Number of appraisers	3	
Number of sessions	2	
# Opportunities for appraiser self-agreement	45	These should be at least 30 for quantitative, at least 60 for categorical.
# Opportunities for appraiser cross-agreement	30	
Total sample size	90	

- Better balance of opportunities for self and cross agreement
- Same total sample size

Examples of step 3

Best plan, assuming there are actually 7 appraisers



Number of items	5	
Number of appraisers	7	
Number of sessions	2	
# Opportunities for appraiser self-agreement	35	These should be at least 30 for quantitative, at least 60 for categorical.
# Opportunities for appraiser cross-agreement	30	
Total sample size	70	

- Adequate opportunities for self and cross agreement
- Smaller total sample size

Conducting a quantitative MSA

1. Perform this sequence for each session:

First appraiser measures all items once

Second appraiser measures all items once

.

.

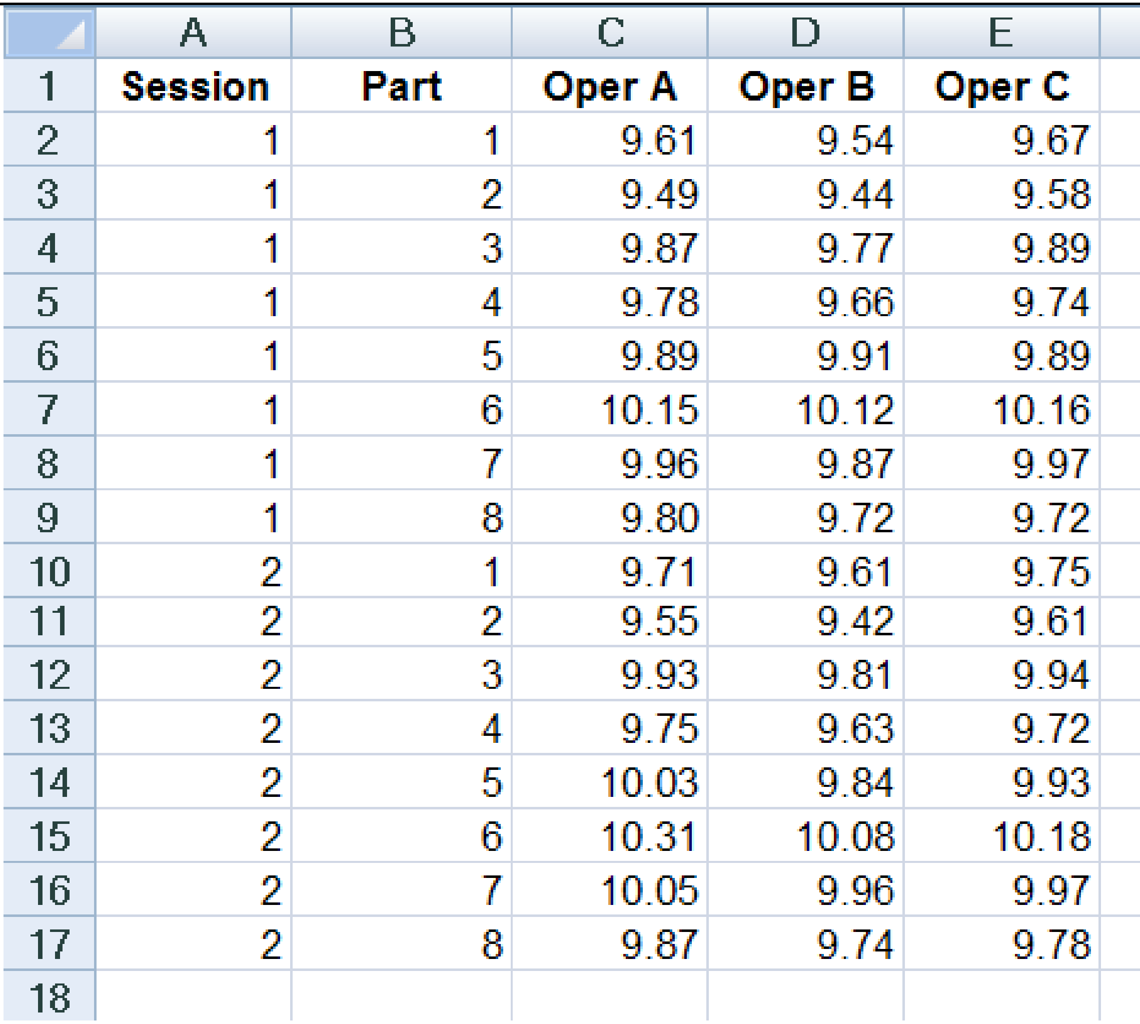
.

Last appraiser measures all items once.

2. The order in which the items are measured should be reversed each time the appraiser changes. Or, better yet, randomize the order each time.

Analyzing a quantitative MSA

- Open *Data Sets → msa velocity gage*
- Measurements are of Drop Velocity
- This is the data format required for continuous MSA in Excel
- The standard analysis requires that every appraiser measures every part the same number of times
- I = 8, A = 3, S = 2
- Was this a well designed MSA?



	A	B	C	D	E
1	**Session**	**Part**	**Oper A**	**Oper B**	**Oper C**
2	1	1	9.61	9.54	9.67
3	1	2	9.49	9.44	9.58
4	1	3	9.87	9.77	9.89
5	1	4	9.78	9.66	9.74
6	1	5	9.89	9.91	9.89
7	1	6	10.15	10.12	10.16
8	1	7	9.96	9.87	9.97
9	1	8	9.80	9.72	9.72
10	2	1	9.71	9.61	9.75
11	2	2	9.55	9.42	9.61
12	2	3	9.93	9.81	9.94
13	2	4	9.75	9.63	9.72
14	2	5	10.03	9.84	9.93
15	2	6	10.31	10.08	10.18
16	2	7	10.05	9.96	9.97
17	2	8	9.87	9.74	9.78
18					

What do the numbers in cell range C2:C9 represent:
part variation, measurement variation, or observed variation?

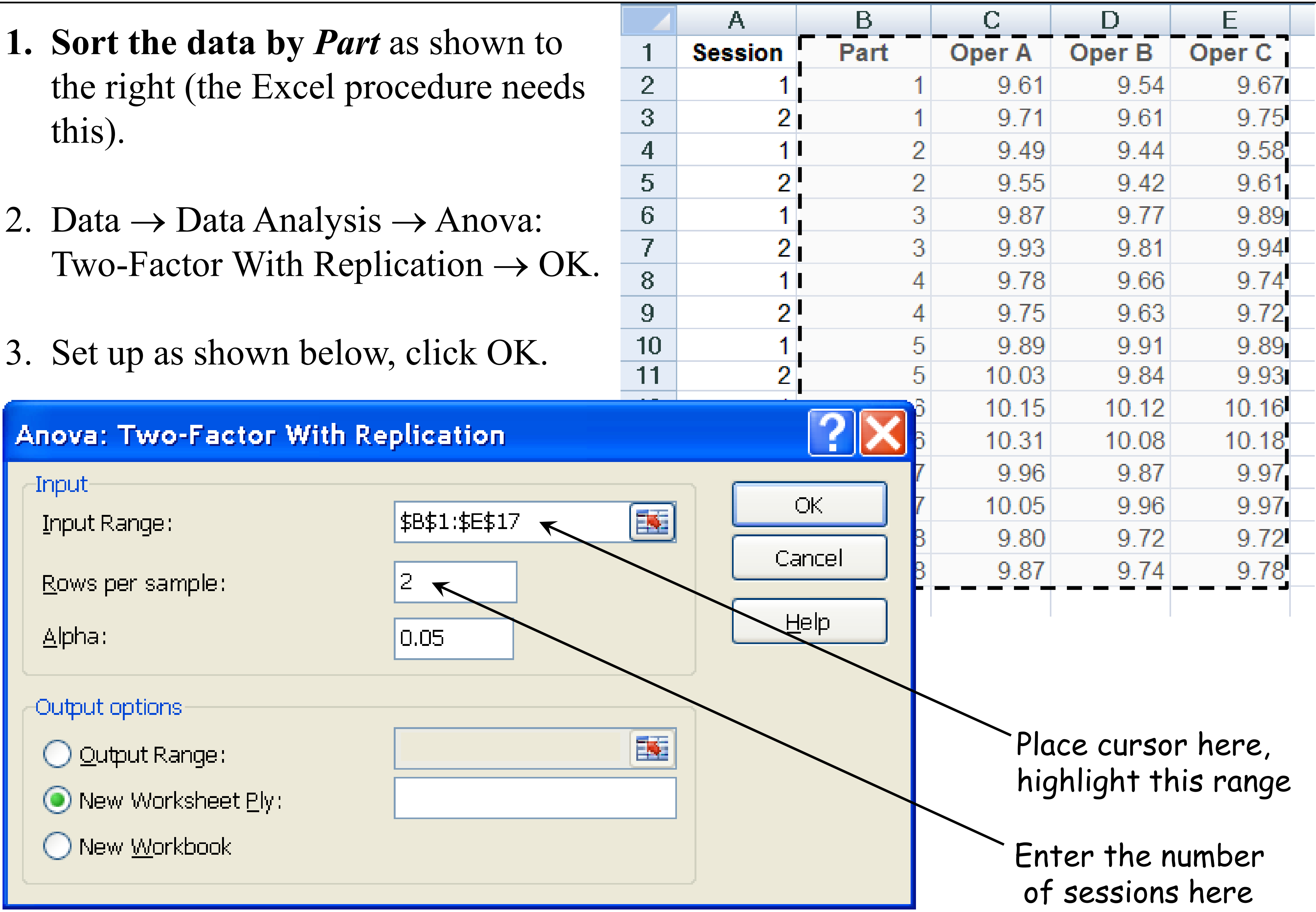
What do the numbers in cell range C2:E2 represent:
part variation, measurement variation, or observed variation?

Worked example

1. **Sort the data by *Part*** as shown to the right (the Excel procedure needs this).

2. Data → Data Analysis → Anova: Two-Factor With Replication → OK.

3. Set up as shown below, click OK.



	A	B	C	D	E
1	Session	Part	Oper A	Oper B	Oper C
2	1	1	9.61	9.54	9.67
3	2	1	9.71	9.61	9.75
4	1	2	9.49	9.44	9.58
5	2	2	9.55	9.42	9.61
6	1	3	9.87	9.77	9.89
7	2	3	9.93	9.81	9.94
8	1	4	9.78	9.66	9.74
9	2	4	9.75	9.63	9.72
10	1	5	9.89	9.91	9.89
11	2	5	10.03	9.84	9.93
			10.15	10.12	10.16
			10.31	10.08	10.18
			9.96	9.87	9.97
			10.05	9.96	9.97
			9.80	9.72	9.72
			9.87	9.74	9.78

Anova: Two-Factor With Replication

Input

Input Range: $B$1:$E$17

Rows per sample: 2

Alpha: 0.05

Output options

○ Output Range:

● New Worksheet Ply:

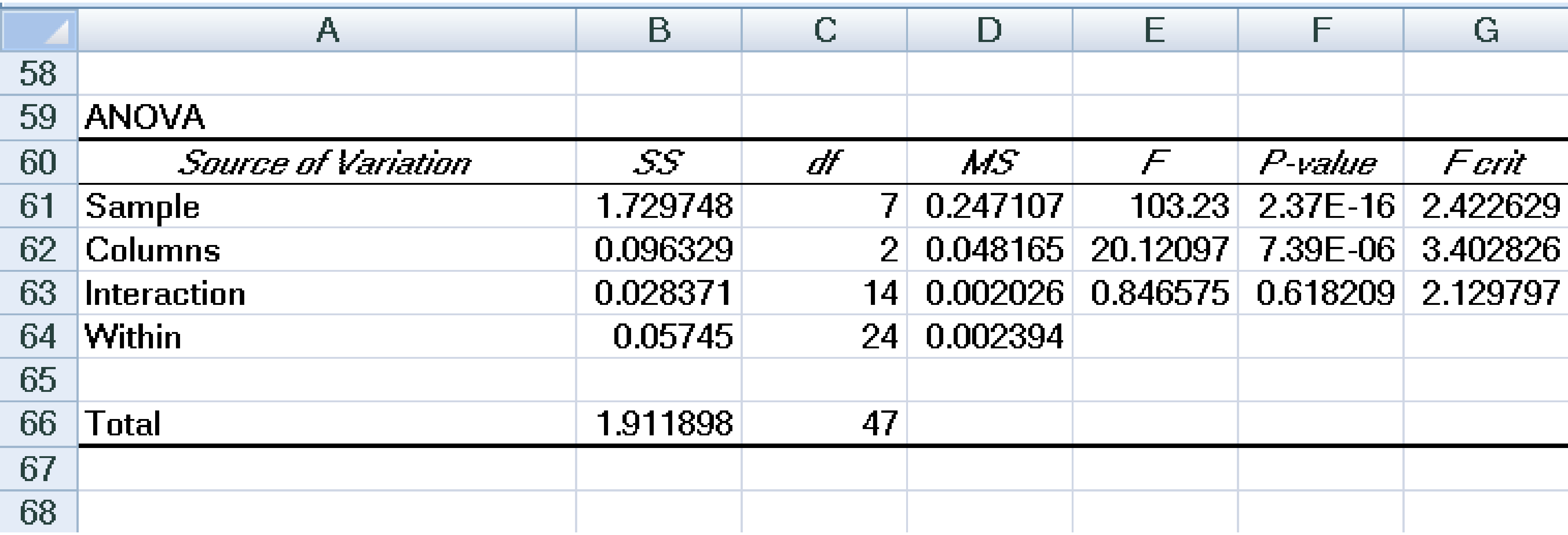
○ New Workbook

Place cursor here, highlight this range

Enter the number of sessions here

Example (cont'd)

4. Scroll down to the ANOVA table as shown here.

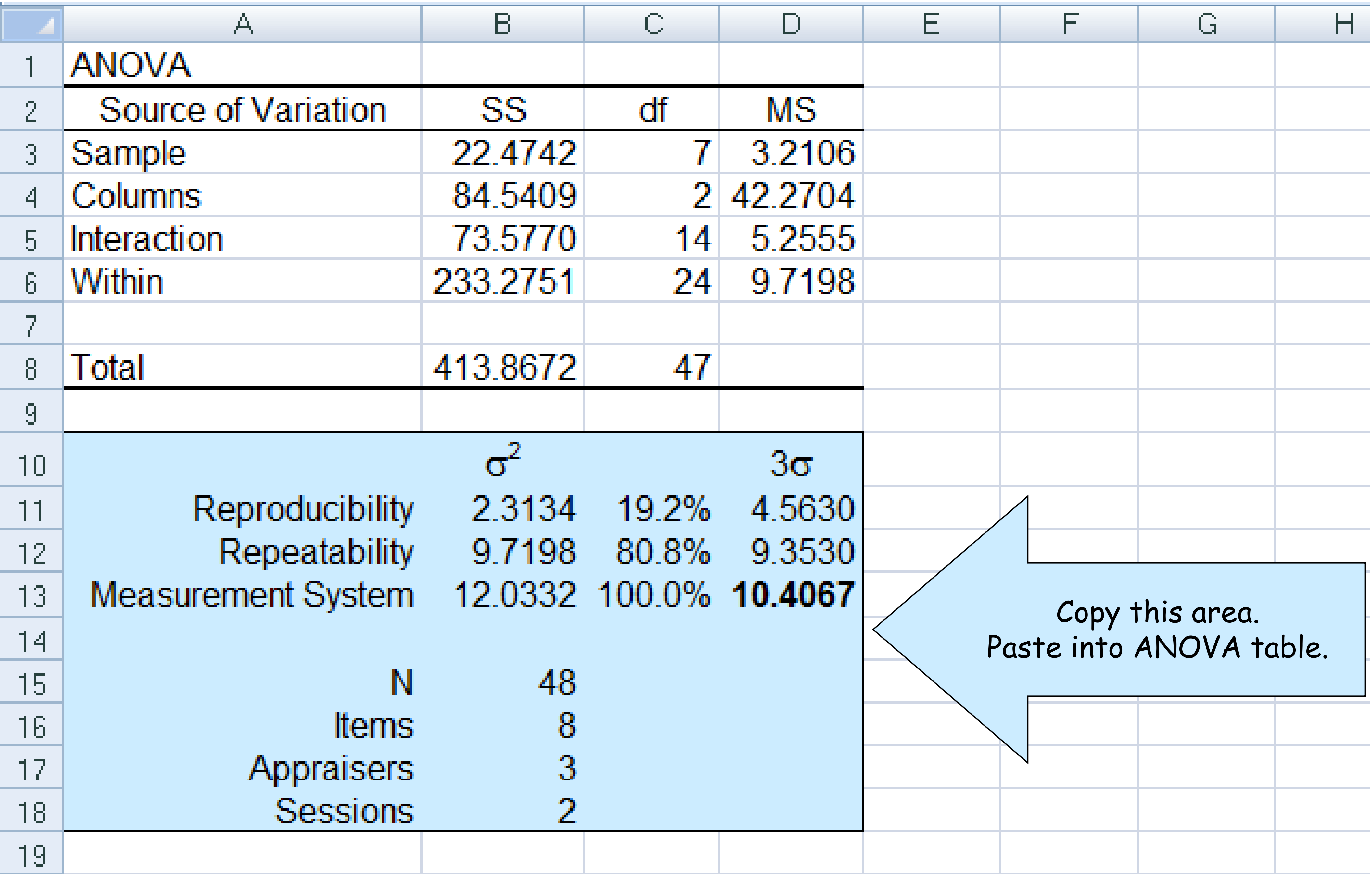


	A	B	C	D	E	F	G
58							
59	ANOVA						
60	*Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
61	Sample	1.729748	7	0.247107	103.23	2.37E-16	2.422629
62	Columns	0.096329	2	0.048165	20.12097	7.39E-06	3.402826
63	Interaction	0.028371	14	0.002026	0.846575	0.618209	2.129797
64	Within	0.05745	24	0.002394			
65							
66	Total	1.911898	47				
67							
68							

5. Open *Student Files* → *calculator – Gage R&R*.

Example (cont'd)

6. Copy the shaded area.



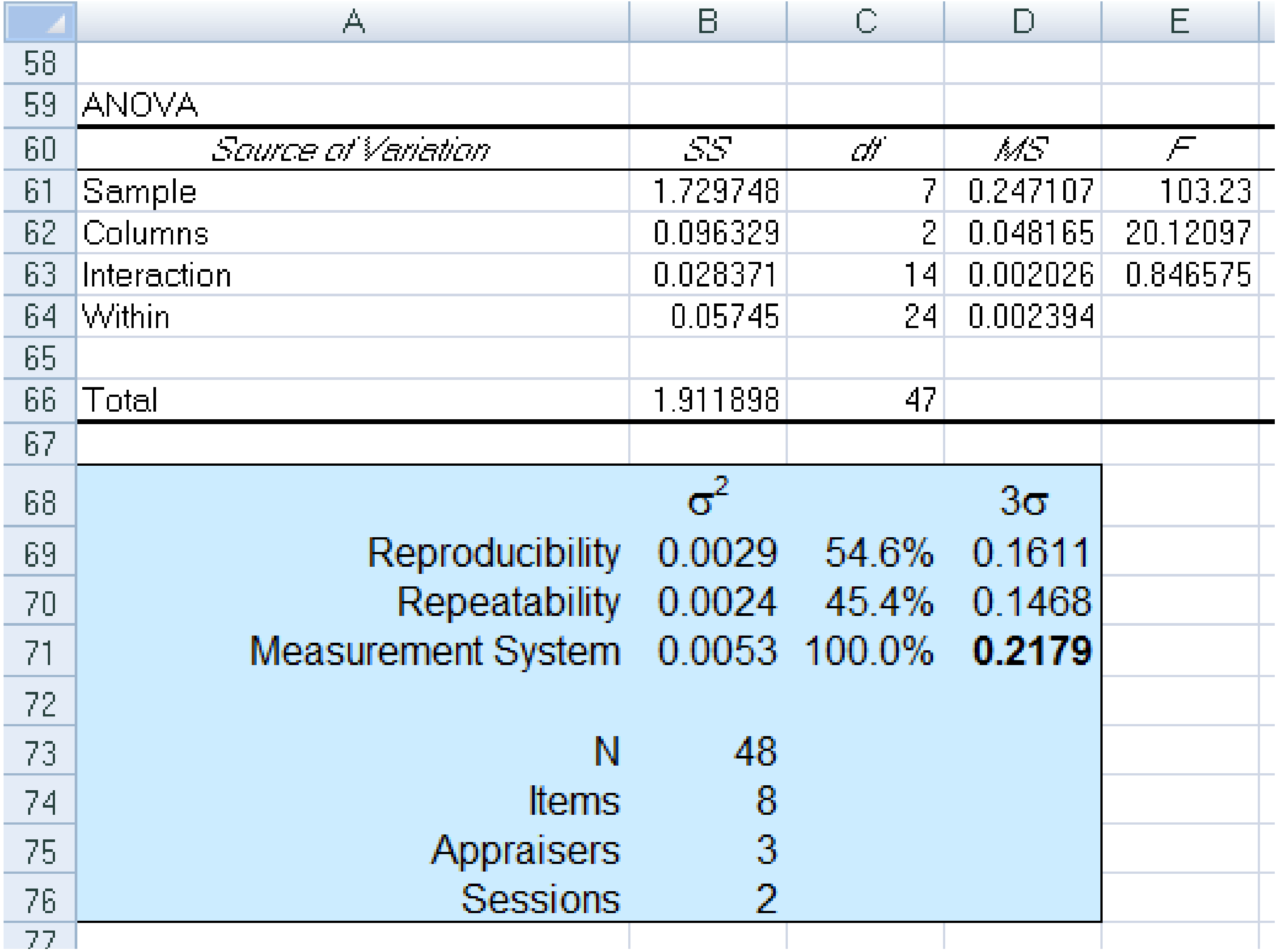
	A	B	C	D	E	F	G	H
1	ANOVA							
2	Source of Variation	SS	df	MS				
3	Sample	22.4742	7	3.2106				
4	Columns	84.5409	2	42.2704				
5	Interaction	73.5770	14	5.2555				
6	Within	233.2751	24	9.7198				
7								
8	Total	413.8672	47					
9								
10		σ^2		3σ				
11	Reproducibility	2.3134	19.2%	4.5630				
12	Repeatability	9.7198	80.8%	9.3530				
13	Measurement System	12.0332	100.0%	**10.4067**				
14								
15	N	48						
16	Items	8						
17	Appraisers	3						
18	Sessions	2						
19								

Copy this area.
Paste into ANOVA table.

Example (cont'd)

7. Paste the shaded area below your ANOVA table as shown.

$$3\sigma_{ms} = 0.2179$$



	A	B	C	D	E
58					
59	ANOVA				
60	*Source of Variation*	*SS*	*df*	*MS*	*F*
61	Sample	1.729748	7	0.247107	103.23
62	Columns	0.096329	2	0.048165	20.12097
63	Interaction	0.028371	14	0.002026	0.846575
64	Within	0.05745	24	0.002394	
65					
66	Total	1.911898	47		
67					
68		σ^2		3σ	
69	Reproducibility	0.0029	54.6%	0.1611	
70	Repeatability	0.0024	45.4%	0.1468	
71	Measurement System	0.0053	100.0%	**0.2179**	
72					
73	N	48			
74	Items	8			
75	Appraisers	3			
76	Sessions	2			
77					

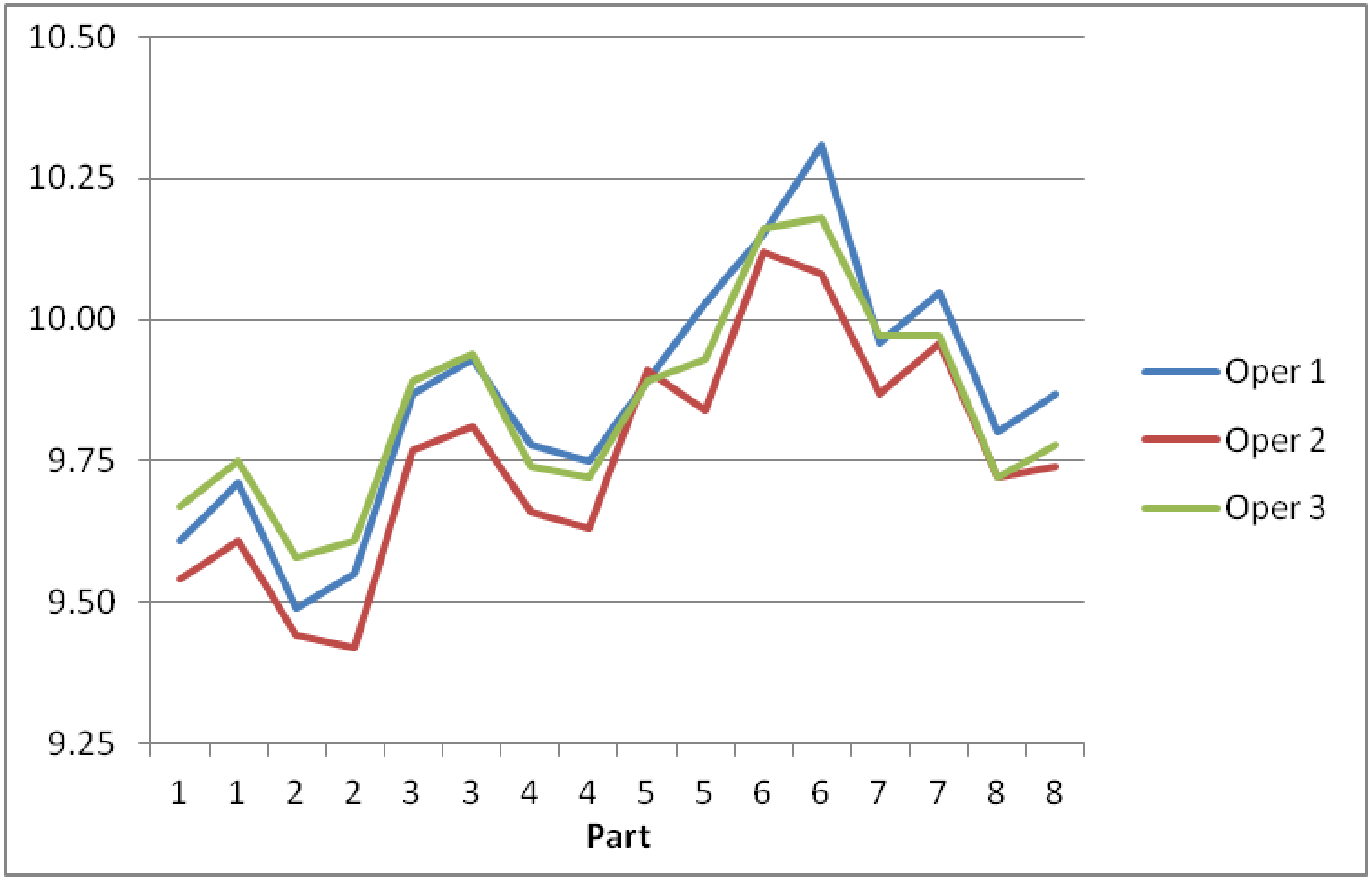
Reproducibility is the dominant component, but not by much.

8. For this measurement "Drop Velocity," (USL–LSL)/2 = 1.65. Use Excel to calculate the *% Tolerance* metric.

$$\%\mathrm{Tol} = 100 \times \frac{3\sigma_{\mathrm{ms}}}{1.65} = 13.2\%$$

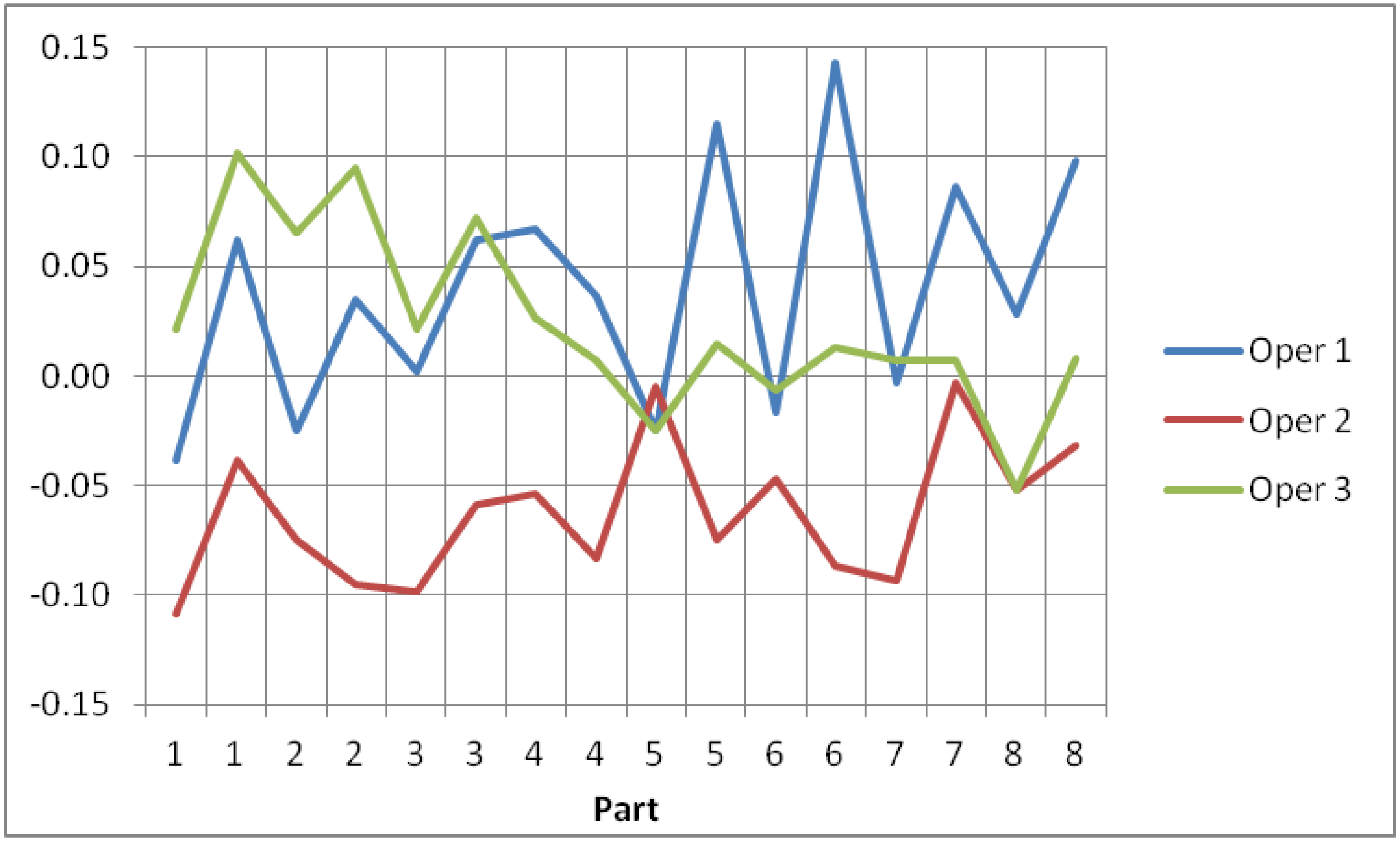
Example (cont'd)

9. Create a line chart of the operator columns by part (Highlight columns > Insert Line Chart)
10. This is what a good one looks like. The operator curves are close together and roughly parallel, showing they are getting similar measurements for each part.



Example (cont’d)

- If part variation is large enough relative to measurement variation, the lines on the previous chart will appear to be superimposed on each other
- The file *Data Sets* → *msa velocity gage with charts* gives the calculations for the chart below, which shows the data with the part averages subtracted out.
- This helps you see what’s going on with the measurements by each operator, when part variation in the study is large compared to measurement variation.



Interpreting 3σ_{ms}

- In this example, $3\sigma_{ms} = 0.2179$

- For a given measurement *m*, the true value lies in the interval

$$m \pm 0.2179$$

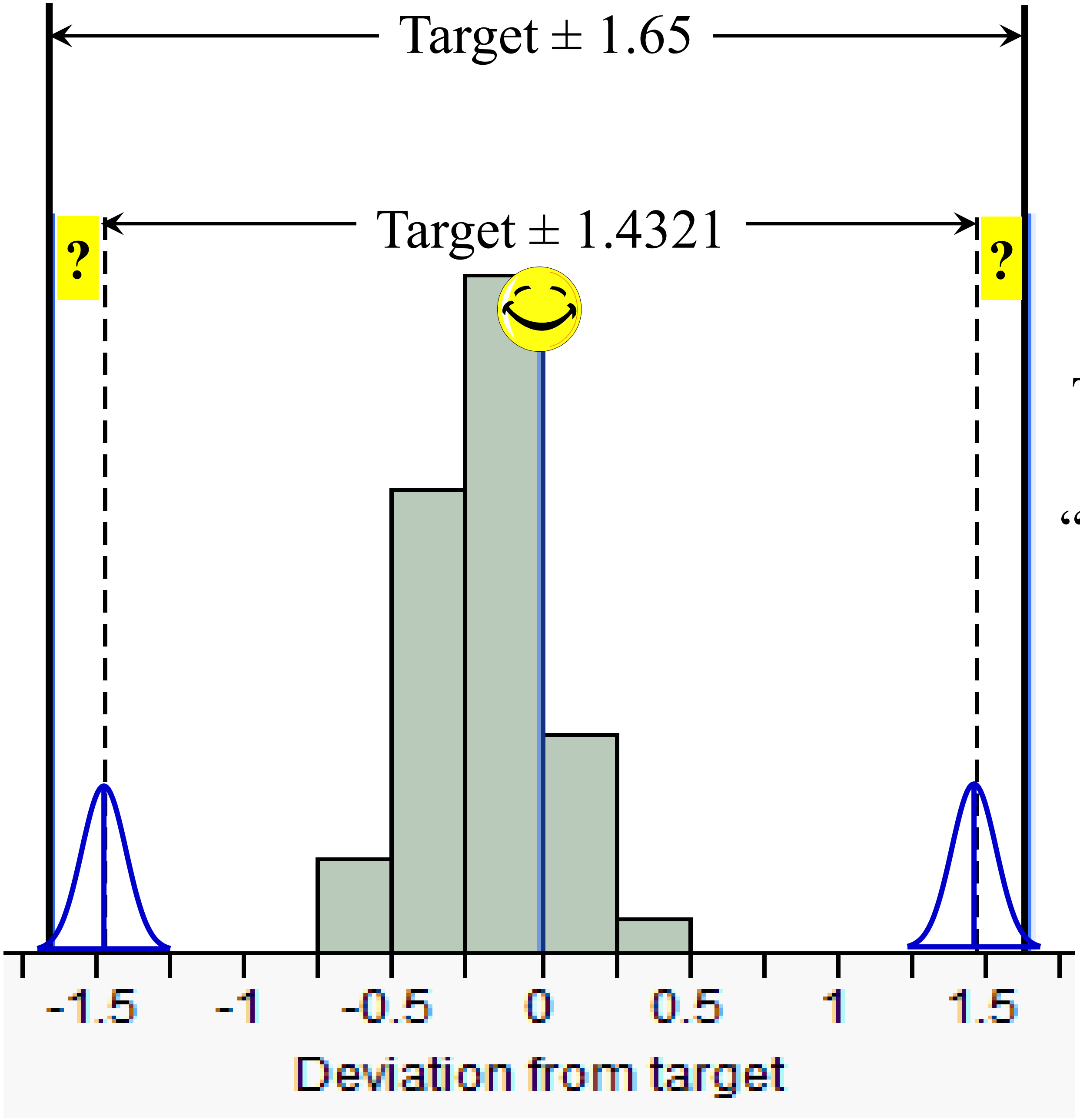
  with 99.7% confidence

- The tolerance for drop velocity is ± 1.65 (Given on previous slide)

- 1.65 – 0.2179 = 1.4321

- To be confident that a drop velocity is in spec, it must be within 1.4321 of the target value (see next slide)

Interpreting $3\sigma_{ms}$ (cont'd)



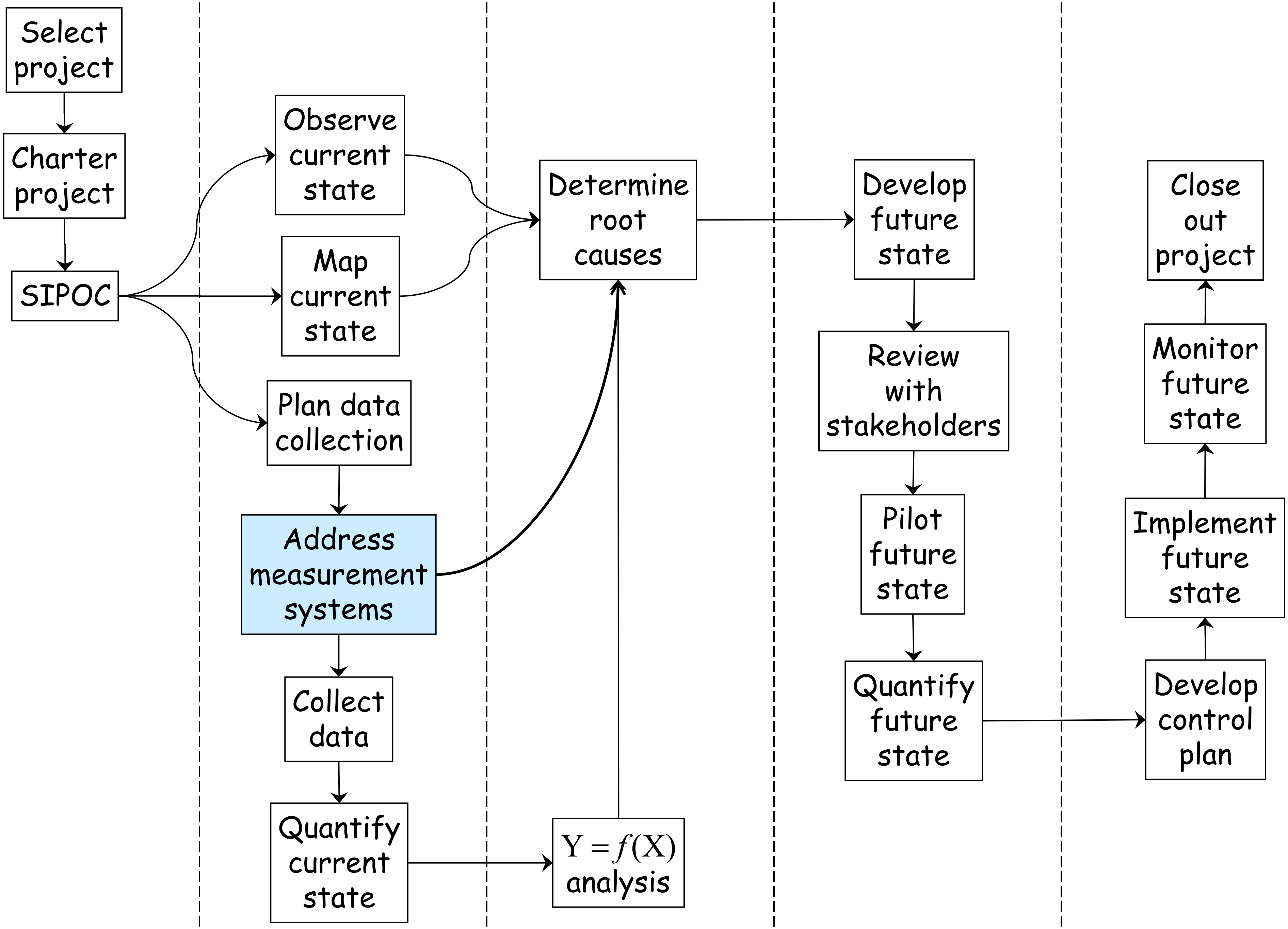
These are also known as "Guard Bands"

Exercise 12.1

Open *Data Sets* → *msa calipers*. These are dimensional inspections of PVC extrusions made with a hand-held digital caliper.

(a) The tolerance for this dimension is Target ± 0.020″. Find $3\sigma_{ms}$ and calculate the *% Tolerance* metric. Classify the measurement system as excellent, good, acceptable, or unacceptable.

13 Categorical MSA



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

Y = f(X) analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

Implement future state

Develop control plan

Categorical MSA

- Also known as *Attribute Gage Study*
- Applied most often to pass/fail inspections
- The terms *repeatability* and *reproducibility* are not used in this context
- In this section we assume that the study is based on *standards* (items for which we know the true value)
- Primary objective in this case:

Determine the % agreement with standard
(Also known as % correct)

Designing a categorical MSA

1. Choose at least 10 items (parts, samples, documents…) to be inspected. There should be roughly equal numbers of items that are clearly passing, borderline passing, borderline failing and clearly failing. Choose an expert appraiser to function as the reference standard.

2. If the measurement system has only a few appraisers, include them all in the study. If there are many appraisers, include as large a representative sample as possible.

3. Let I = the number of items, A = the number of appraisers, and S = the number of measurements per item per appraiser.

   - The quantity IA(S – 1) is the number of independent opportunities for appraisers to agree *with themselves*. It should be at least 60.

   - The quantity I(A – 1) is the number of independent opportunities for appraisers to agree *with each other*. It should be at least 60.

   It is best to satisfy these requirements by increasing A with I = 10 and S = 2. If this is not possible, increase I.

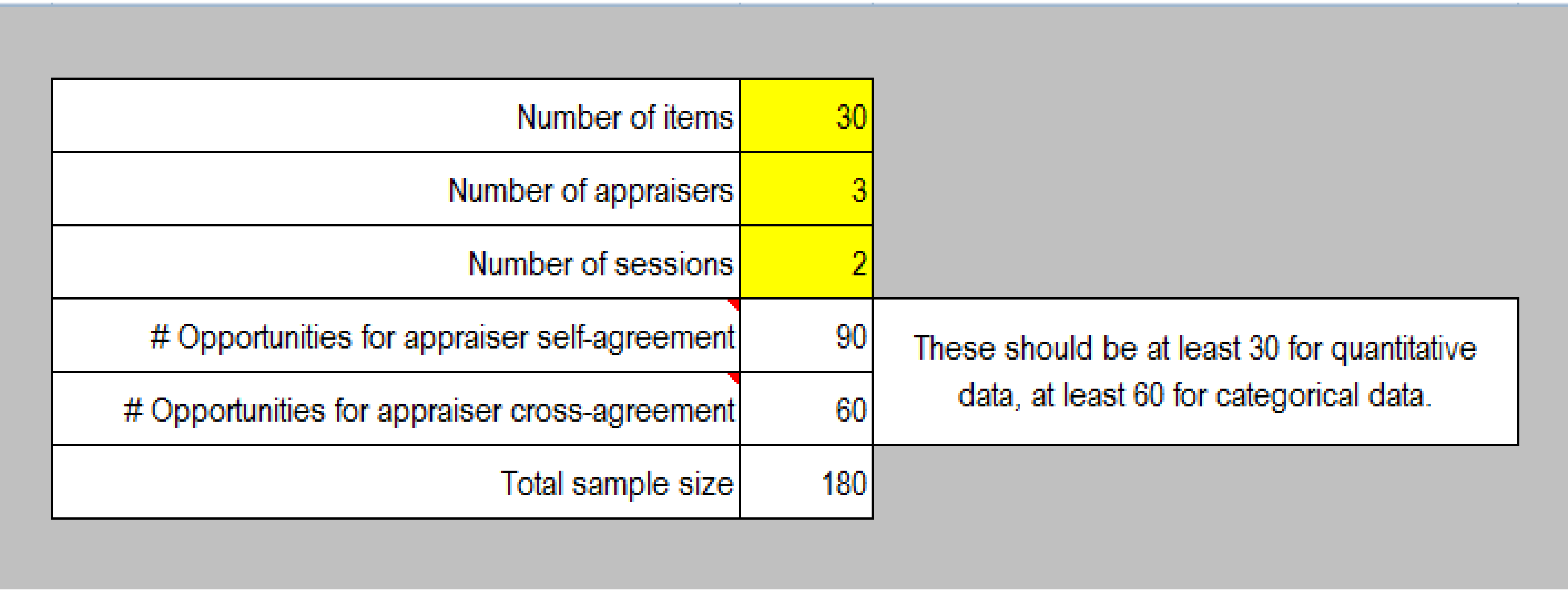
Designing a categorical MSA (cont'd)

4. If the measurements are taken by devices, and operators have no influence on the results, the devices are the appraisers.

5. If devices are used to aid human inspection, combinations of devices and human inspectors should be treated as the appraisers. The ideal is to use all possible combinations of human inspectors and devices. If this is not possible, a DOE matrix with an acceptable number of combinations should be created.

Examples of step 3

Open *Student Files* → *calculator - sample size* → *MSA* sheet

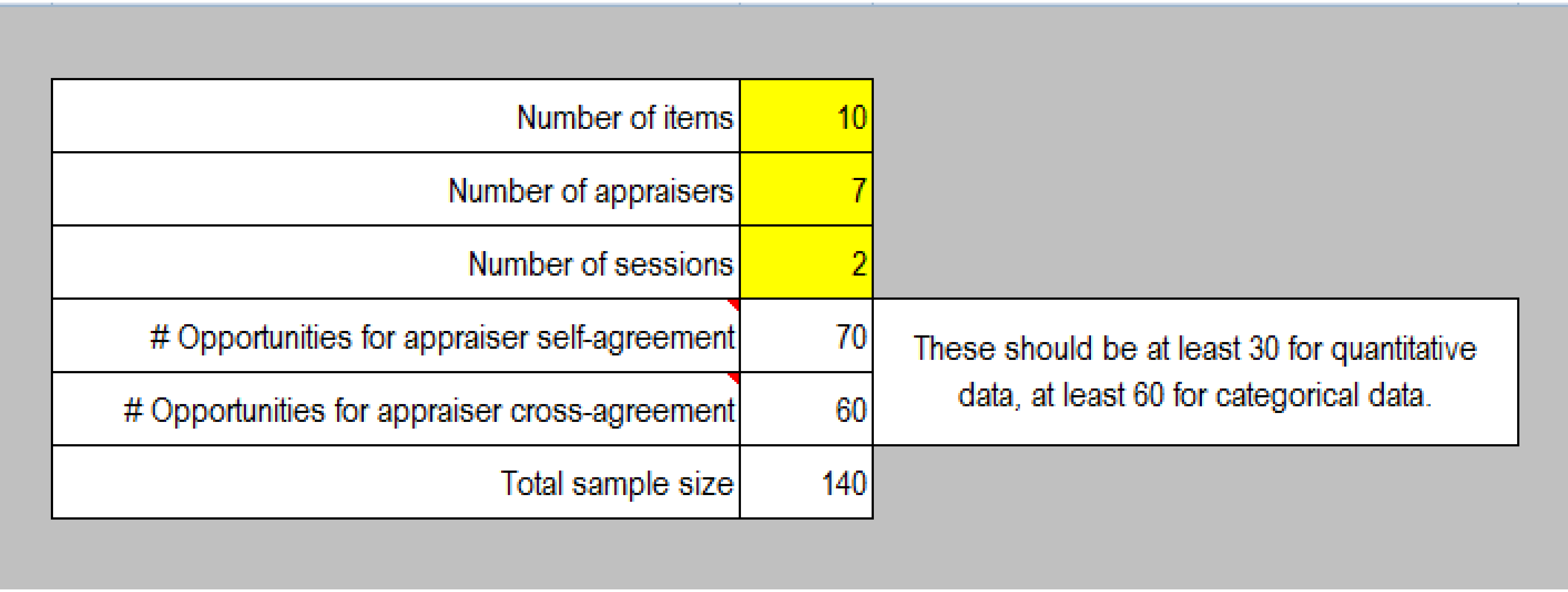


Number of items	30
Number of appraisers	3
Number of sessions	2
# Opportunities for appraiser self-agreement	90
# Opportunities for appraiser cross-agreement	60
Total sample size	180

These should be at least 30 for quantitative data, at least 60 for categorical data.

Best plan if there are only 3 appraisers

Examples of step 3



Number of items	10	
Number of appraisers	7	
Number of sessions	2	
# Opportunities for appraiser self-agreement	70	These should be at least 30 for quantitative data, at least 60 for categorical data.
# Opportunities for appraiser cross-agreement	60	
Total sample size	140	

Best plan if there are 7 appraisers

Conducting a categorical MSA*

1. Perform this sequence for each session:

First appraiser measures all items once

Second appraiser measures all items once

.

.

.

Last appraiser measures all items once.

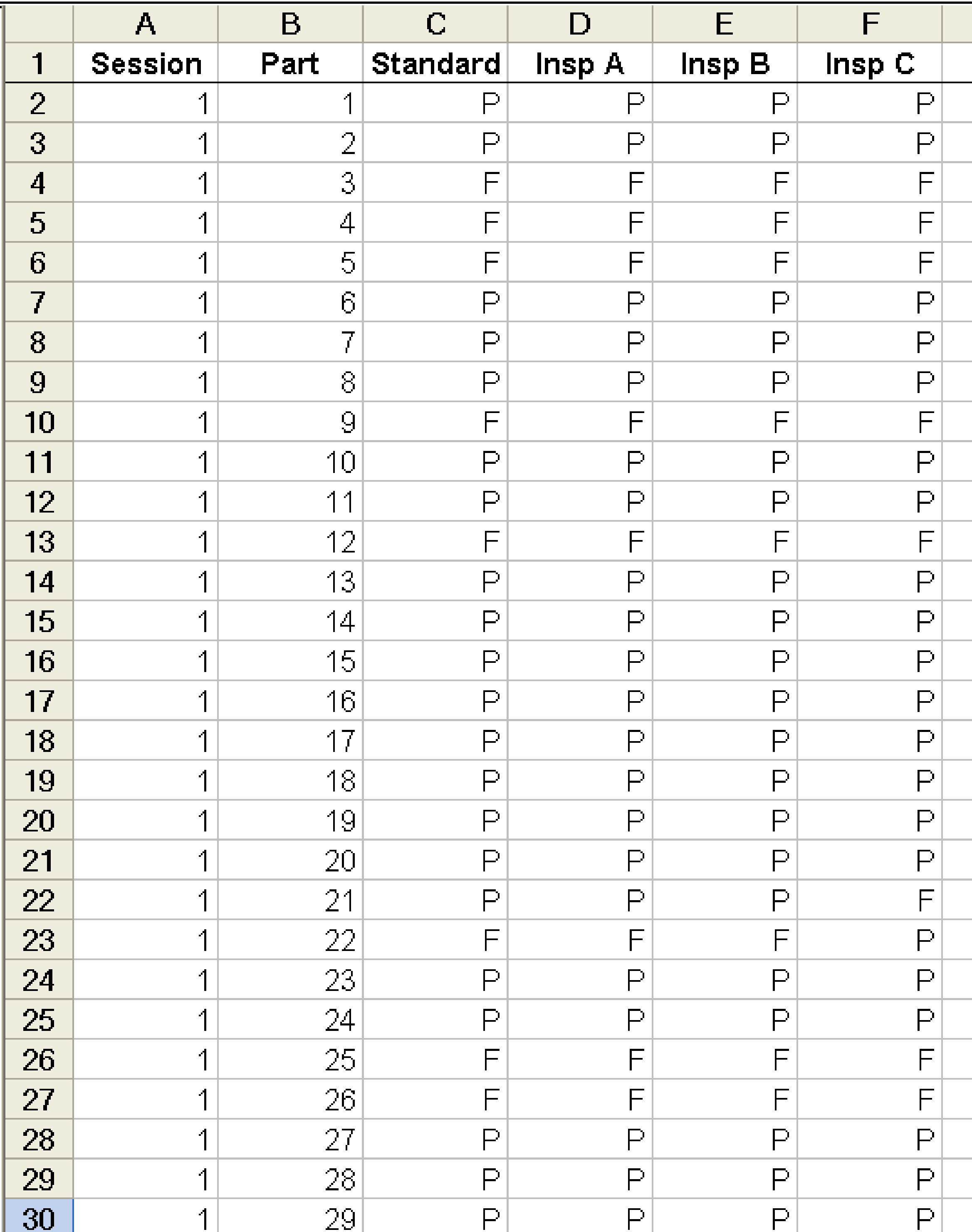
2. The order in which the items are measured should be reversed each time the appraiser changes.

---

*Same as for quantitative MSA

Analyzing a categorical MSA

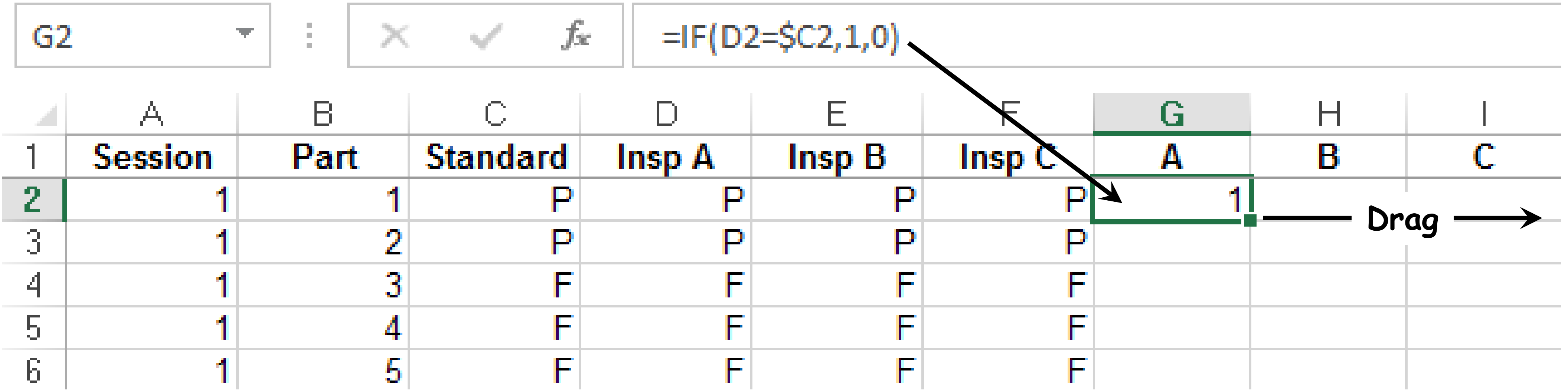
- Open *Data Sets \ msa passfail*
- I = 50, A = 3, S = 3
- Did they follow the best plan for 3 appraisers?
- P = pass, F = fail
- *Standard* gives the correct answer for each part inspected
- The analysis is based on % agreement with the standard



	A	B	C	D	E	F
1	Session	Part	Standard	Insp A	Insp B	Insp C
2	1	1	P	P	P	P
3	1	2	P	P	P	P
4	1	3	F	F	F	F
5	1	4	F	F	F	F
6	1	5	F	F	F	F
7	1	6	P	P	P	P
8	1	7	P	P	P	P
9	1	8	P	P	P	P
10	1	9	F	F	F	F
11	1	10	P	P	P	P
12	1	11	P	P	P	P
13	1	12	F	F	F	F
14	1	13	P	P	P	P
15	1	14	P	P	P	P
16	1	15	P	P	P	P
17	1	16	P	P	P	P
18	1	17	P	P	P	P
19	1	18	P	P	P	P
20	1	19	P	P	P	P
21	1	20	P	P	P	P
22	1	21	P	P	P	F
23	1	22	F	F	F	P
24	1	23	P	P	P	P
25	1	24	P	P	P	P
26	1	25	F	F	F	F
27	1	26	F	F	F	F
28	1	27	P	P	P	P
29	1	28	P	P	P	P
30	1	29	P	P	P	P

Worked example

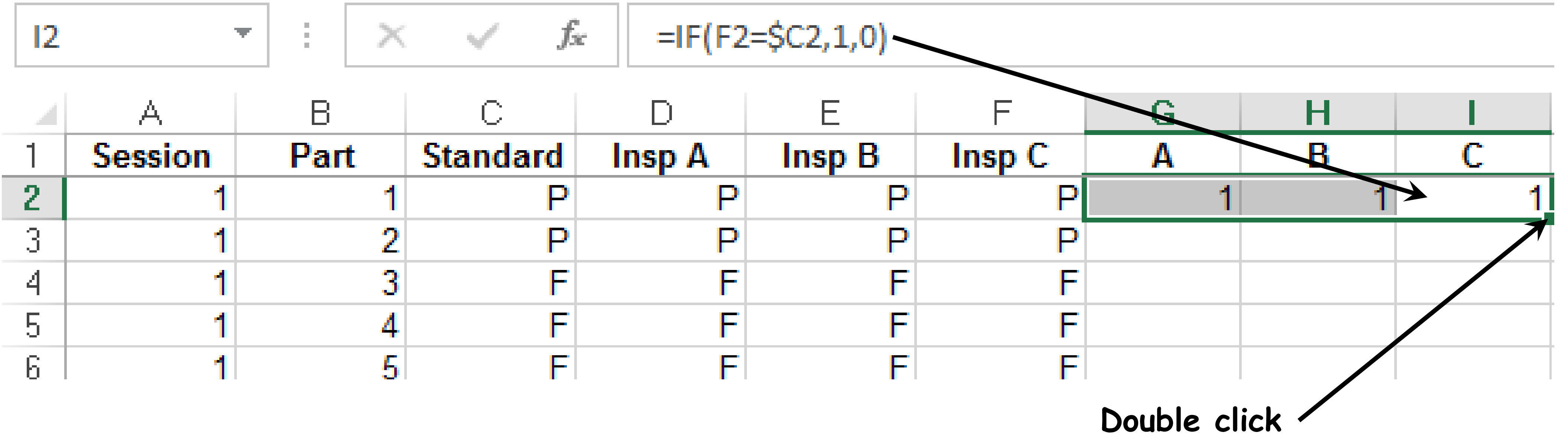
The first step is to define new columns indicating whether A, B, and C agree or disagree with *Standard* in each case (1 = agree, 0 = disagree)



G2 =IF(D2=$C2,1,0)

	A	B	C	D	E	F	G	H	I
1	Session	Part	Standard	Insp A	Insp B	Insp C	A	B	C
2	1	1	P	P	P	P	1		
3	1	2	P	P	P	P			
4	1	3	F	F	F	F			
5	1	4	F	F	F	F			
6	1	5	F	F	F	F			

Drag



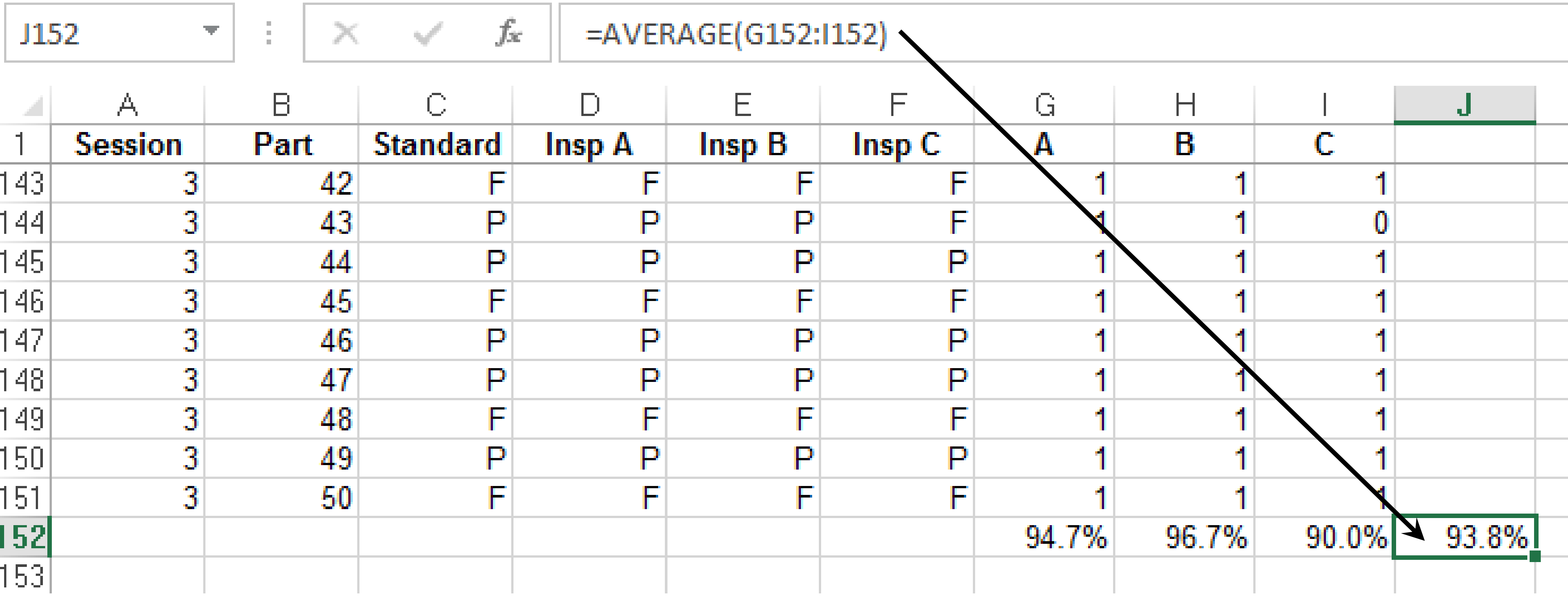
I2 =IF(F2=$C2,1,0)

	A	B	C	D	E	F	G	H	I
1	Session	Part	Standard	Insp A	Insp B	Insp C	A	B	C
2	1	1	P	P	P	P	1	1	1
3	1	2	P	P	P	P			
4	1	3	F	F	F	F			
5	1	4	F	F	F	F			
6	1	5	F	F	F	F			

Double click

Example (cont'd)

- Use the *Average* function on the *AutoSum* button to get the % agreement with standard for each inspector (cells G152 through I152)
- Use it again to get the overall % agreement with standard (cell J152)
- If improvement is needed, Inspector C is the greatest opportunity



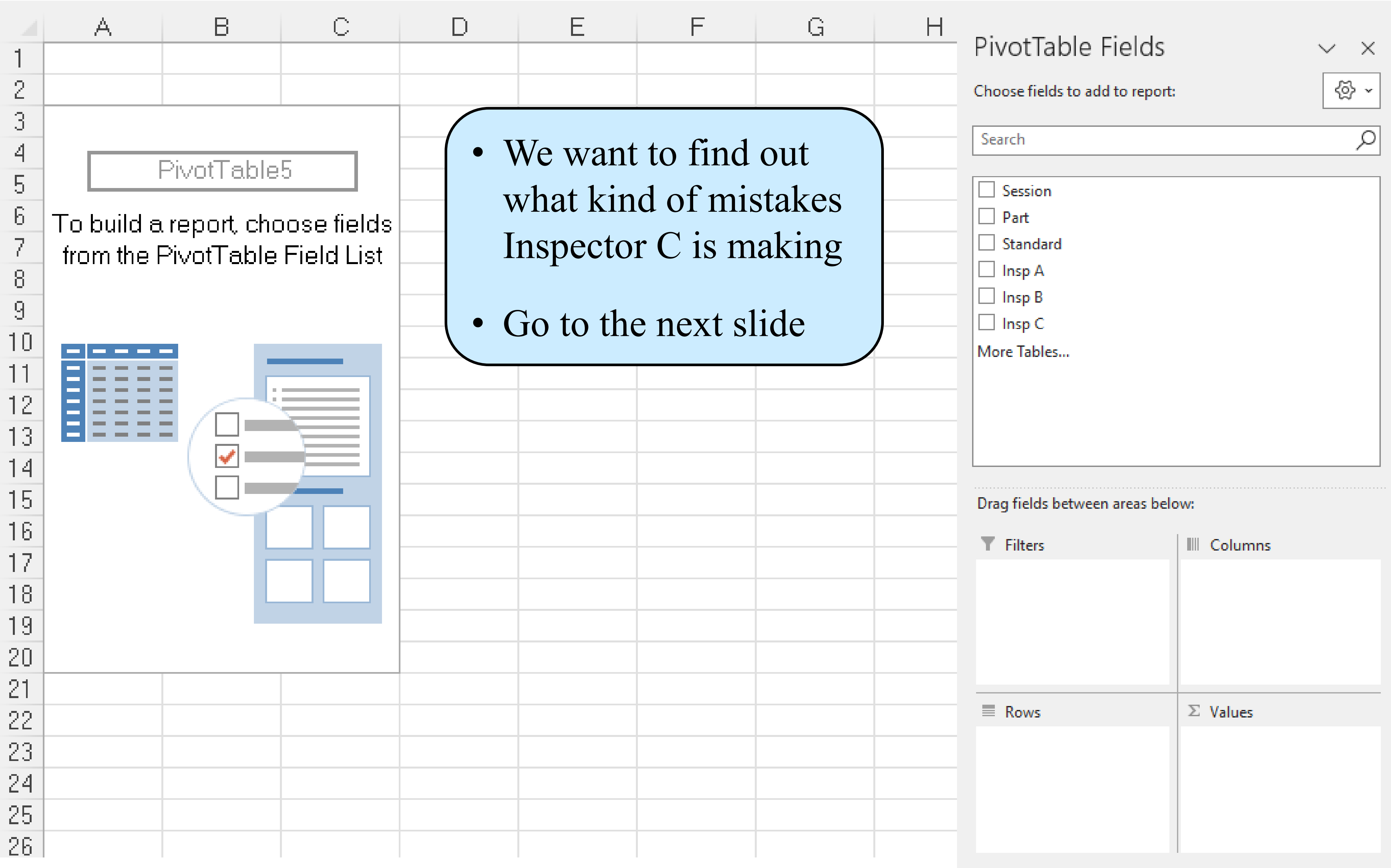
J152

=AVERAGE(G152:I152)

	A	B	C	D	E	F	G	H	I	J
1	Session	Part	Standard	Insp A	Insp B	Insp C	A	B	C	
143	3	42	F	F	F	F	1	1	1	
144	3	43	P	P	P	F	1	1	0	
145	3	44	P	P	P	P	1	1	1	
146	3	45	F	F	F	F	1	1	1	
147	3	46	P	P	P	P	1	1	1	
148	3	47	P	P	P	P	1	1	1	
149	3	48	F	F	F	F	1	1	1	
150	3	49	P	P	P	P	1	1	1	
151	3	50	F	F	F	F	1	1	1	
152							94.7%	96.7%	90.0%	93.8%
153										

Example (cont’d)

Highlight columns A-F → select the *Insert* ribbon → select *PivotTable* → OK



PivotTable5

To build a report, choose fields from the PivotTable Field List

PivotTable Fields

Choose fields to add to report:

Search

☐ Session
☐ Part
☐ Standard
☐ Insp A
☐ Insp B
☐ Insp C

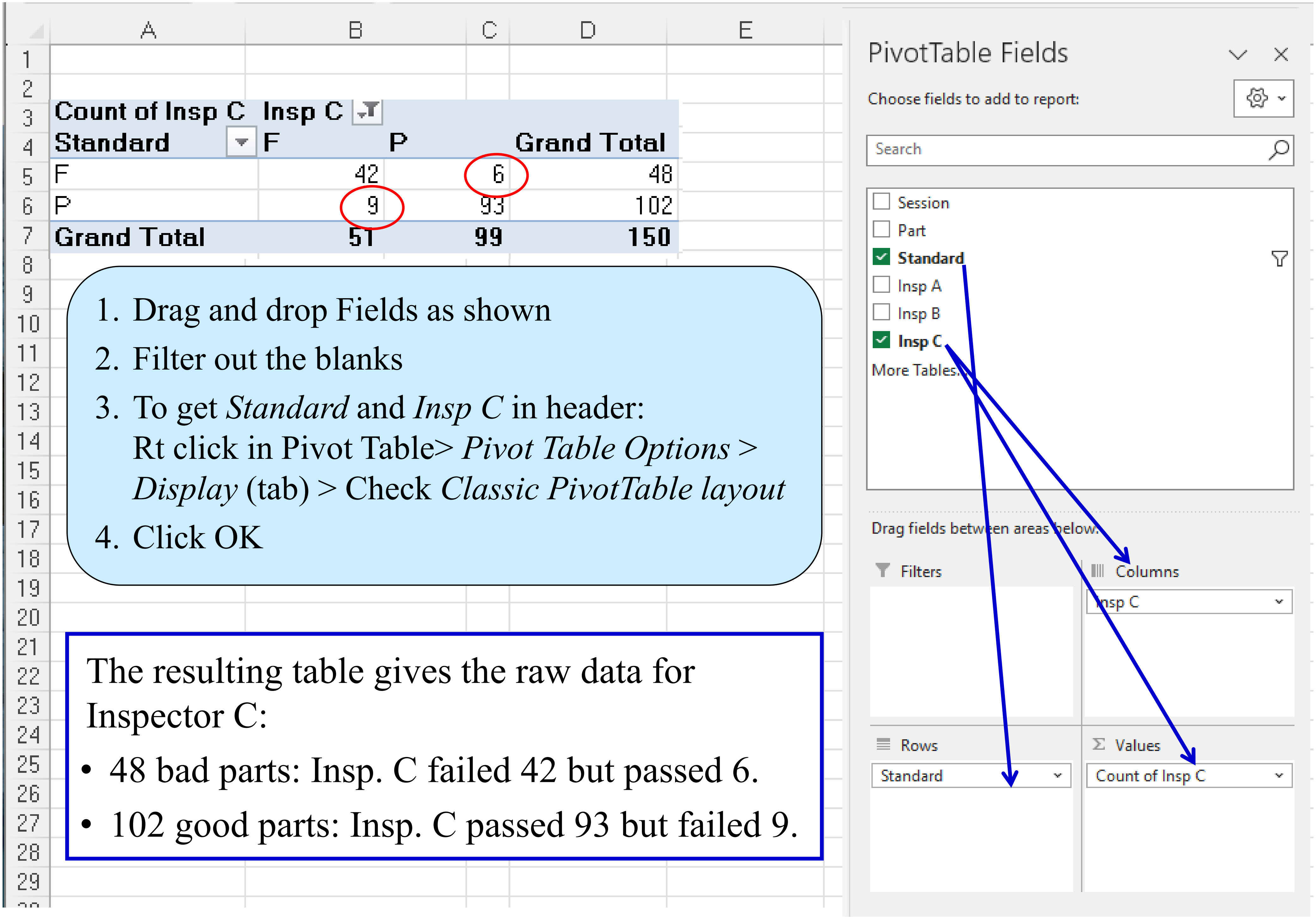
More Tables...

Drag fields between areas below:

Filters
Columns
Rows
Values

- We want to find out what kind of mistakes Inspector C is making
- Go to the next slide

Example (cont'd)



Count of Insp C	Insp C		
Standard	F	P	Grand Total
F	42	6	48
P	9	93	102
Grand Total	51	99	150

1. Drag and drop Fields as shown
2. Filter out the blanks
3. To get *Standard* and *Insp C* in header:
   Rt click in Pivot Table> *Pivot Table Options* > *Display* (tab) > Check *Classic PivotTable layout*
4. Click OK

The resulting table gives the raw data for Inspector C:

- 48 bad parts: Insp. C failed 42 but passed 6.
- 102 good parts: Insp. C passed 93 but failed 9.

PivotTable Fields

Choose fields to add to report:

Search

☐ Session
☐ Part
☑ **Standard**
☐ Insp A
☐ Insp B
☑ **Insp C**

More Tables...

Drag fields between areas below:

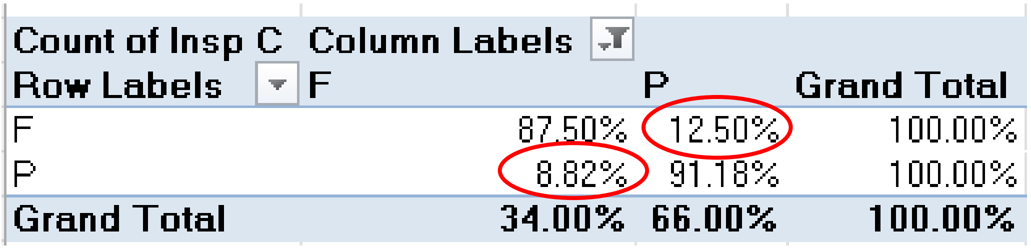
Filters

Columns: Insp C

Rows: Standard

Values: Count of Insp C

Example (cont'd)



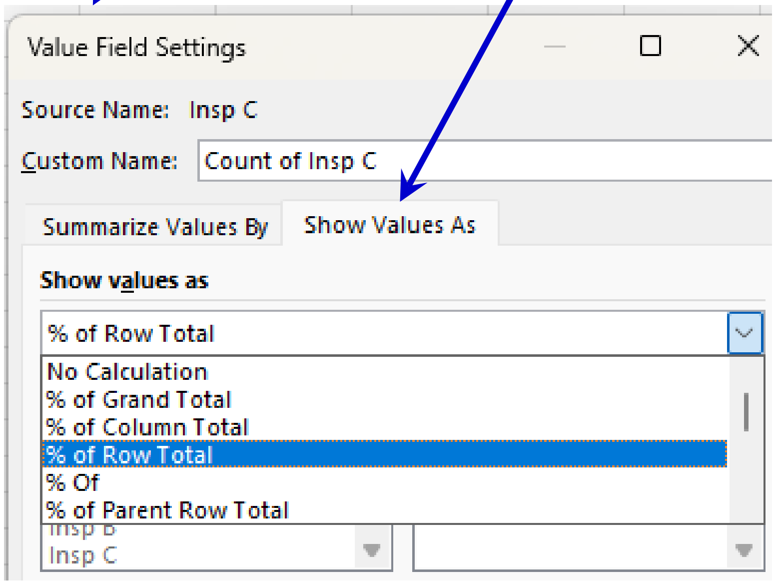
Count of Insp C	Column Labels		
Row Labels	F	P	Grand Total
F	87.50%	12.50%	100.00%
P	8.82%	91.18%	100.00%
Grand Total	**34.00%**	**66.00%**	**100.00%**

- Inspector C passed 12.5% of the bad parts
- and failed 8.8% of the good parts
- Inspector C needs further training to reduce both types of errors

Click dropdown on *Count of Insp C >*

Value Field Settings >

Show Values As > *% of row total*

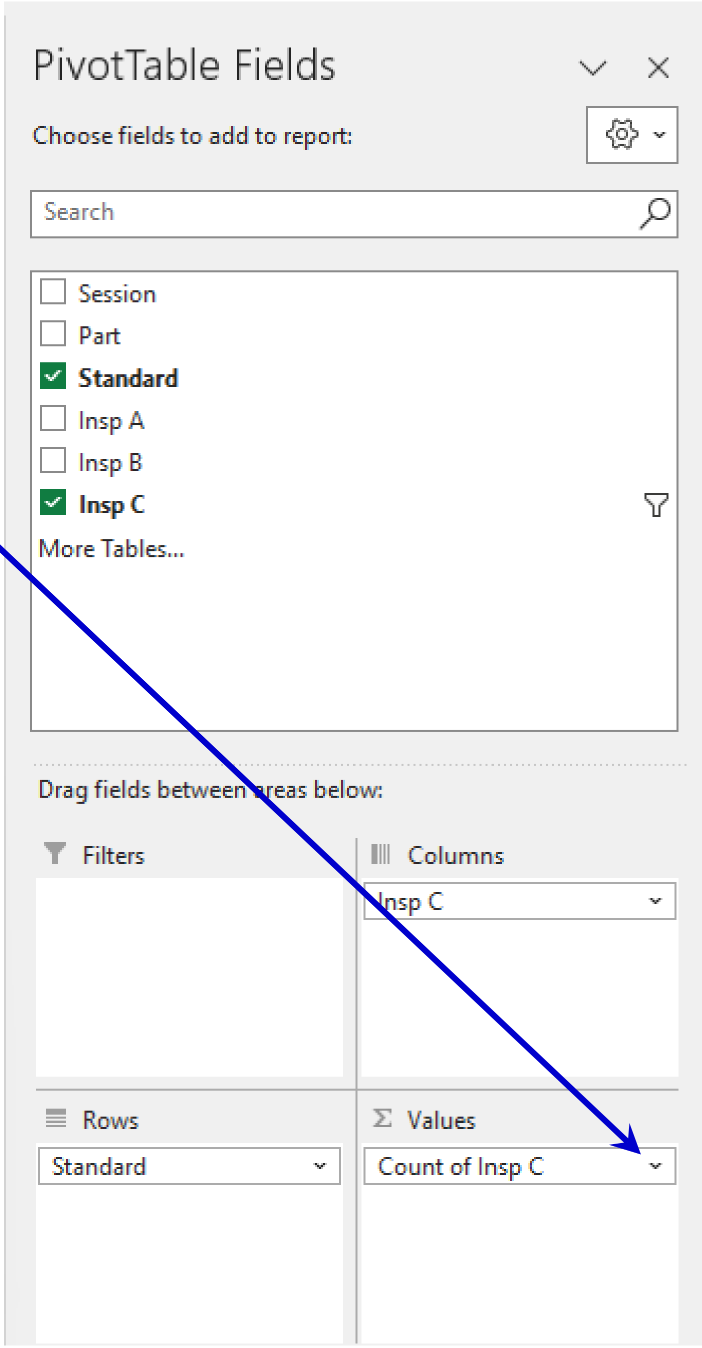


Value Field Settings

Source Name: Insp C

Custom Name: Count of Insp C

Show values as: % of Row Total



PivotTable Fields

Choose fields to add to report:

☐ Session
☐ Part
☑ **Standard**
☐ Insp A
☐ Insp B
☑ **Insp C**

Drag fields between areas below:

Filters:

Columns: Insp C

Rows: Standard

Values: Count of Insp C

Exercise 13.1

Open *Data Sets* → *msa print samples 1*. These are visual inspections of print samples by 3 inspectors. The standards were determined by a committee of experienced print quality evaluators.

(a) Calculate the % agreement with standard by inspector and overall.

(b) Which inspector offers the greatest opportunity for improvement? Make a pivot table to determine whether the main problem is passing bad samples, failing good ones, or both.

(c) Save your work.

Exercise 13.2

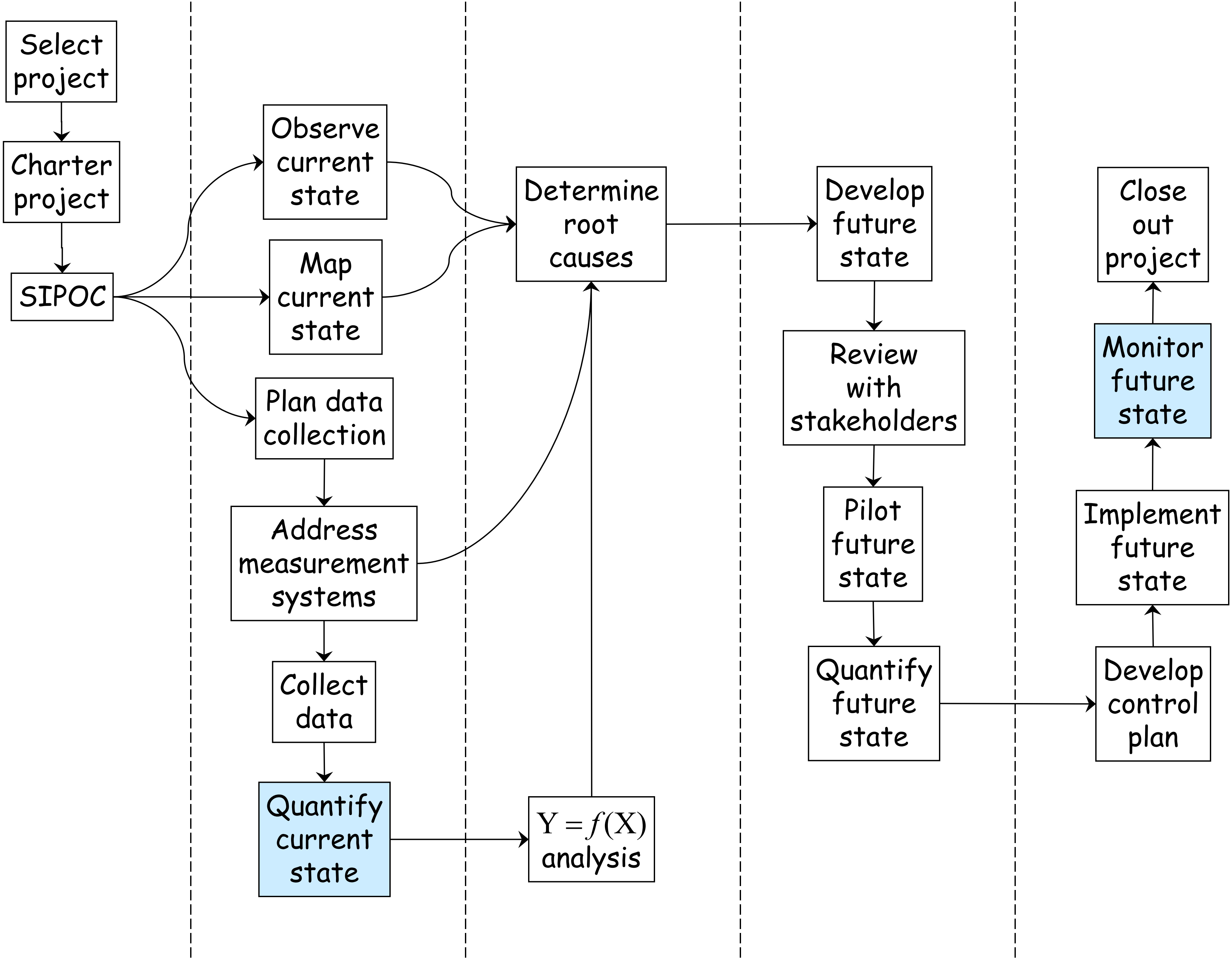
Open *Data Sets* → *msa print samples 2*. These are visual inspections of new print samples by the same 3 inspectors after additional training.

(a) Calculate the % agreement with standard by inspector and overall. Have we improved?

(b) There is something interesting about the data for sample 18 (not row 18). What are the possible explanations? (Sorting by sample number will help.)

(c) It turns out the standard for sample 18 was wrong. Reclassify the standard for sample 18 as passing. What is the % agreement now?

(d) Save your work.



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Close out project

Monitor future state

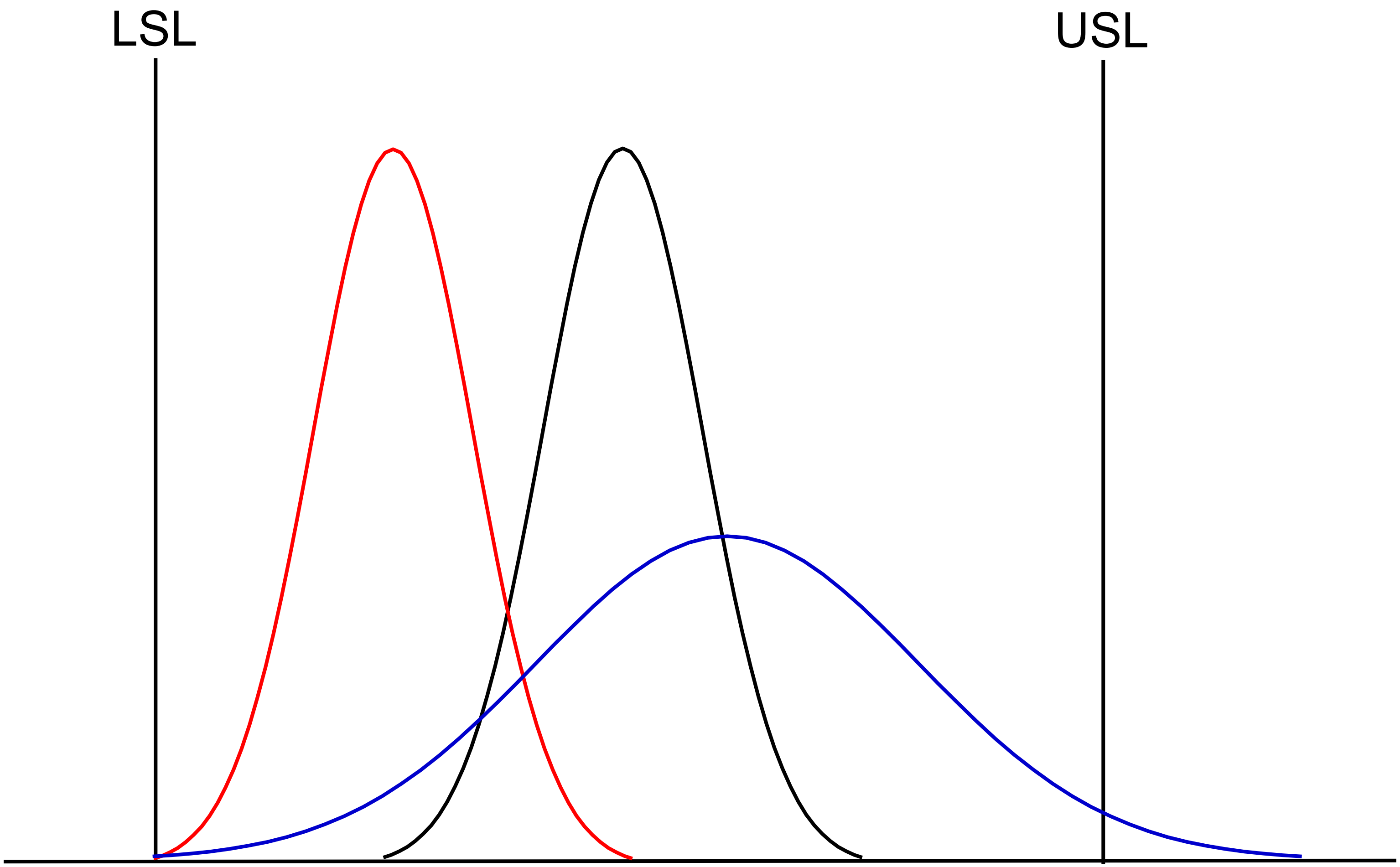
Implement future state

Develop control plan

Topics

- Purpose of Process Capability Indices
- Commonly used indices
- Important assumptions for validity

Process capability indices



- Some industries focus on “capability indices” instead of DPPM or DPMO
- These are calculated from the specification limit(s) and a fitted distribution
- Back in the day, the distribution was always assumed to be Normal

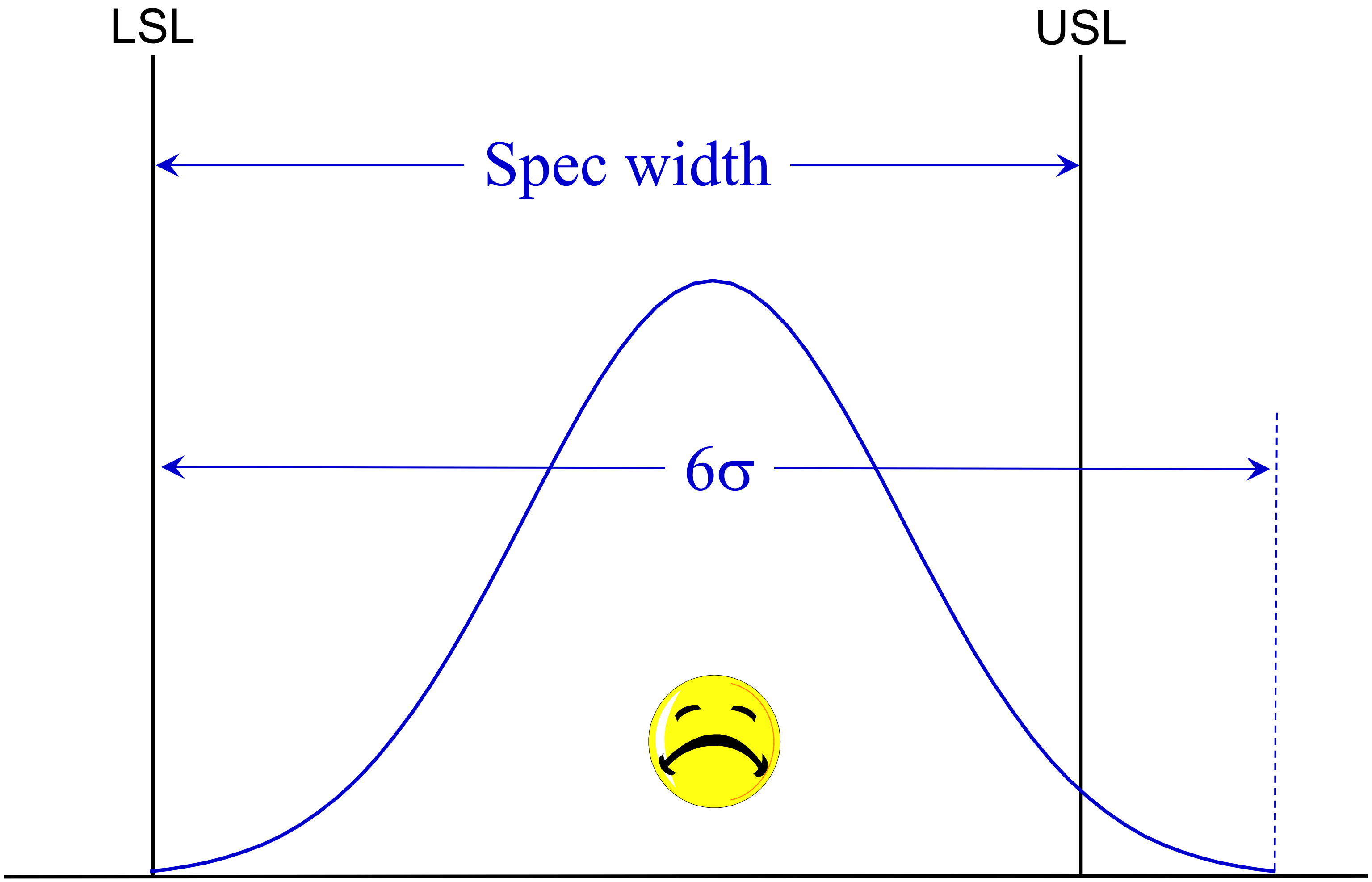
Process capability indices (cont’d)

- Do your organization’s external customers ask for process capability reporting?

- Are there internal requirements or needs for process capability reporting?

C_p index

$$C_p = \frac{\text{Spec width}}{6\sigma}$$



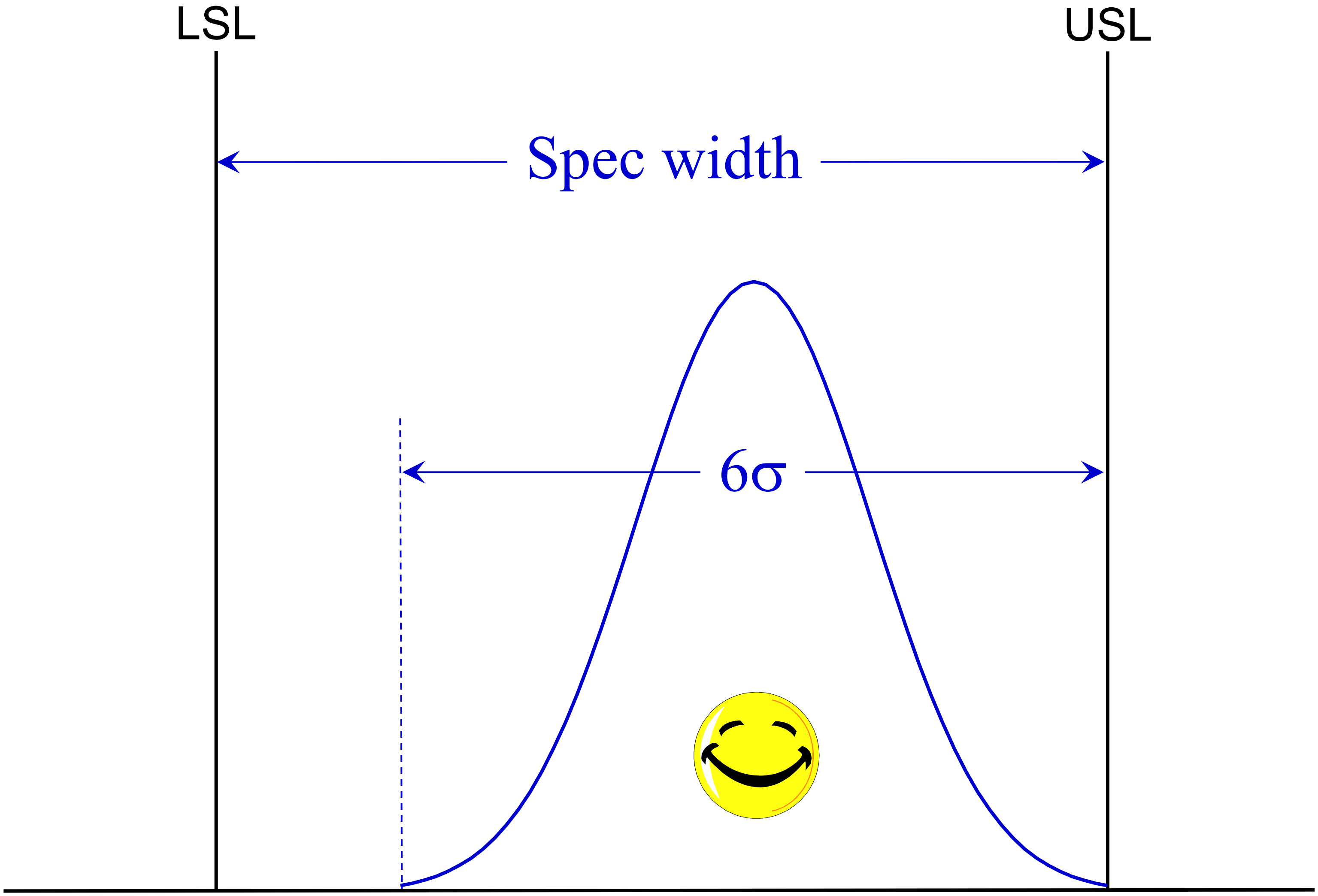
In this case, C_p is less than 1

C_p (cont'd)

The C_p index was historically the first to be used. It is defined as the specification width (USL – LSL) divided by the process spread (6σ). It set the precedent for capability indices to be defined so that "higher is better."

In the example above, the process spread is greater than the spec width, so C_p is less than 1. It is common for customers to push suppliers to achieve index values of 1.33 or higher for key Y variables.

C_p (cont'd)



In this case, C_p is greater than 1, but what's a potential problem here?

C_p (cont'd)

In the example above, the process spread is less than the spec width, so C_p is greater than 1.

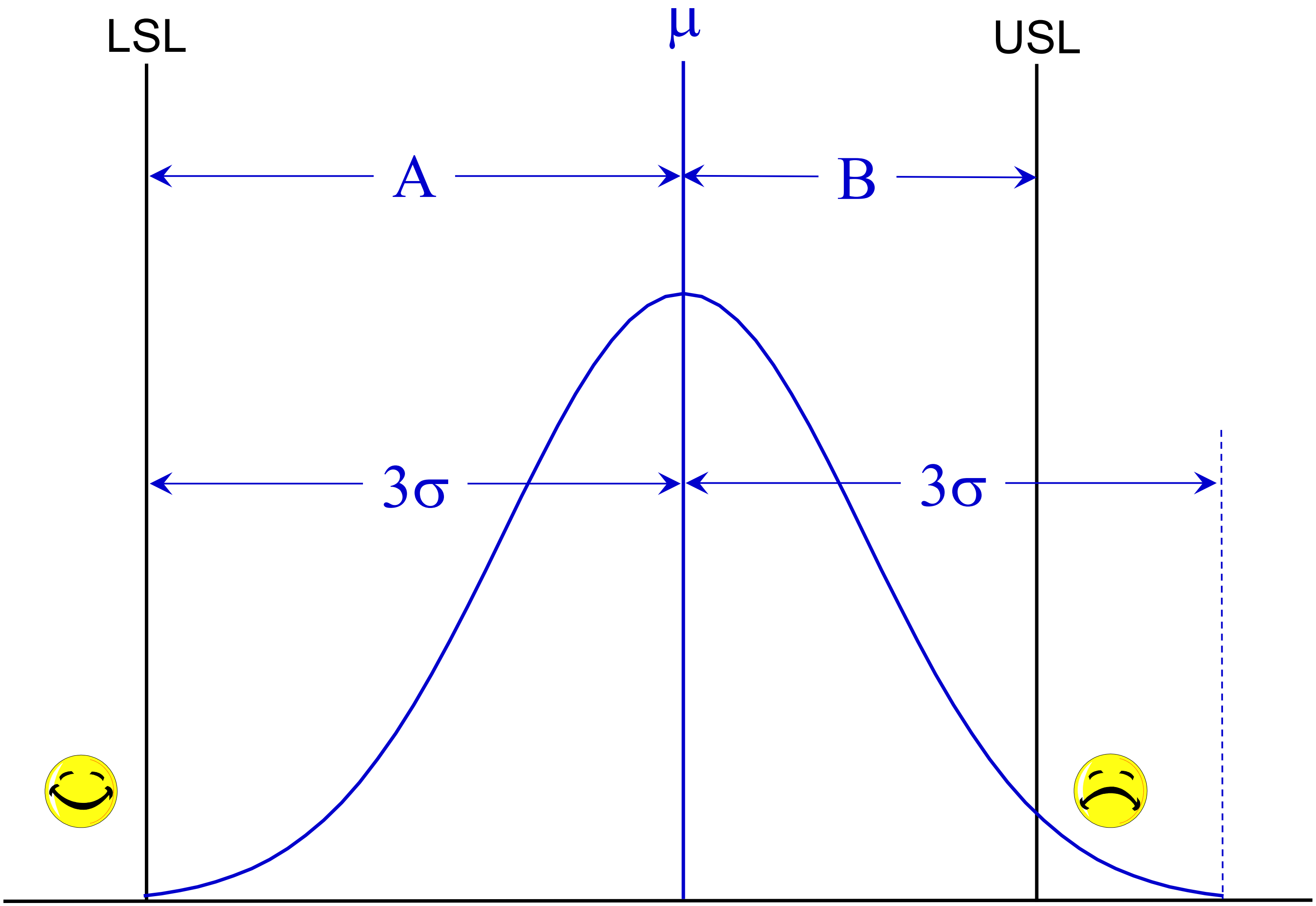
The limitation of C_p is that it doesn't depend on the process mean. If the process mean is equal to the midpoint of the specification range, then C_p is directly related to first pass yield.

If the process mean does not equal the midpoint of the specification range, C_p represents the capability that could be attained by moving the process mean to the midpoint.

C_{pl} and C_{pu} indices

$$C_{pl} = \text{"}C_p \text{ lower"} = \frac{A}{3\sigma}$$

$$C_{pu} = \text{"}C_p \text{ upper"} = \frac{B}{3\sigma}$$

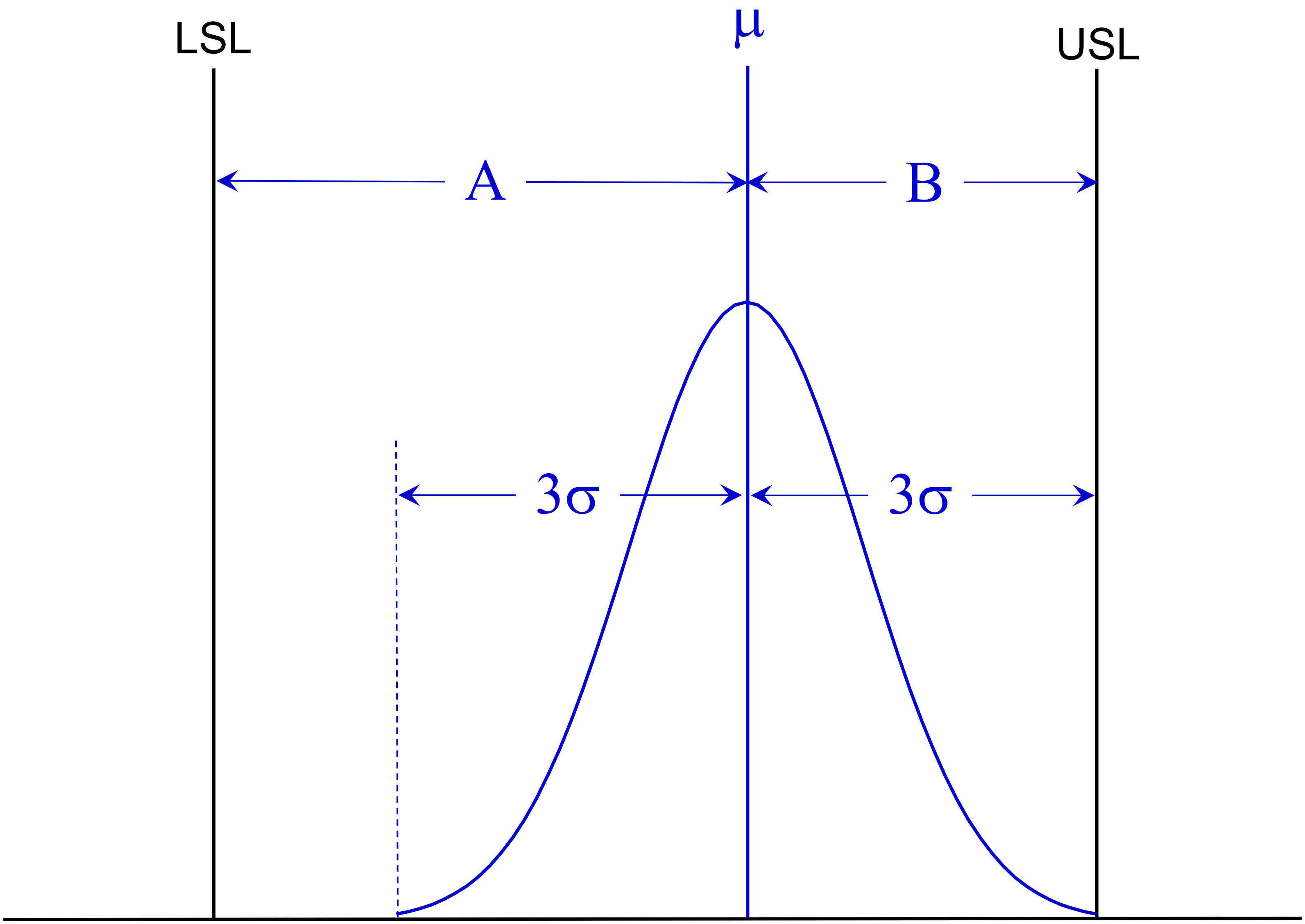


C_{pl} and C_{pu} (cont'd)

The indices C_{pl} and C_{pu}, pronounced "C_p lower" and "C_p upper", were introduced to overcome the deficiency of C_p. They depend on both the mean and standard deviation of the process. If we know both C_{pl} and C_{pu} we can determine the first pass yield of the process.

Like the C_p index, C_{pl} and C_{pu} are defined so that "higher is better." In the example shown above, the main problem is on the high side, with C_{pk} less than 1.

C_{pl} and C_{pu} (cont'd)



C_{pl} is greater than 1, C_{pu} is equal to 1

C_{pl} and C_{pu} (cont'd)

C_{pk} is equal to 1 in the example above. If improvement is needed, the opportunity is on the high side.

Many people have asked what the *k* in C_{pk} stands for. To everyone's great disappointment, the *k* seems to have been chosen arbitrarily and may not stand for anything.

There is, however, a bit of historical trivia that may give us a clue:

- C_{pk} was first popularized by a man named Victor Kane.
- Is it possible Victor simply used the first letter of his last name?

Guidelines

- Use C_{pl} if you have only a lower spec limit
- Use C_{pu} if you have only an upper spec limit
- Use C_{pk} (smaller of C_{pl} and C_{pu}) if you have both lower and upper spec limits
- As noted previously, C_p indicates what C_{pk} would be if the process mean were equal to the midpoint of the spec range.
  - If this is not the case, C_p represents a potential capability.
  - Centering a process at this midpoint may not always be desirable.

Important assumptions in Process Capability

For Process Capability indices to be valid, the following must be true:

- The process is in statistical control (we will cover this during the Control phase)
- The measurement data is normally distributed*
- The sampling method used is representative of day-to-day process operation

There are times when we want to calculate process capability before the process is under control, for example to set an initial baseline or make a rough prediction.

- The purpose of a process capability study should always be communicated along with the numbers.

**Handling situations when the data is not normally distributed is beyond the scope of this course. Some statistical software packages offer options for calculating Process Capability for non-Normal distributions, along with indices for other special cases.*

Formulas (Normal distribution)

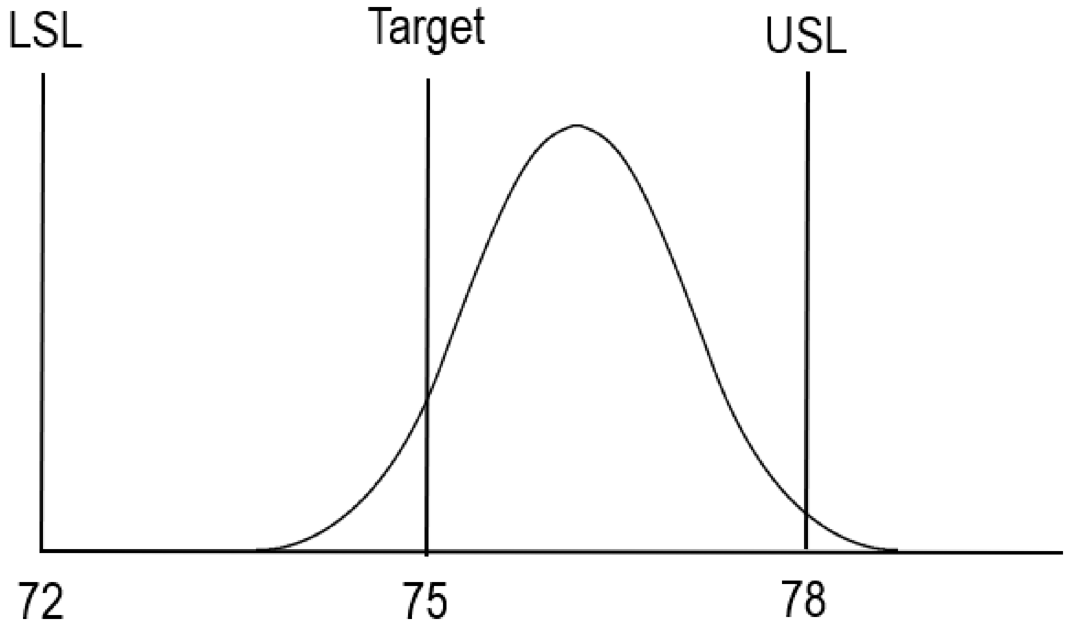
$$C_{pl} = \frac{\mu - LSL}{3\sigma}$$

$$C_{pu} = \frac{USL - \mu}{3\sigma}$$

$$C_p = \frac{C_{pl} + C_{pu}}{2} = \frac{USL - LSL}{6\sigma}$$

$$C_{pk} = \min\left(C_{pl}, C_{pu}\right)$$

Example: Calculating Process Capability indices



For this distribution, the mean = 76 and the standard deviation = 1.

$$C_p = \frac{USL-LSL}{6\sigma} = \frac{78-72}{6*1} = \frac{6}{6} = 1.0$$

$$C_{pl} = \frac{\mu-LSL}{3\sigma} = \frac{76-72}{3*1} = \frac{4}{3} = 1.33$$

$$C_{pu} = \frac{USL-\mu}{3\sigma} = \frac{78-76}{3*1} = \frac{2}{3} = 0.67$$

$$C_{pk} = \min\left(C_{pu}, C_{pl}\right) = 0.67$$

Exercise 14.1

(a) Calculate C_p and C_{pk} for a process with mean = 55, standard deviation = 1, USL = 60 and LSL = 50.
Sketch the distribution.

(b) Calculate C_p and C_{pk} for a process with mean = 100.20, standard deviation = 0.20, USL = 101.00 and LSL = 100.00.
Sketch the distribution.

What is “good” process capability?

Capability	How good is this?	Sigma Level
$C_p = 1.0$	Marginally capable	3 sigma
$C_p = 1.33$	Good	4 sigma
$C_p = 2.0$	World-class	6 sigma

The indices C_p and C_{pk} are assumed to be measures of the long-term capability of the process. Therefore,

- the data needs to be gathered over a long enough period of time to capture all regular contributors to process variation,
- *and* a sample size of at least 70 is needed, with 100 preferred.

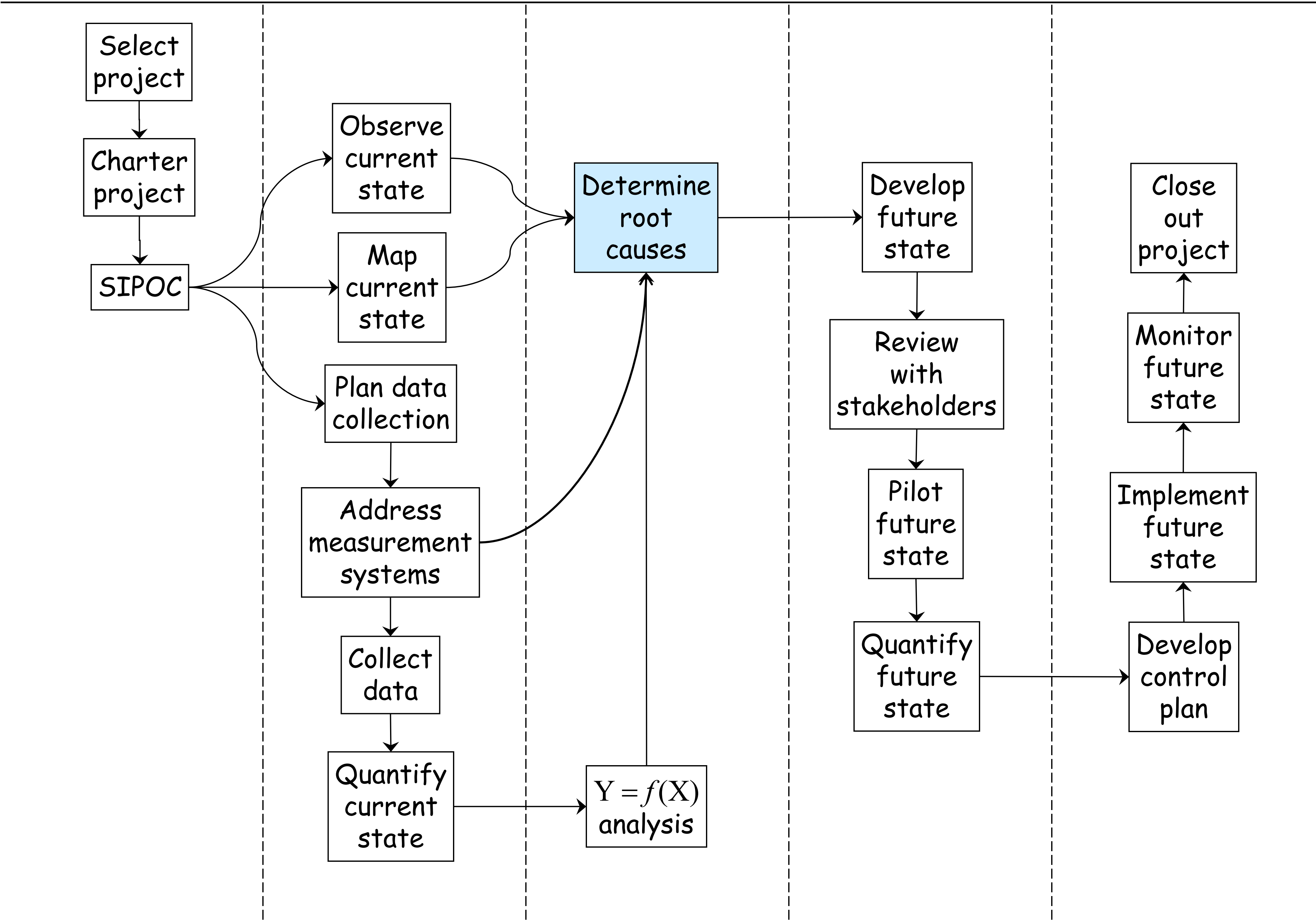
Predicting defects

C_p, C_{pk} Value	C_p Fallout (centered)	C_{pk} Fallout (not centered)
.5	133,620 PPM	66,810 PPM
.6	71,860	35,930
.7	35,720	17,860
.8	16,400	8,200
.9	6,940	3,470
1.0	2,700	1,350
1.1	966	483
1.2	318	159
1.3	96	48
1.33	66	33
1.4	26	13
1.5	7	3
1.6	2	800 PPB
1.7	340 PPB	170
1.8	60	30
1.9	12	6
2.0	2	1

PPM = Parts Per Million
PPB = Parts Per Billion
Note: 1%=10,000 PPM

Analyze Phase

15 Root Cause Analysis



Tools used in Root Cause Analysis

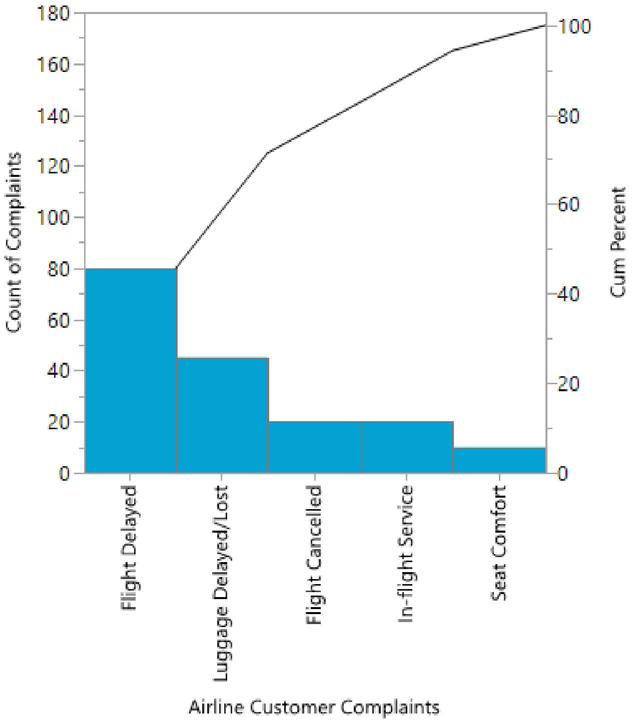
We usually identify problems while mapping and observing the current state during the *Measure* phase

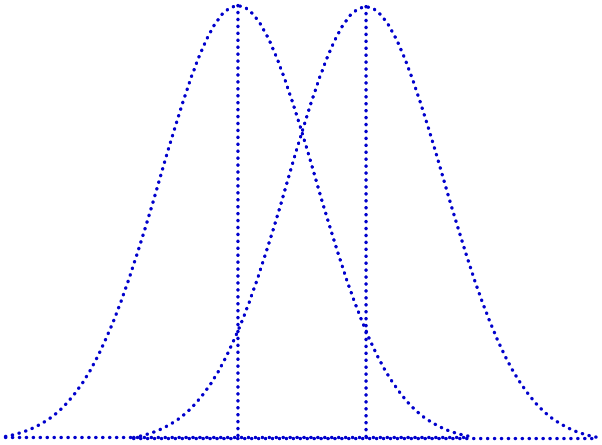
Observed problems

(*a.k.a.* opportunities for improvement)

Tools used in Root Cause Analysis (cont.)

Analyses such as Pareto Charts point us in the direction of the root causes or critical x’s





$H_0\!: \mu_1 = \mu_2$

$H_1\!: \mu_1 \neq \mu_2$

But, we usually need to dig deeper . . .

Topics

Additional tools and techniques to identify root causes:

- Failure Modes and Effects Analysis (FMEA)
- Multi-level Pareto Analysis
- Five whys
- Five whys based on $Y = f(X)$

Failure Modes and Effects Analysis (FMEA)

FMEA can be used in the Analyze Phase to prioritize x’s

- It is used at the *beginning* of the Analyze Phase:
    - to identify the inputs that are likely to have a significant impact on the primary metric Y, and to remove from consideration those that are deemed trivial
    - data collection and analysis are required for verification of those failure modes with high RPNs, to validate their significant impact on Y, as FMEA is an opinion-based tool
- Actions for remedying failure modes with high RPNs are *not* discussed or taken in Analyze
- We will learn about FMEA in the Improve Phase, when it is used to evaluate risk and prevent problems before they occur in the proposed process, its original application.

FMEA: Design vs. Process

- *Principles and steps are the same*
  - *Purpose and objectives differ*
- *Rating scale definitions will differ*

Design

Discover potential problems with the design of the product that will result in safety concerns, malfunctions, or shortened life

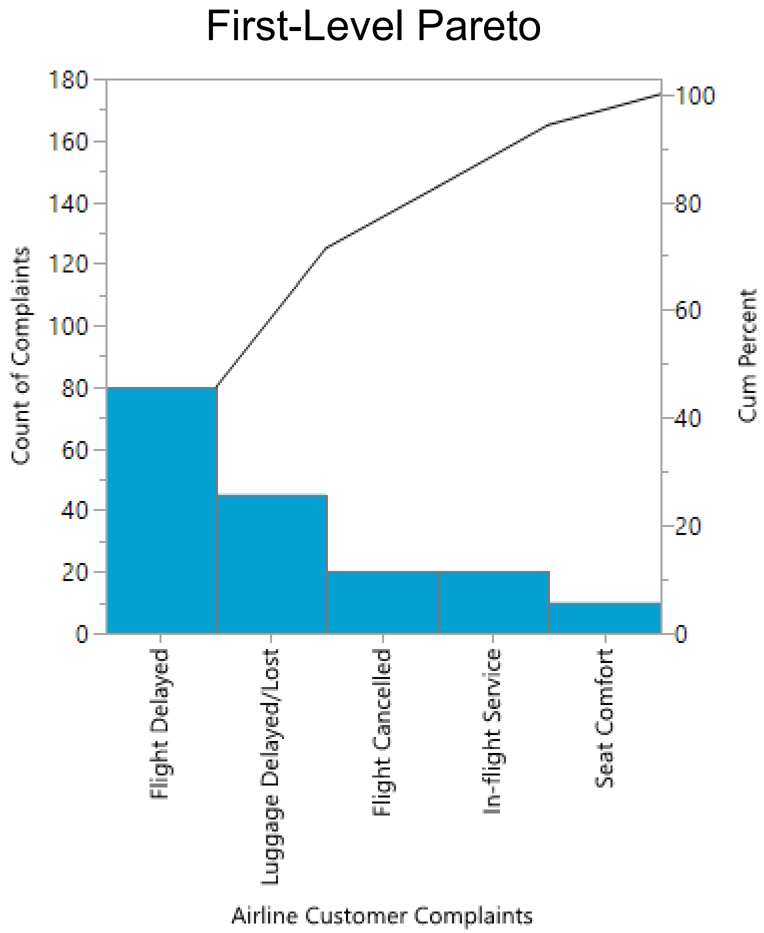
Process

Discover potential problems related to the manufacture of the product that will affect the product, safety, or processing efficiency

Multi-Level Pareto Analysis

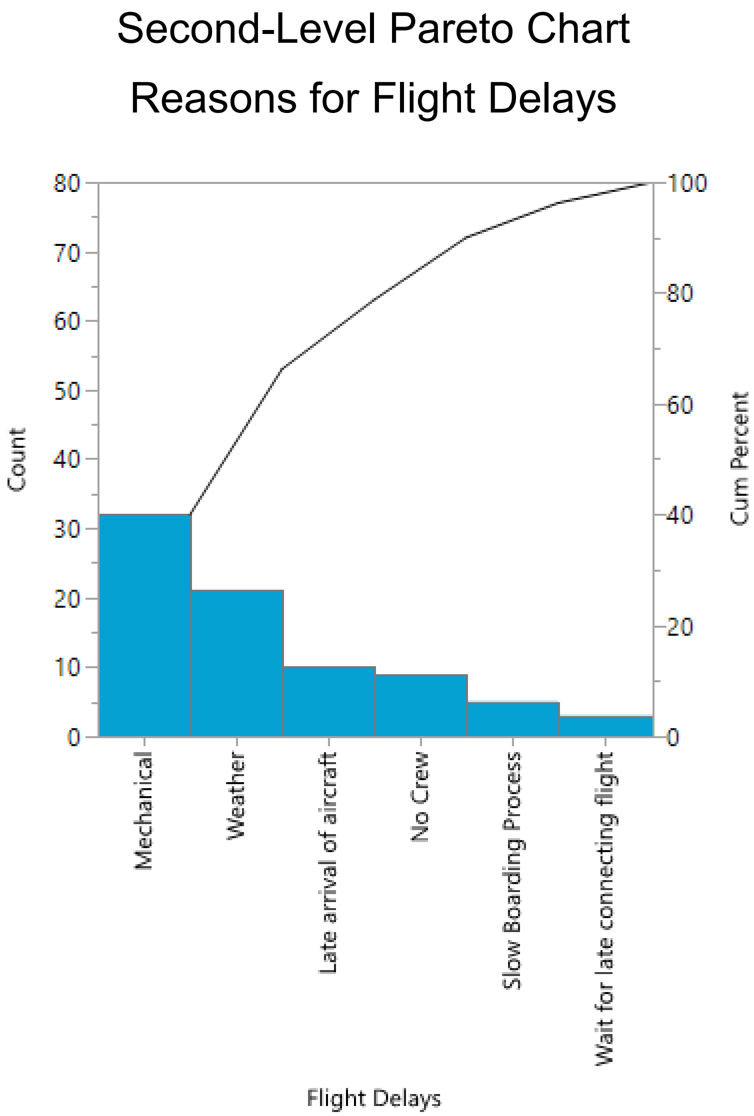
We can drill down to root causes using a series of Pareto Charts

- From a first-level Pareto Chart, we can see which categories are contributing the most to our problem



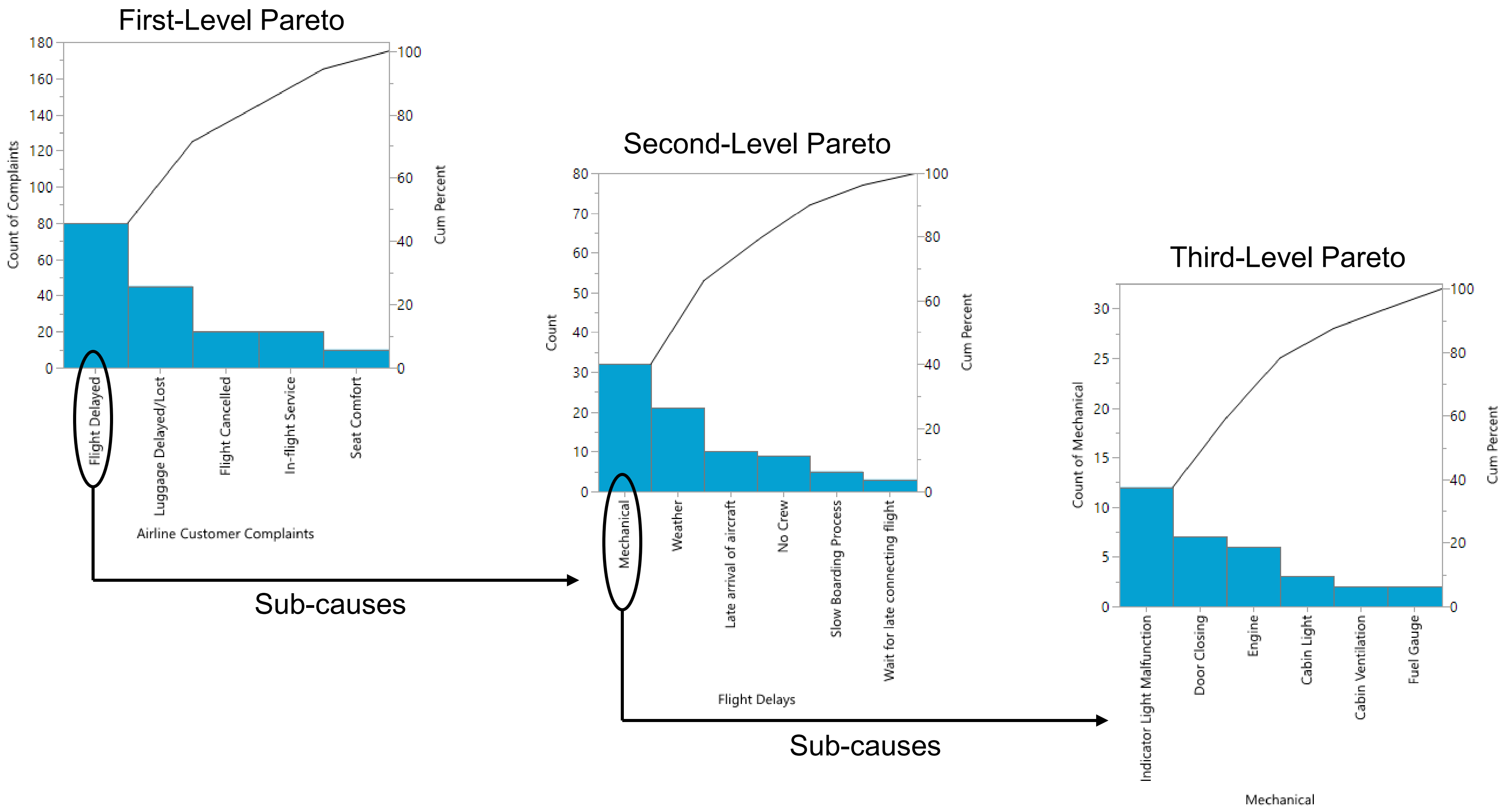
Second-Level Pareto Chart

The highest bar(s) from the first-level Pareto can be broken down further into a second-level Pareto Chart:



Multi-Level Pareto Analysis (cont.)

By continuing to drill down, we can determine root causes of most frequently occurring defects.


First-Level Pareto

Second-Level Pareto

Third-Level Pareto

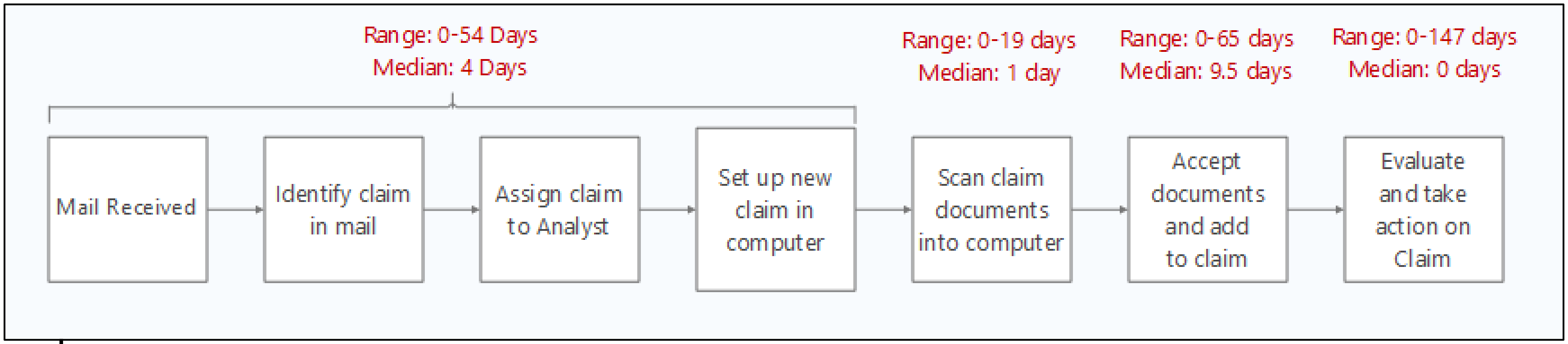
Sub-causes

Sub-causes

When data is not available for multi-level Pareto analysis, use the first-level Pareto Chart with 5 Whys to determine root causes.

Example 2: Multi-Level Pareto Analysis

Lead time by high-level process step is measured:



Range: 0-54 Days
Median: 4 Days

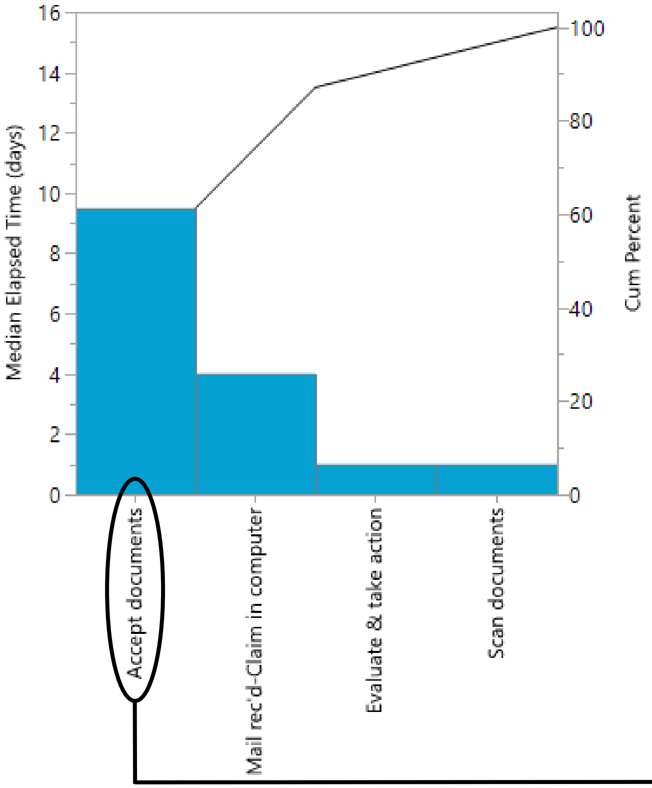
Range: 0-19 days
Median: 1 day

Range: 0-65 days
Median: 9.5 days

Range: 0-147 days
Median: 0 days

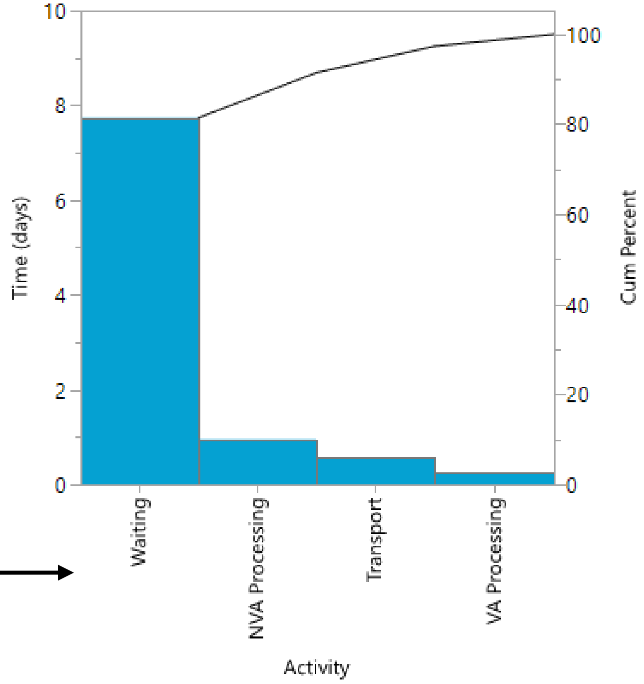
- Mail Received
- Identify claim in mail
- Assign claim to Analyst
- Set up new claim in computer
- Scan claim documents into computer
- Accept documents and add to claim
- Evaluate and take action on Claim

First-Level Pareto



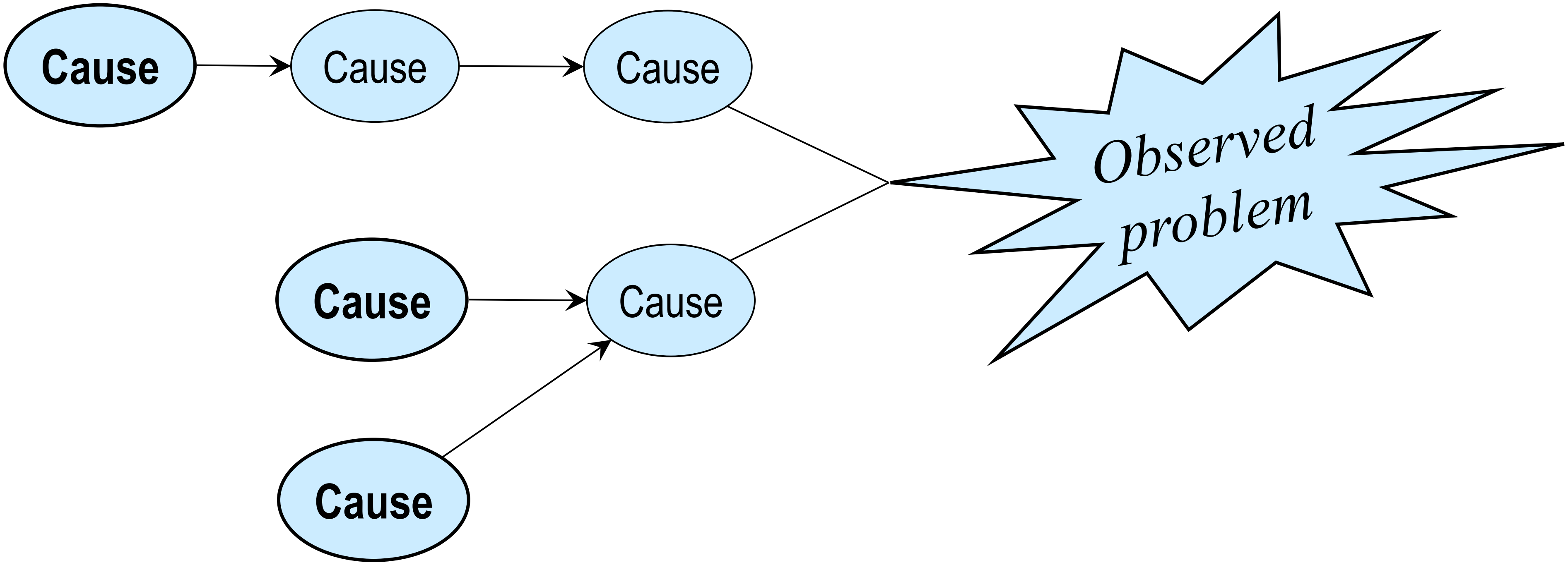
Sub-causes

Second-Level Pareto



5 Whys

- We work our way back to root causes by asking “why” questions



- This process is called “5 whys” because it usually takes no more than 5 questions

- The goal of 5 Whys is to get to a deep, actionable cause.

Getting to root cause with five whys

"The number of accidents in the plant was way up last month"

Do you know what caused the increase?	Workers are slipping and falling in Aisle 7 next to the molding machine.
Why are workers slipping and falling?	There's a puddle of water on the floor.
Where did the water on the floor come from?	It's dripping from the ceiling.
What caused it to start dripping from the ceiling?	A pane of glass is broken in the skylight.
How did the glass get broken?	A tree branch broke the glass during a storm.
How did the tree branch manage to hit the skylight?	The tree it came from was close to the building.

“There’s too much scrap in the Coiling Department”

What kinds of defects are causing the scrap?	The vast majority is due to bad welds.
Why do we have so many bad welds?	The welders aren’t very good.
Why aren’t they very good?	Well, they’re hired off the street, and they don’t get much training.
You don’t hire certified welders?	Are you kidding? We would have to pay them too much.
In that case, why aren’t your welders given more training?	I don’t know. I guess there isn’t enough time. This is the way we’ve always done it.
Don’t they get better as they become more experienced?	Well yeah, but they don’t stay in this department long enough for that to help.

(cont’d)

Why do they leave this department so soon?	There’s another department where welders are used. As soon as there’s an opening over there, everybody here applies for it.
Why are they so eager to work in the other department?	For one thing, the working conditions over there are much better. We have the highest accident rate in the company.
Is there another reason?	Over there they pay a dollar an hour more than here.

“I was late for work today.”

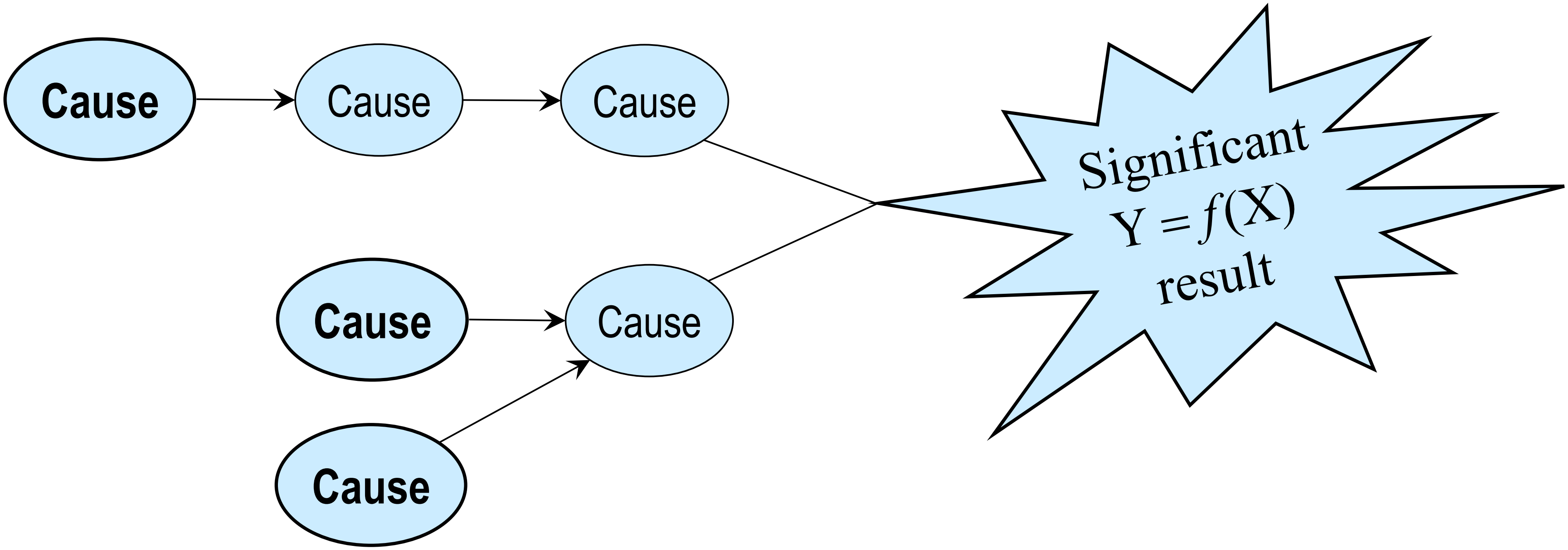
Why were you late for work today?	I overslept.
Why did you oversleep?	My alarm didn’t go off.
Why didn’t your alarm go off?	The power went out last night.
Why did the power go out last night?	There was a thunderstorm.

What is wrong with this 5 Whys path?

If you get to a non-actionable root cause, back up and try to find a different path to an answer.

Five whys based on $Y = f(X)$ analysis

- Data analysis provides the basis for penetrating questions
- After we have completed our $Y = f(X)$ analyses, we should interview process participants again to determine the causes of significant comparisons or correlations.
- 5 Whys and Cause and Effect (Fishbone) Diagrams are helpful "interviewing" tools.



Want to reduce external failures

Q “There is a significant correlation between dwell time and DPPM. What causes the variation in dwell time?”

A “The dwell time stretches out when operators are called away to do other things while they’re getting ready to mold parts.”

Q “Isn’t there an upper spec on the dwell time?”

A “Yes. The operators are supposed to purge the tank if the dwell time gets too long, but they don’t always do that.”

Q . . .

Whenever we can collect data to verify the root cause found through 5 Whys, that should be done.

Want to reduce turnaround time

Q “The turnaround time is significantly longer for some account managers than for others. What do you think causes that?”

A “They don’t all use the same quotation preparation process.”

Q “Why not?”

A “There is no standard process. They have all developed their own way of doing it.”

Q . . .

Whenever observation can verify the root cause found through 5 Whys, that should be done

(cont’d)

Q “The turnaround time is significantly longer for some business units than for others. What do you think causes that?”

A “Some of the business units aren’t using the automated configuration tool.”

Q “Why not?”

A . . .

Whenever observation or data collection can verify the root cause found through 5 Whys, that should be done.

Want to improve internal customer satisfaction

Q “The tool development process often results in slow line speeds and overweight material. What causes that?”

A “The testers slow the line down and increase the weight to get the dimensions on target.”

Q “Why do they use weight and line speed instead of other variables?”

A “They’re usually in a hurry. They’ve discovered that manipulating weight and line speed is the fastest way.”

Q . . .

Whenever observation or data collection can verify the root cause found through 5 Whys, that should be done.

Identifying root causes

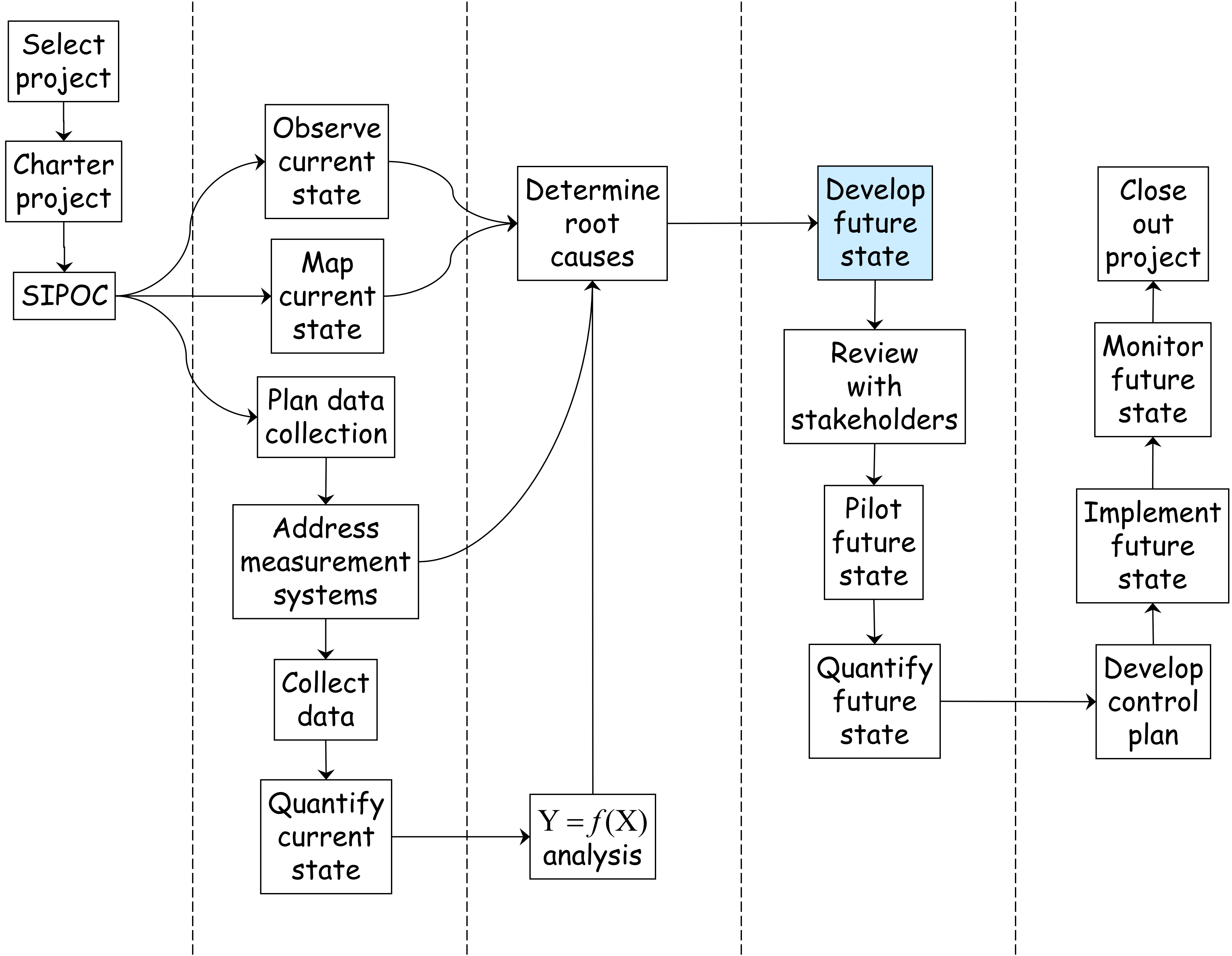
At the conclusion of the Analyze Phase, the team must list those specific root causes or critical x's to be acted upon during the Improve Phase

- Review the analyses completed to:
  - ✓ determine those critical x's and root causes that have been validated as significant contributors to unsatisfactory performance in the primary metric
  - ✓ list those that are no longer under consideration

- The team should show the analyses that support their decision on which opportunities to address in the Improve Phase

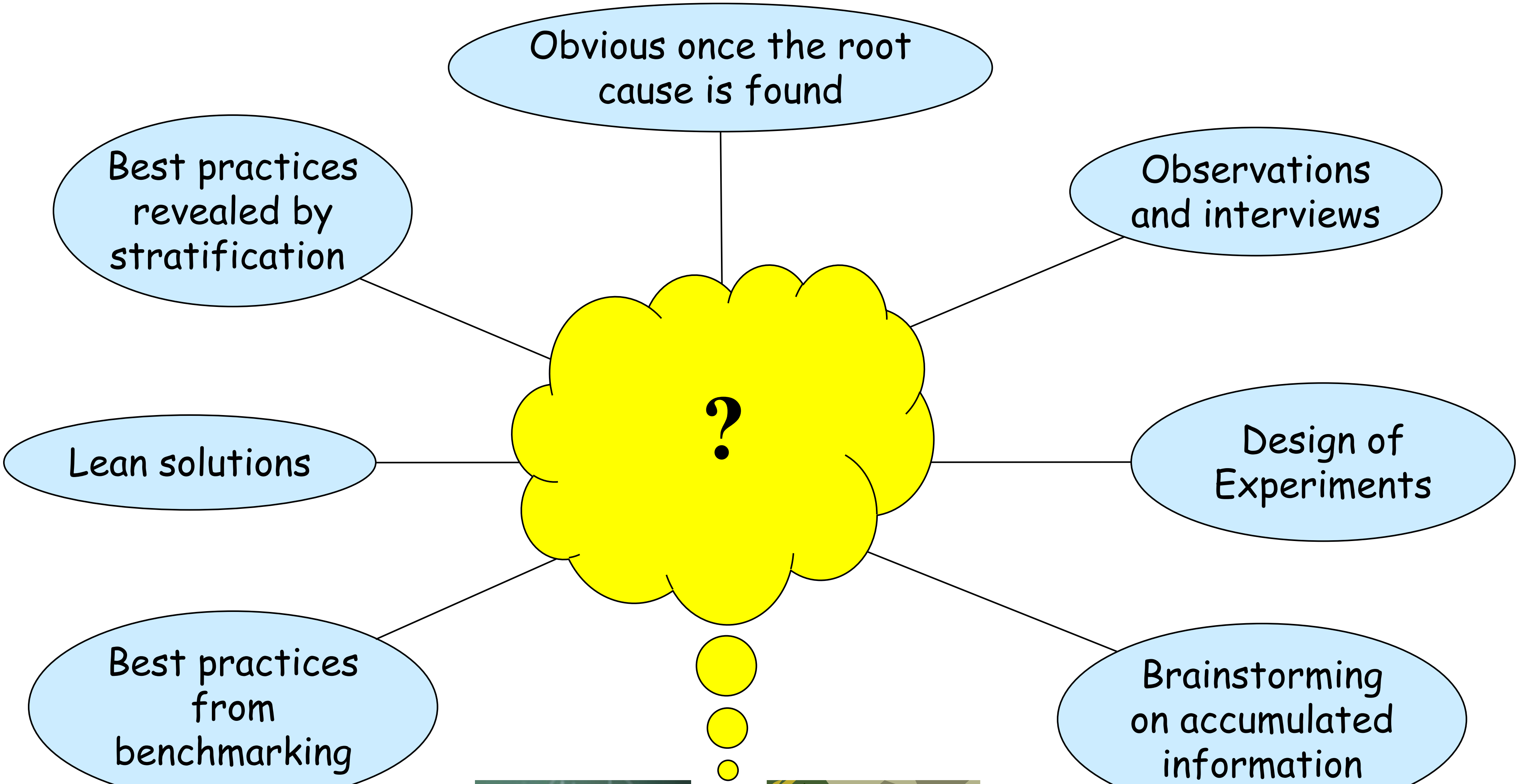
Improve Phase

16 Developing and Prioritizing Solutions



Developing solutions

Solutions come from many sources



Obvious once the root cause is found

Best practices revealed by stratification

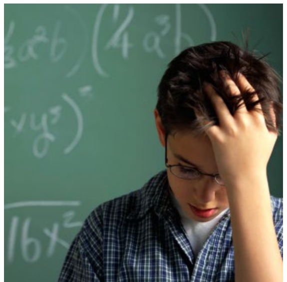
Observations and interviews

Lean solutions

Design of Experiments

Best practices from benchmarking

Brainstorming on accumulated information



Developing solutions (cont’d)

Improvement ideas can come from many sources. Some ideas will contribute more to the success of the future state than others. The greater the number of ideas, the greater the probability of discovering successful solutions. The team should generate as many improvement ideas as possible.

The nature of this process is that the initial list gets shorter. Some ideas are discarded along the way, others are retained intact, still others are modified or combined. This process leads to a future state that is likely to be best available within the constraints of the project.

Common solution categories

- Technology upgrades
- Lean solutions (we’ll learn more about these in the next section of the course)
- Standardization
- Modification of procedures
- “Just do it” solutions that haven’t yet been implemented

Solution categories (cont’d)

LSS projects address problems for which solutions are not known. Nevertheless, there are commonly occurring categories.

A common example of technology upgrade would be switching to a better measurement system.

We don’t need a LSS project to tell us that Lean is good. But what if the organization lacks consensus on the benefits of these methods? A high priority LSS project that makes significant improvements by applying Lean solutions could help the organization recognize the value of Lean across the board.

The same applies for “just do it” solutions. Everyone knows what needs to be done, but it isn’t getting done. A LSS project identifying and quantifying the need for the “just do it” solution might get some high-level attention, cut through the lethargy, and stimulate action on the issue.

Prioritizing solutions

- Uses the impact/feasibility method — same as prioritizing projects

- Defines "impact" as addressing the root causes identified by the project team

- Gives the organization a basis for making sound decisions in light of project findings

    - ✓ Opportunity to expedite implementation of solutions with high impact or high feasibility

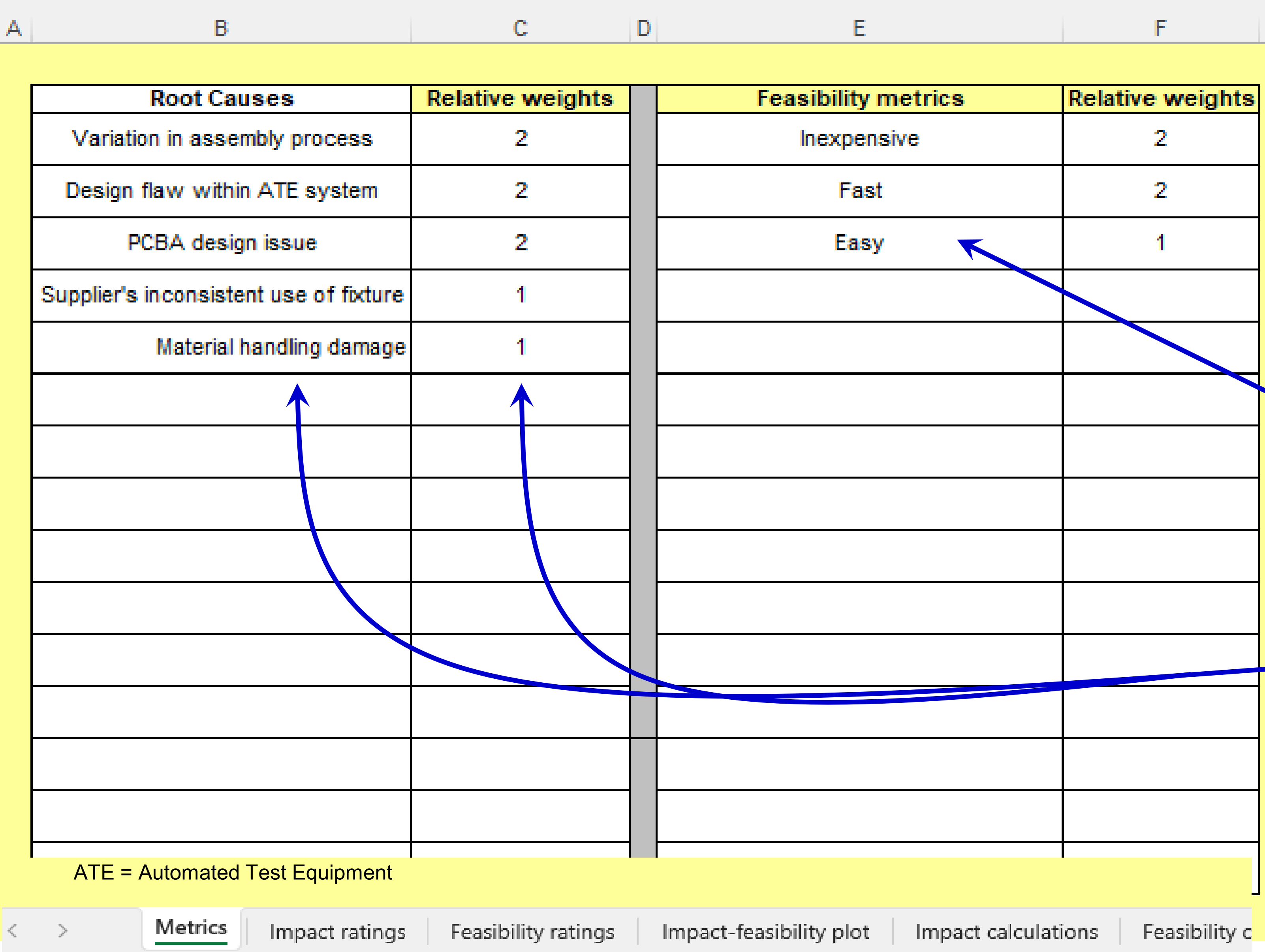
    - ✓ Opportunity to postpone implementation of solutions with low impact and low feasibility

Instructions for prioritizing solutions

1. Open *Student Files* → *blank C&E matrix - impact & feasibility*.
2. In the *Metrics* sheet, change *Impact metrics* to *Root causes*.
3. List your prioritized root causes and relative weights (overall rankings).
4. List your feasibility metrics and relative weights.
5. Go to the *Impact ratings* sheet, change *Items to be ranked* to *Solutions*.
6. List the solutions you wish to rank.
7. Rate each solution for impact on each root cause.
8. Go to the *Feasibility ratings* sheet, rate each solution for each feasibility metric.
9. Go to the sheet *Impact - feasibility plot* to evaluate the results.

Student Files → prioritizing solutions - exercise

Root causes of Long Lead Time



Root Causes	Relative weights	Feasibility metrics	Relative weights
Variation in assembly process	2	Inexpensive	2
Design flaw within ATE system	2	Fast	2
PCBA design issue	2	Easy	1
Supplier's inconsistent use of fixture	1		
Material handling damage	1		

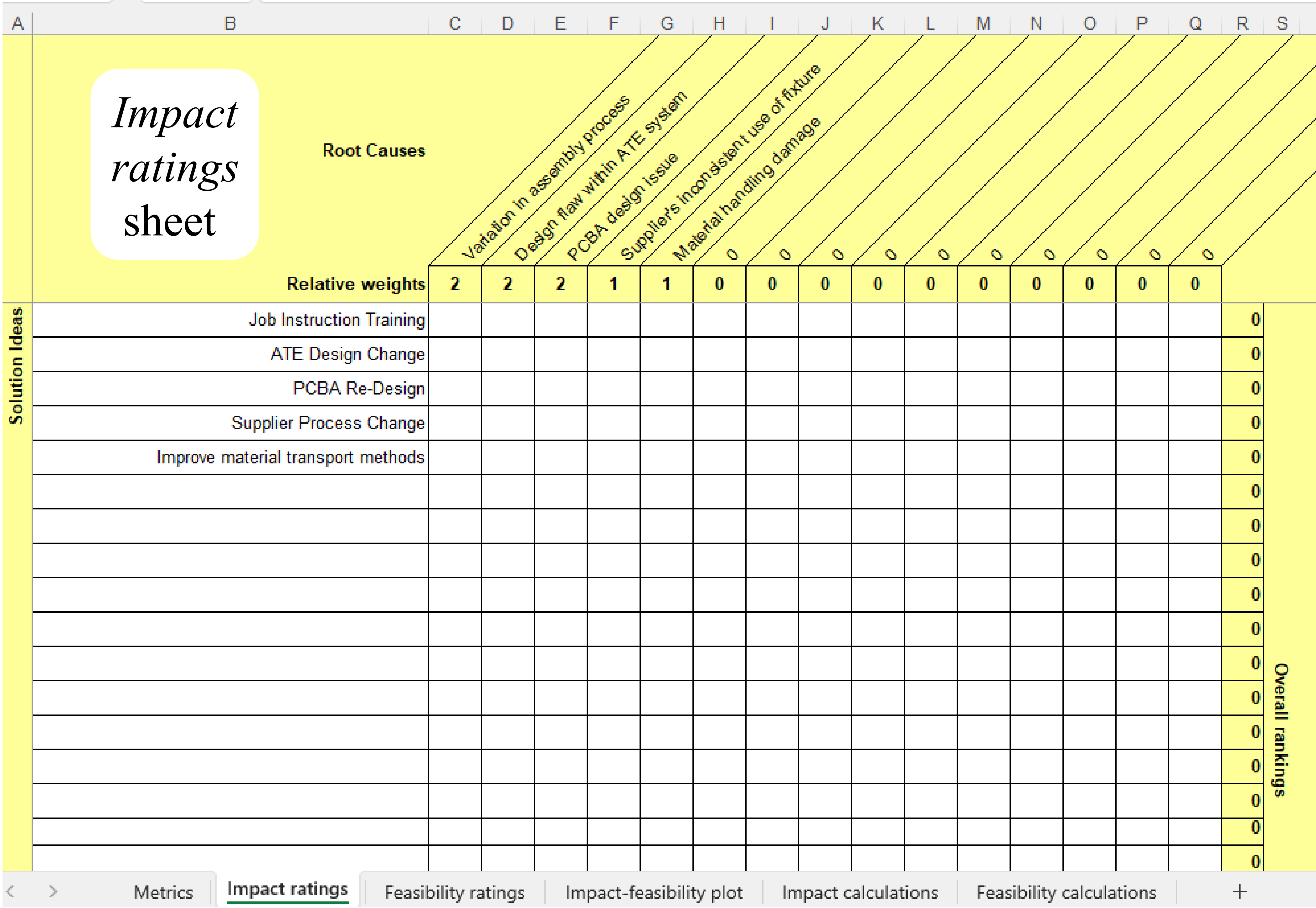
ATE = Automated Test Equipment

Metrics sheet

These are common feasibility metrics, but you can define the metrics and weights to suit your own situation.

Root causes determined in **Analyze** Phase. Weights indicate relative impact of cause on project metric

Prioritizing solutions (cont'd)



Impact ratings sheet

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
	Root Causes	Variation in assembly process	Design flaw within ATE system	PCBA design issue	Supplier's inconsistent use of fixture	Material handling damage	0	0	0	0	0	0	0	0	0	0		
	Relative weights	**2**	**2**	**2**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		
Solution Ideas	Job Instruction Training																**0**	**Overall rankings**
	ATE Design Change																**0**	
	PCBA Re-Design																**0**	
	Supplier Process Change																**0**	
	Improve material transport methods																**0**	
																	0	
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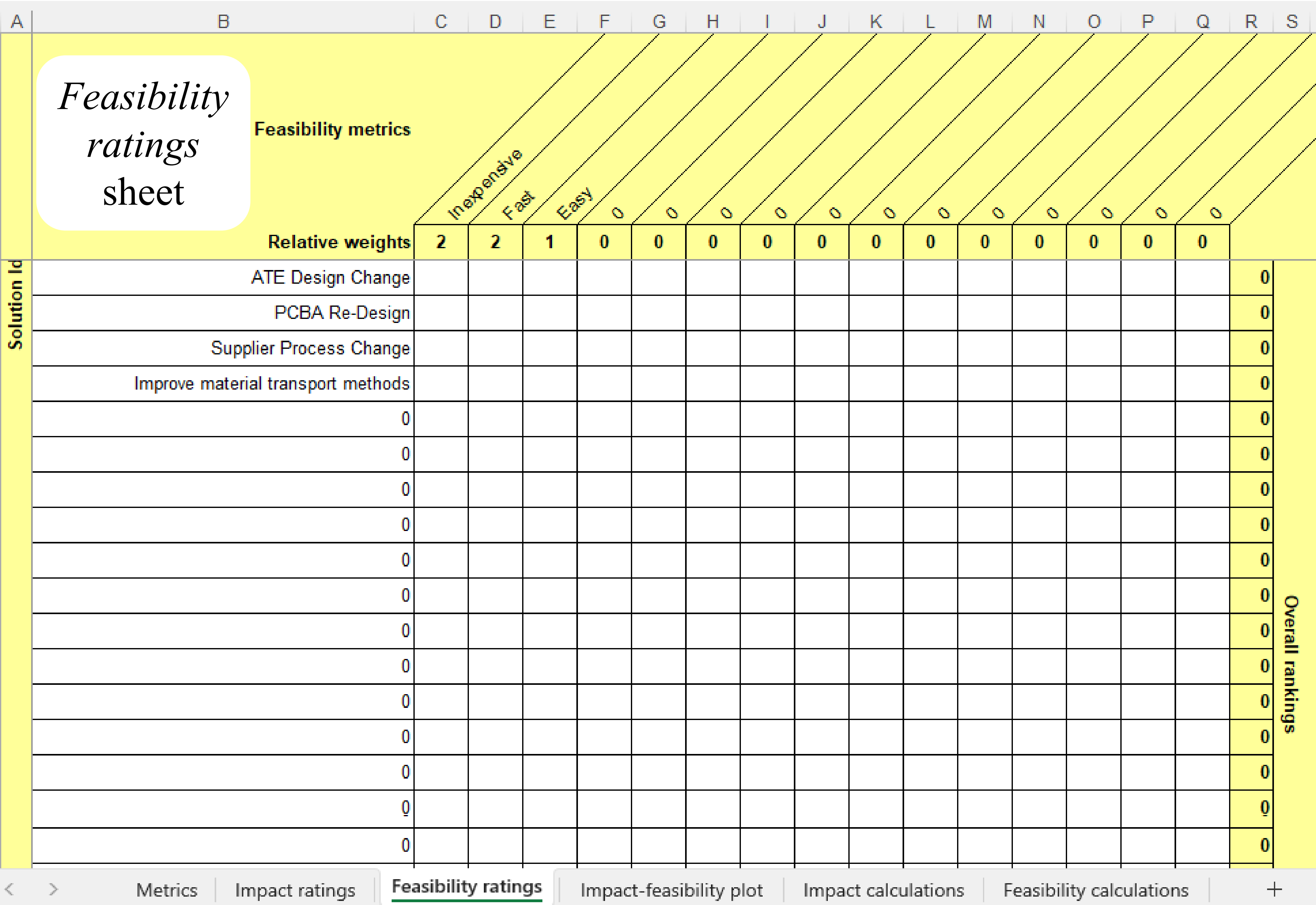
Prioritizing solutions (cont'd)



Feasibility ratings sheet

Solution Id

Feasibility metrics	Inexpensive	Fast	Easy	0	0	0	0	0	0	0	0	0	0	0	0	Overall rankings
Relative weights	**2**	**2**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
ATE Design Change																**0**
PCBA Re-Design																**0**
Supplier Process Change																**0**
Improve material transport methods																**0**
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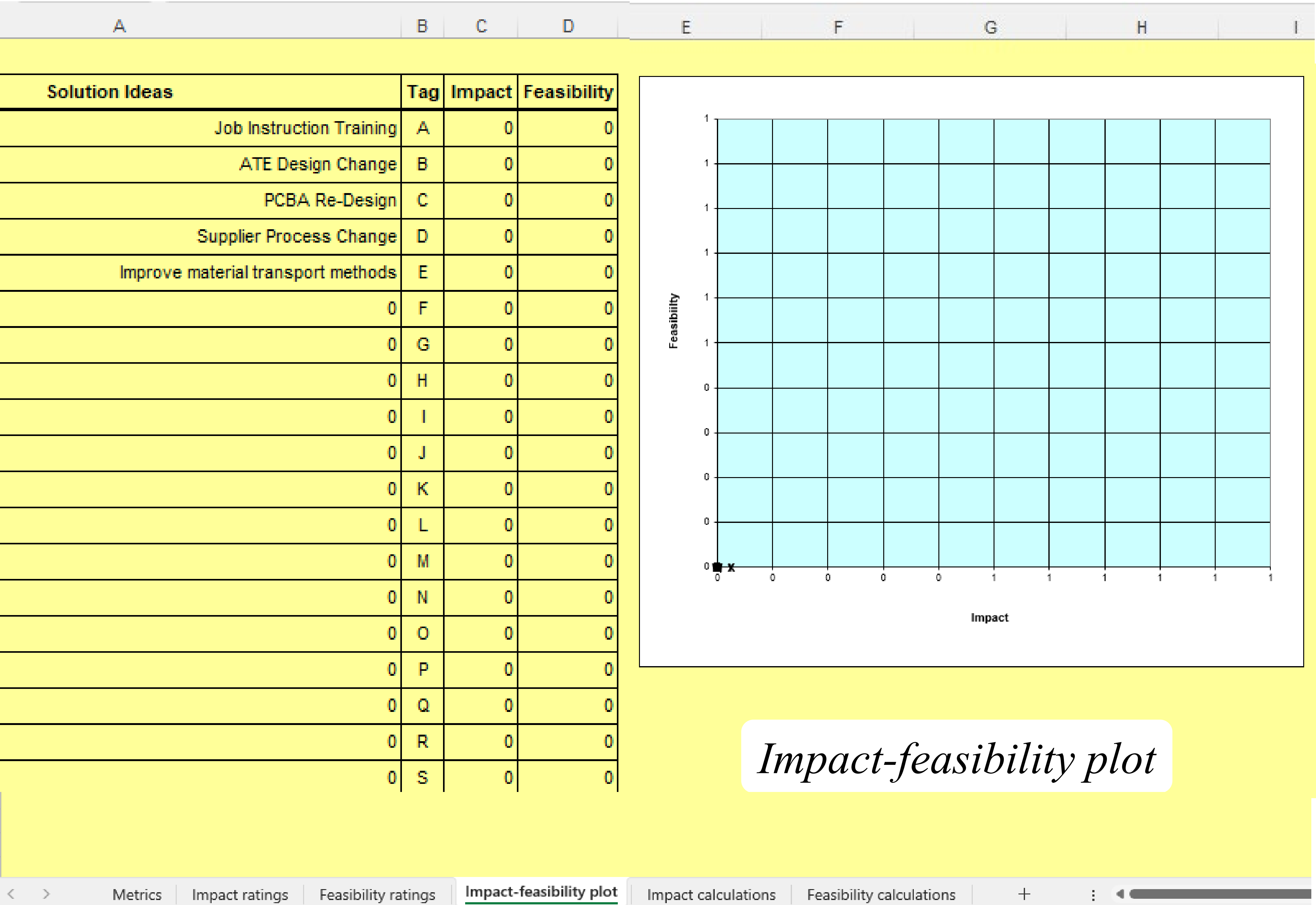
Prioritizing solutions (cont'd)



Solution Ideas	Tag	Impact	Feasibility
Job Instruction Training	A	0	0
ATE Design Change	B	0	0
PCBA Re-Design	C	0	0
Supplier Process Change	D	0	0
Improve material transport methods	E	0	0
0	F	0	0
0	G	0	0
0	H	0	0
0	I	0	0
0	J	0	0
0	K	0	0
0	L	0	0
0	M	0	0
0	N	0	0
0	O	0	0
0	P	0	0
0	Q	0	0
0	R	0	0
0	S	0	0

Impact-feasibility plot

Exercise 16.1

Open *Student Files → prioritizing solutions - exercise*.

Use the root causes and solution ideas as provided. Note that the first row of each sheet is frozen for ease of use during ranking.

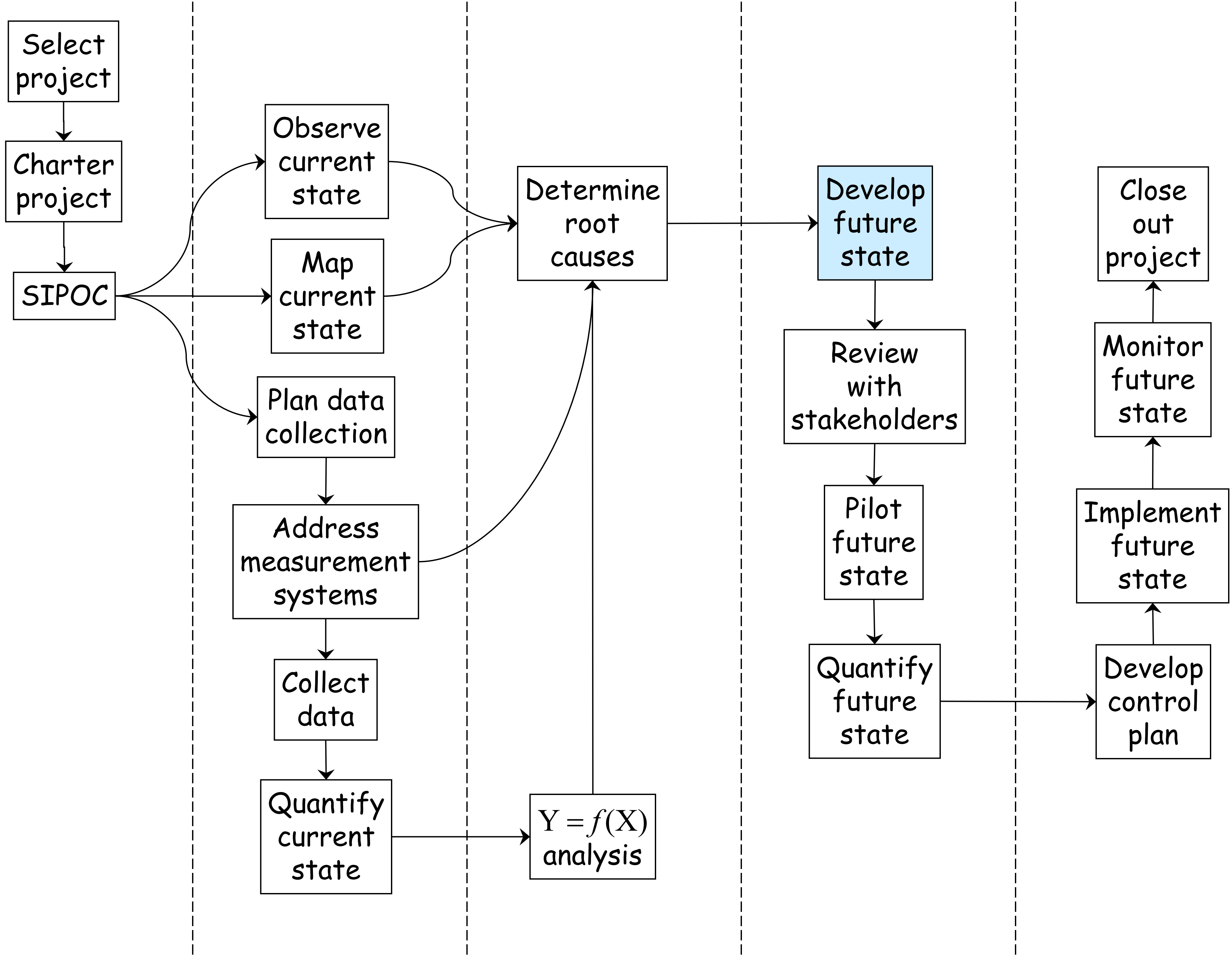
Use your knowledge and experience to complete the following tasks:

a) Change the relative weights for the feasibility metrics as you see fit.

b) Fill out the *Impact ratings* sheet using H, M, L or blank.

c) Fill out the *Feasibility ratings* sheet using H, M, or L.

d) Use your impact-feasibility plot to decide which solution ideas should be implemented sooner, which should be implemented later, and perhaps, which should not be implemented.



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

Monitor future state

Close out project

Commonly used Lean solutions

Continuous Flow Production – 8 Steps

- *Parts Quantity (PQ) Analysis*
- *Establish Standard Routing*
- *Standardize Work*
- *Takt Time, Cycle Time, Lead Time, Processing Time*
- *Work Balancing (leveling)*
- *Pull System*

Standard Work

5S

Mistake proofing (Poke Yoke)

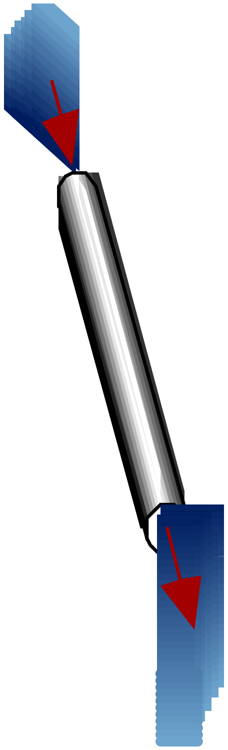
Reducing Batch Sizes

.

Continuous Flow Production Means Steady Velocity

Traditional: Batch Production—meandering stream with many stagnant pools and waterfalls

Lean Production: Pipeline with fast-flowing water



Continuous Flow Production (CFP)

Definition

- Flow of products in a ***level*** manner through the production operations—the ***ideal*** situation is ***one-piece*** flow at and between processes

Benefits

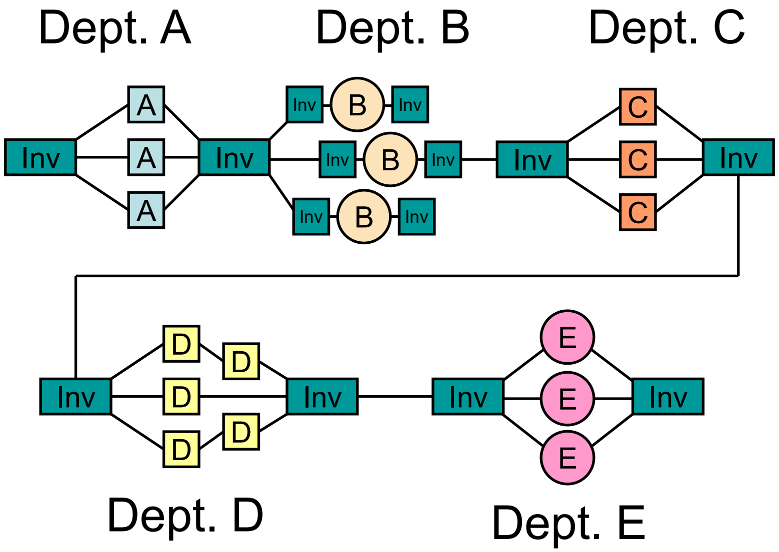
- CFP increases the ***velocity***, ***predictability*** and ***flexibility*** of the production cycle

Continuous Flow Production—Eight Steps

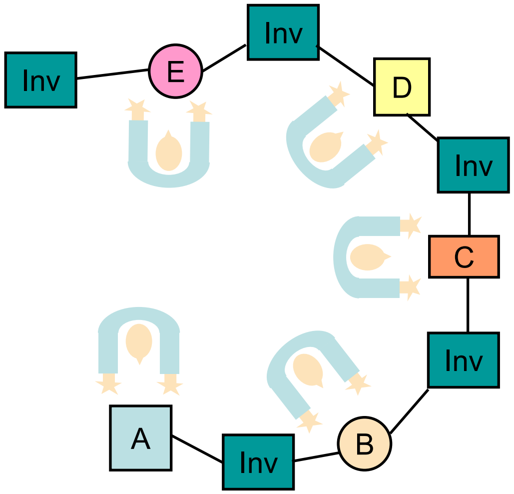
1. Collect data and analyze workflow
2. Design process sequence and cell
3. Standardize the work
4. Produce and move one piece at a time
5. Produce at the rate of customer’s consumption
6. Separate people from machines
7. Train people to operate multiple processes
8. Balance operations in the cell

Continuous Flow Journey

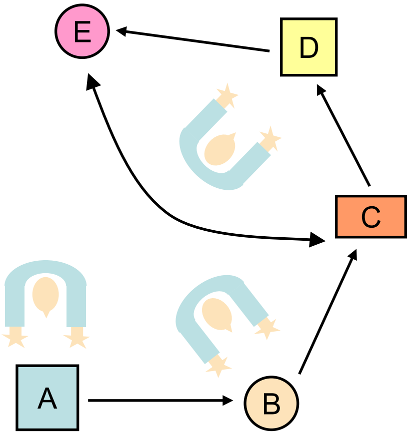
Stage 1
Production in Specialized Departments



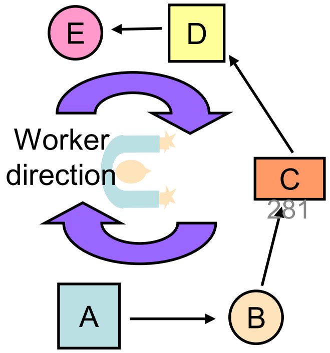
Stage 2
Production in Product Cell



Stage 3
Production in Compact Cell with One-Piece Flow



Stage 4
Production in Compact Cell with
One-Piece Flow and Separation Man/Machine



Step 1: Collect Data and Analyze Work

Conduct a Parts Quantity (PQ) Analysis

Prepare a Process Flow Analysis

Group products with similar routings

Determine possible cells for product groupings

Evaluate capacity bottlenecks and equipment that can be shared or dedicated

Parts Quantity (PQ) Analysis

EXAMPLE:
PQ Analysis List

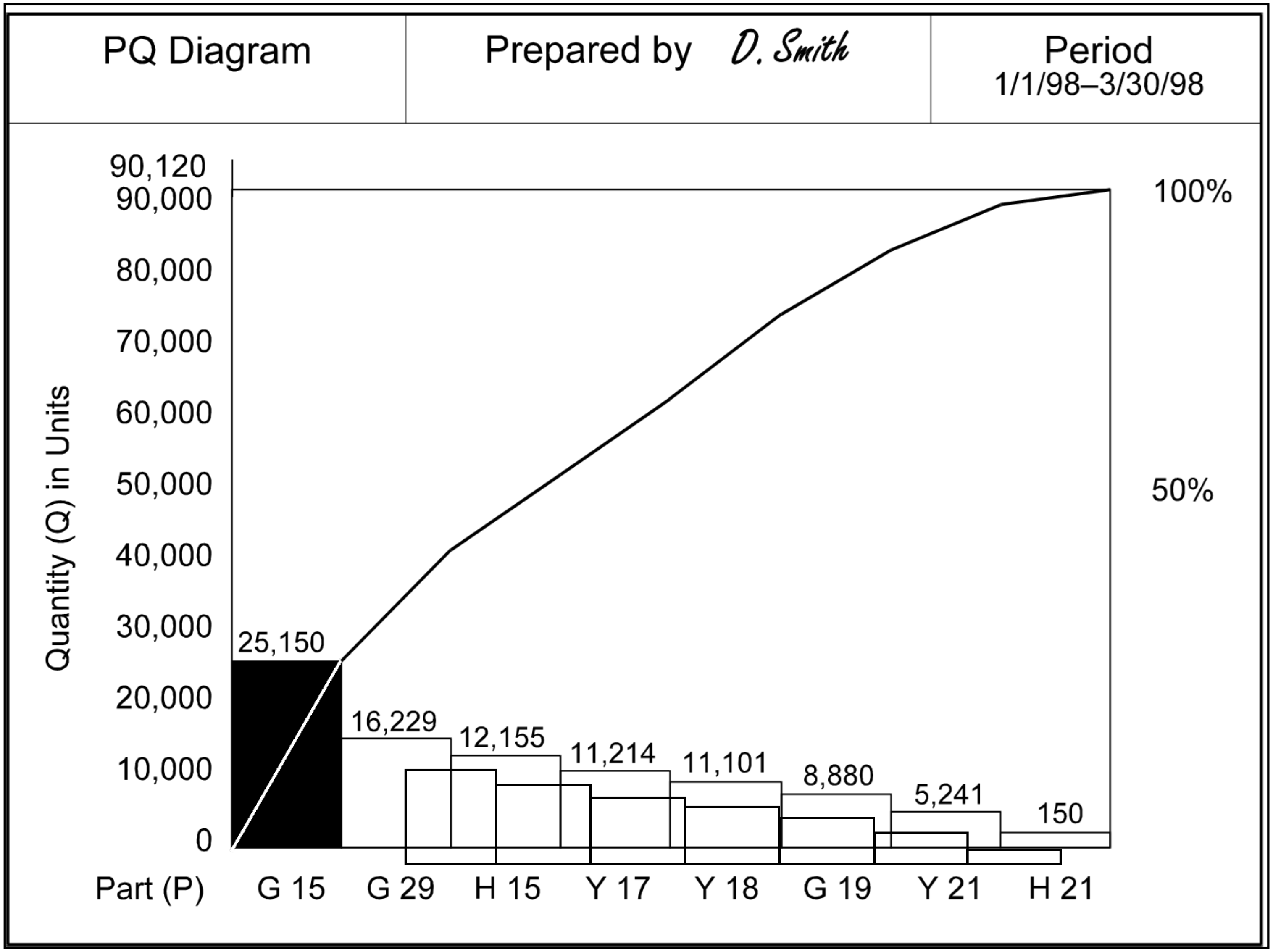
Prepared by D. Smith

Period 1/1/98–3/30/98

Part Number	Qty	Cumulative	%	Cum %
G 15	25,150	25,150	27.9	27.9
G 29	16,229	41,379	18.0	45.9
H 15	12,155	53,534	13.5	59.4
Y 17	11,214	64,748	12.4	71.8
Y 18	11,101	75,849	12.3	84.1
G 19	8,880	84,729	9.9	94.0
Y 21	5,241	89,970	5.7	99.7
H 21	150	90,120	0.3	100.0

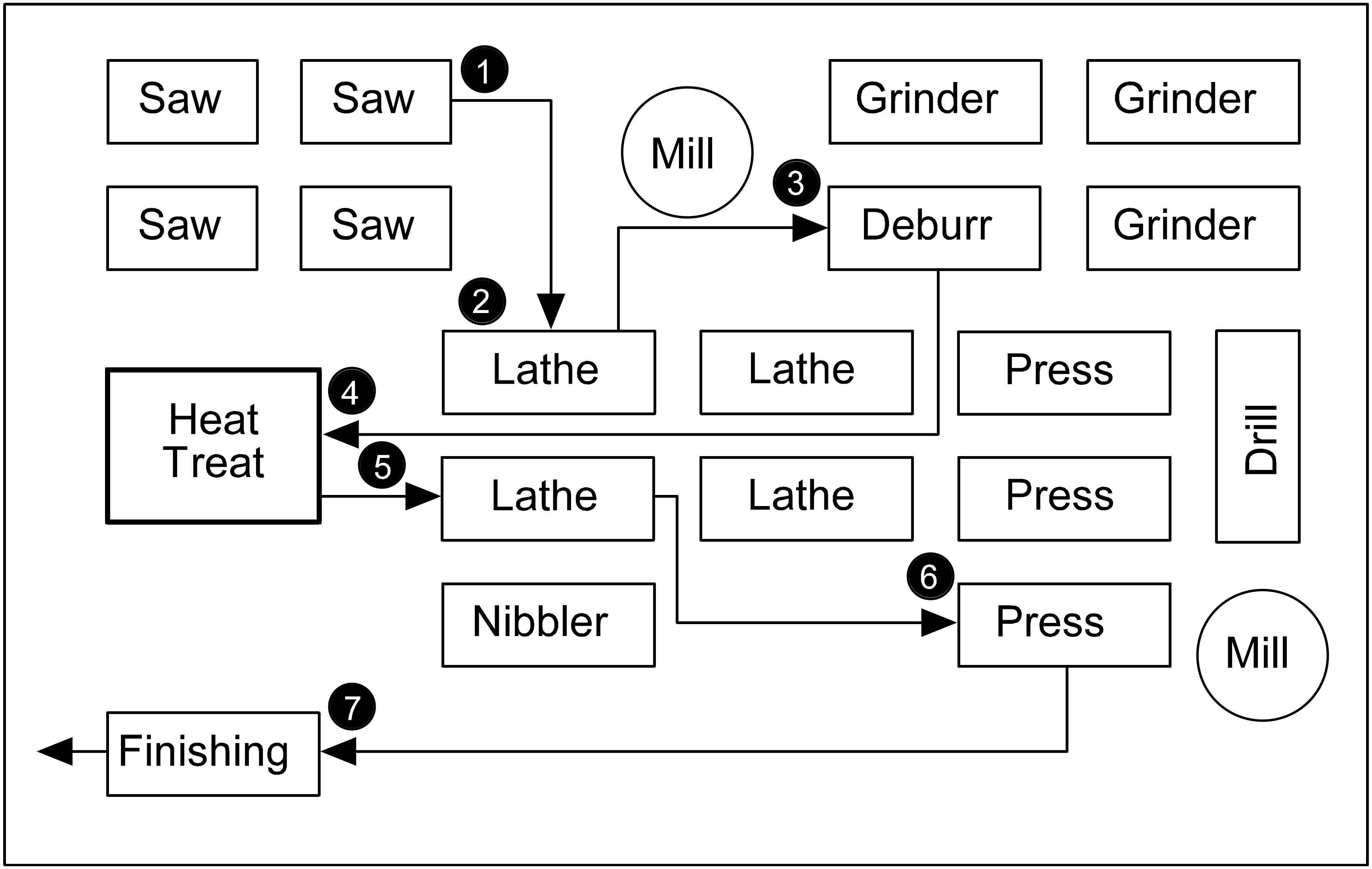
List all part numbers processed in order of decreasing quantity

PQ Analysis



Visually display the part number distribution in a Pareto Chart

Establish Standard Routing



May require changes to existing "routers"

Process Analysis

Part. No.	Saw	Drill	Mill	Lathe	H.T.	Grind	Assy	Cell 1	Cell 2	Cell 3
G15	1	2		3 5	4		6		X	
G29	1	2		3	4		5	X		
H15	1	2	3	4	5	6	7	X		
Y17	1		2		4	3	5			X
Y18	1		2		4	3	5			X
G19	1	2		3	4		5	X		

Record the process sequence for each part number displaying all "loop-backs" and out-of-area processes

Based on common routings, products can be grouped into cells. The PQ Analysis, process cycle times, and equipment quantities determine how many cells can be made and what equipment must be shared

The objective is to identify the minimum number of product groups/cells

Step 2: Design Process Sequence and Cell

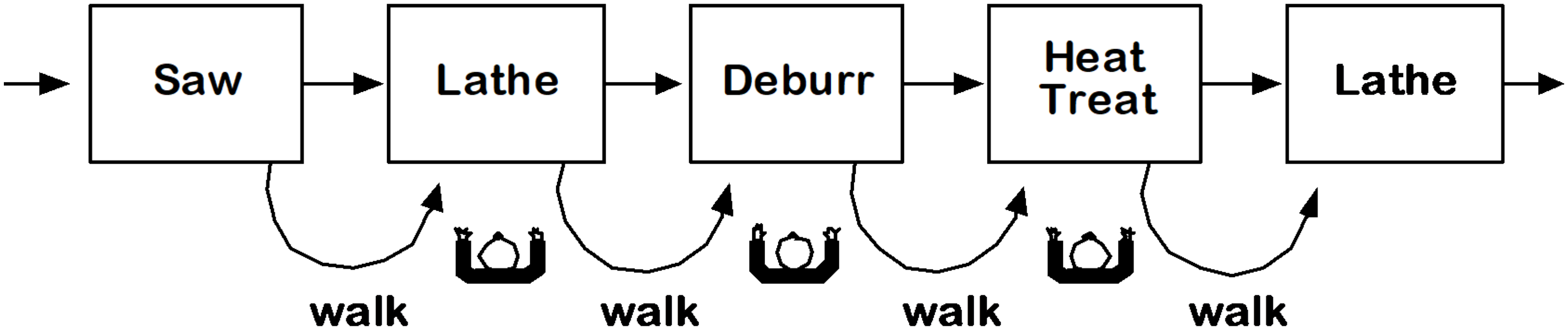
Establish standard routing

Locate equipment in proper sequence

Reduce waste

- Distance: equipment close together
- Inventory: implement pull
- Handling: eliminate wherever possible
- Walking: parts, tools, supplies at point of use

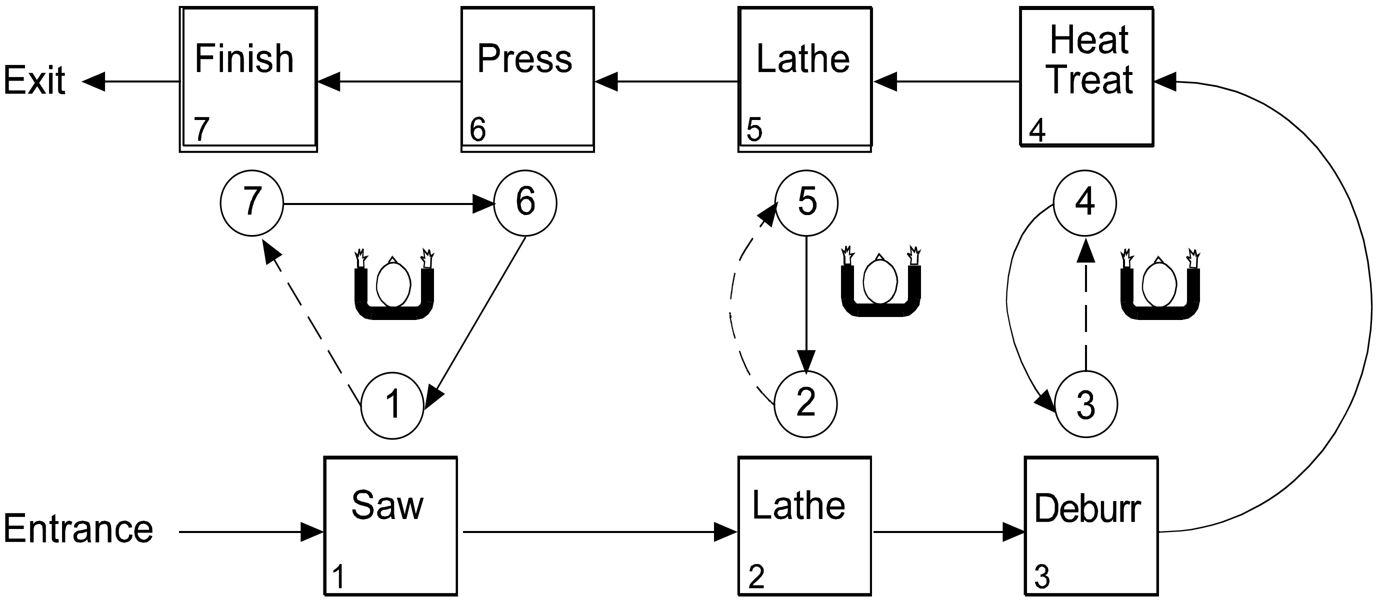
Linear Arrangement



Straight line arrangement disadvantages

- People usually become dedicated to one machine
- Less flexibility between people
- Normal way to increase output is to work faster
- Work is usually not well balanced between machines
- Quality and output problems noticed at the end of the line are difficult to communicate to the front

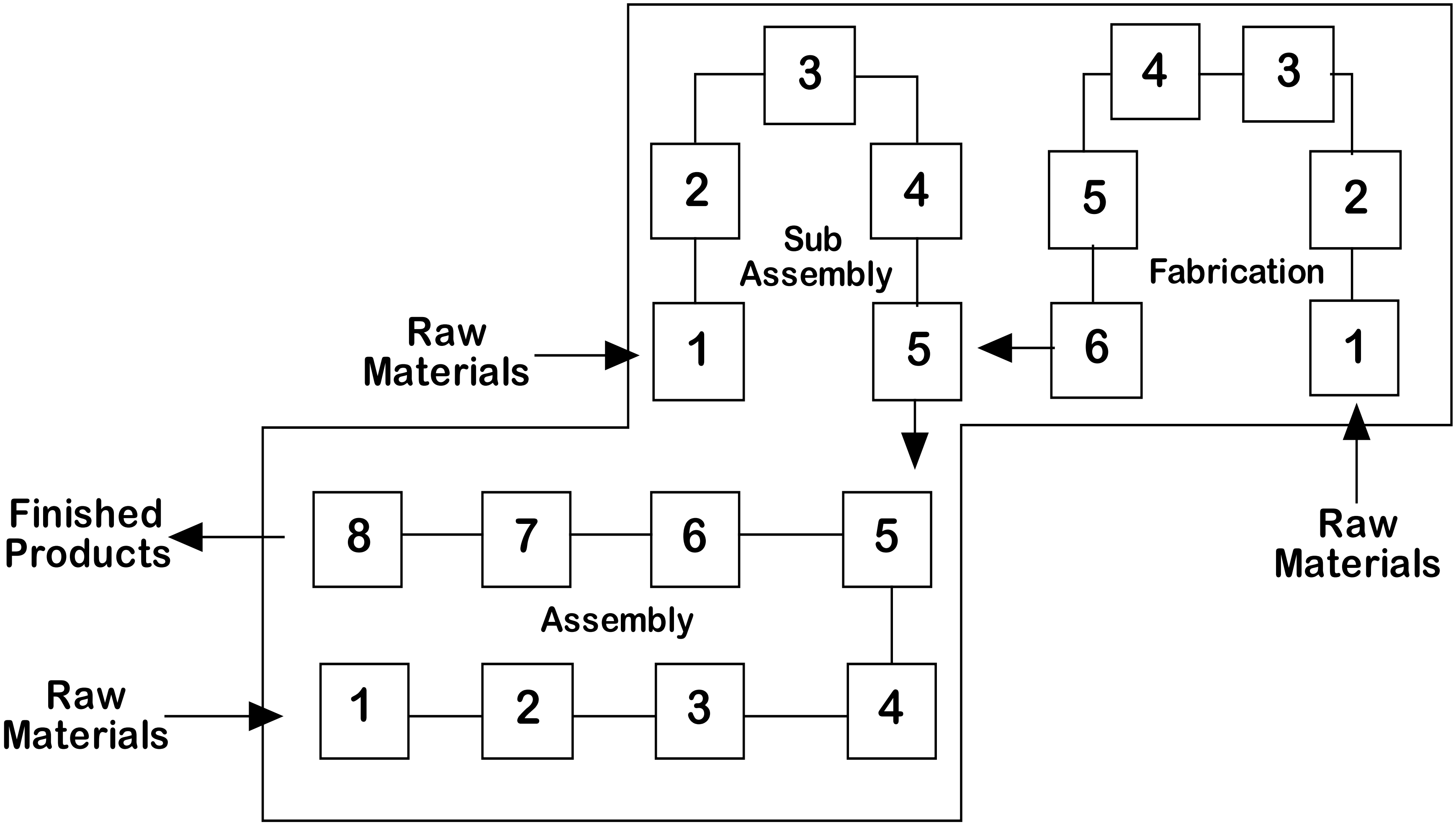
Best Arrangement is Often a "U" Shape



Some advantages:

- Shortest distance for people to walk
- Work enters and leaves near the same location
- Improved communication
- Easier to balance the workload between people

Connecting Several Lines



Step 3: Standardize the Work

To sustain and continue improvement, standard work is needed.

Definition: The documentation of how work is performed by both humans and machines to produce products.

Step 3: Standardize the Work

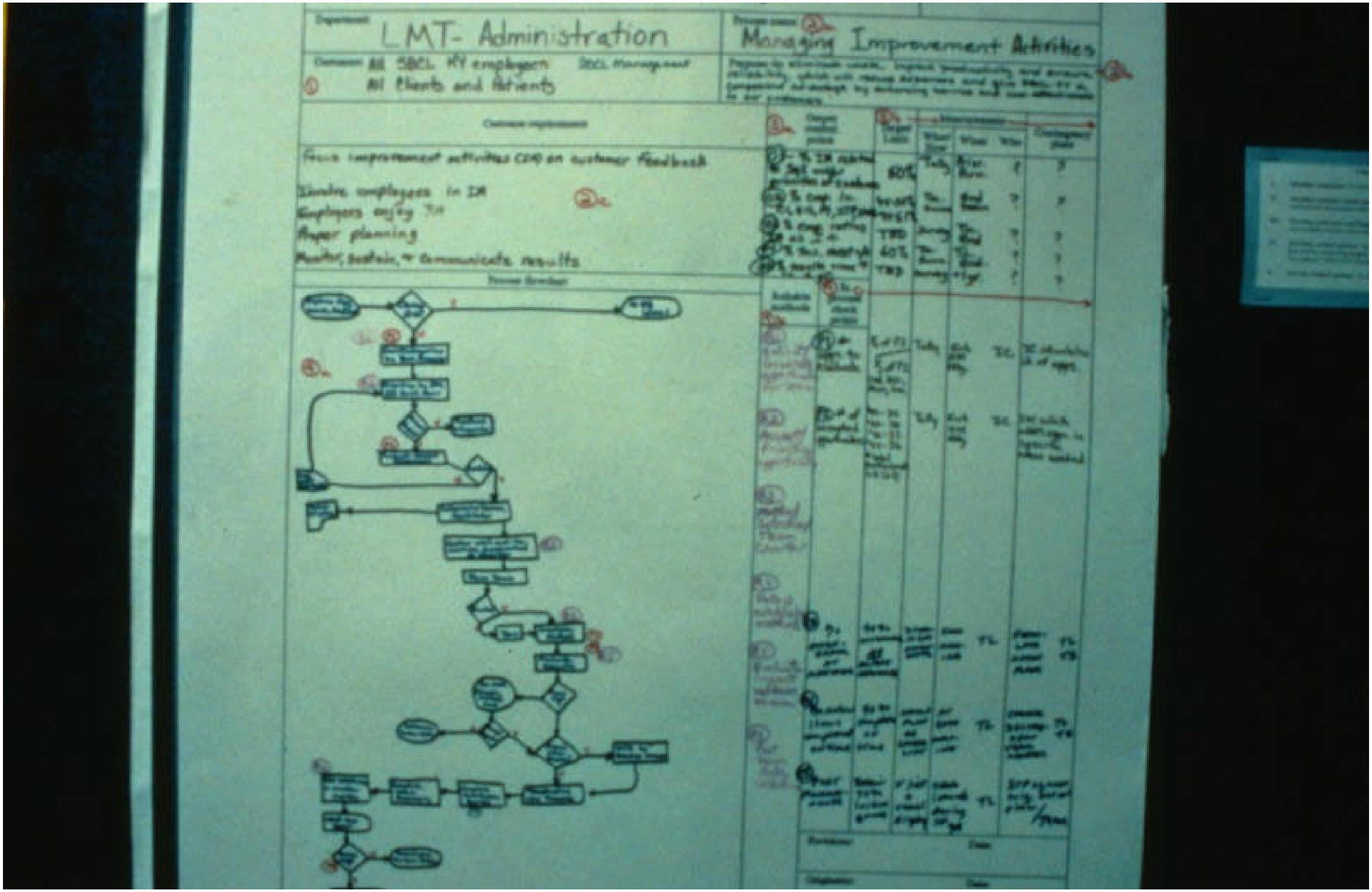
Standard work has three prerequisites:

- People are performing work
- Processes or tasks must be repetitive
- Work procedures must be documented

Standard work has three components:

- Takt time—The pace at which an operation should complete products or transactions to meet customer demand during the Available Working Time.
- Work sequence—order of operations
- Standard quantities—lot sizes, raw materials, work-in-process

Office standard work - example



LMT- Administration

Managing Improvement Activities

All SBCL KY employees SBCL Management
All Clients and Patients

Focus improvement activities (CIA) on customer feedback

Involve employees in IA
Employees enjoy IA
Proper planning
Monitor, sustain, + communicate results

Step 4: Produce and Move One Piece at a Time

Move one piece at a time

- Just try it!

Reduce lot sizes to one

- Eliminate constraints to small lots

Make cell compact

- Minimize distance between equipment
- Install casters on equipment

Deal with monuments

Make cell compact

Move operations as close together as possible:

- Eliminates WIP buildup
- Eliminates travel distance
- Encourages work sharing… line balance

Put equipment on casters where possible:

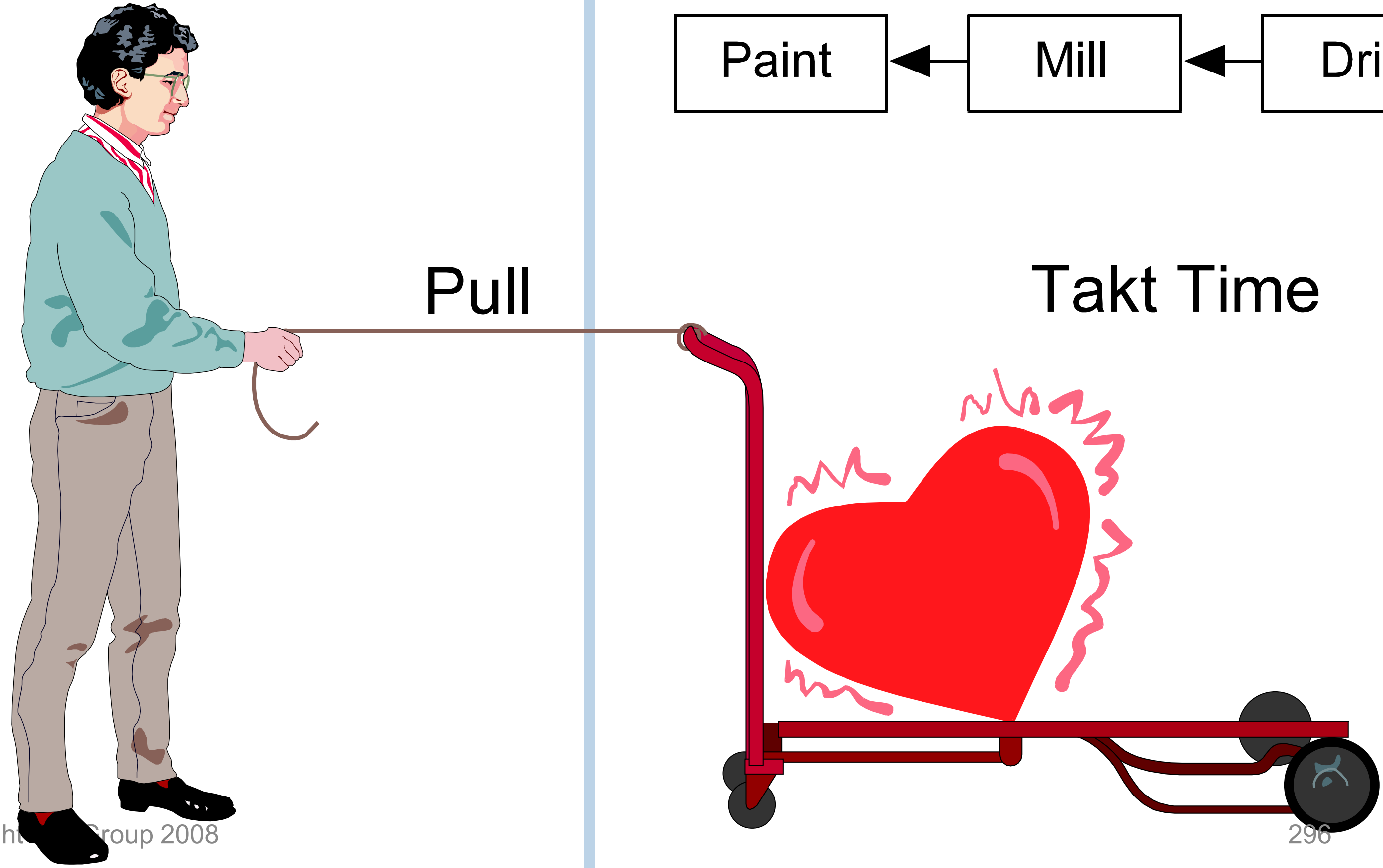
- Easy to reconfigure line if demand changes
- Move equipment out of cell when not being used
- Encourages continuous improvement

Step 5: Produce at the Rate of Customers' Consumption

Customer Needs

Production Heartbeat

Paint ← Mill ← Drill



Pull

Takt Time

Definitions

Takt time

- The pace of production required by the *customer*, calculated as:

Net working time per day

Daily quantity required

Cycle time

- The current pace of production, measured as the time from completion of one good unit to completion of a second good unit

Definitions

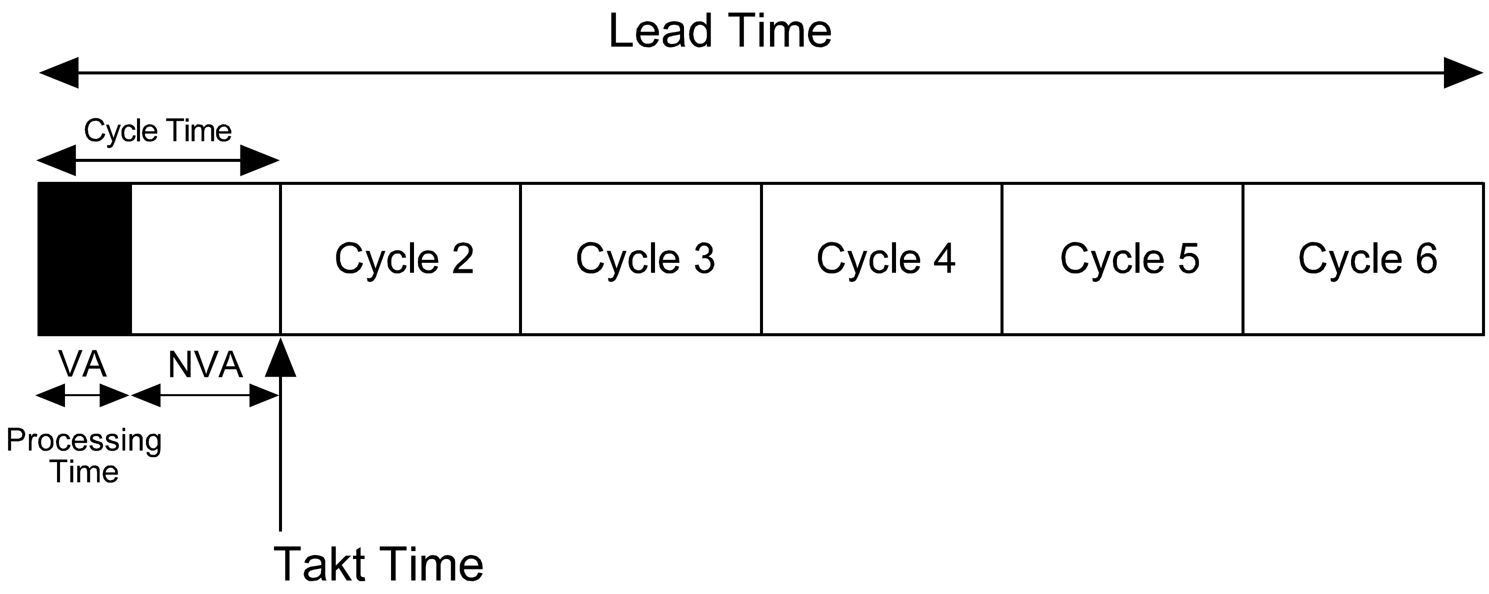
Lead time

- Total elapsed time from start of a process to the end; the boundaries of the process may be very broad, or very narrow

Processing time

- The actual value-added component of cycle time

Definitions



Strive to make cycle time equal takt time

Takt time > Cycle time

- Slow down production
- Redeploy people

Produce at Rate of Customer’s Consumption

$$\text{Takt Time} = \frac{\text{Net Working Time per Day}}{\text{Daily Quantity Required}}$$

“Heartbeat/Drumbeat/Cadence” of Production

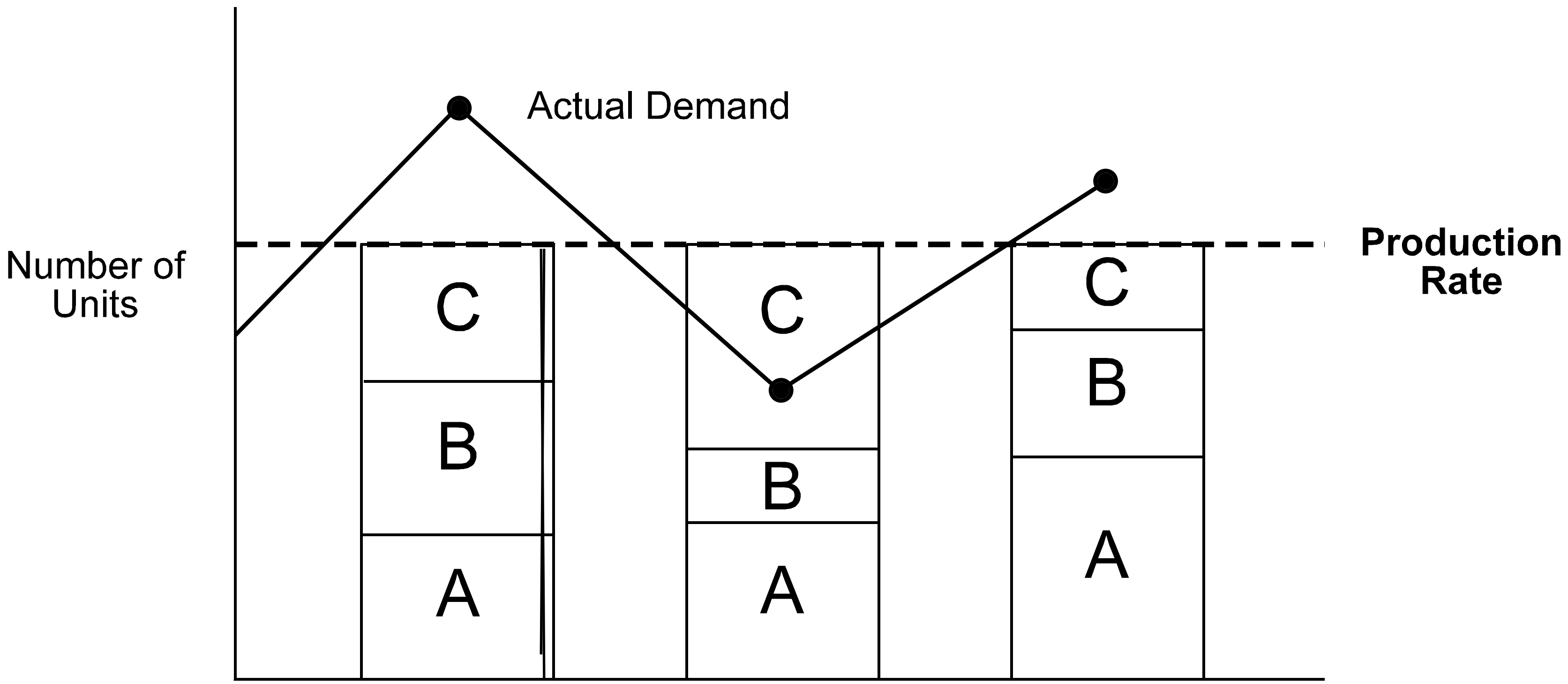
Example:

Net working time per day = 7 hours = 420 minutes

Daily quantity required = 56 pieces

$$\text{Takt Time} = \frac{\text{420 minutes}}{\text{56 pieces}} = \text{7.5 minutes}$$

Level Schedule



Daily Production Schedule

Process Data

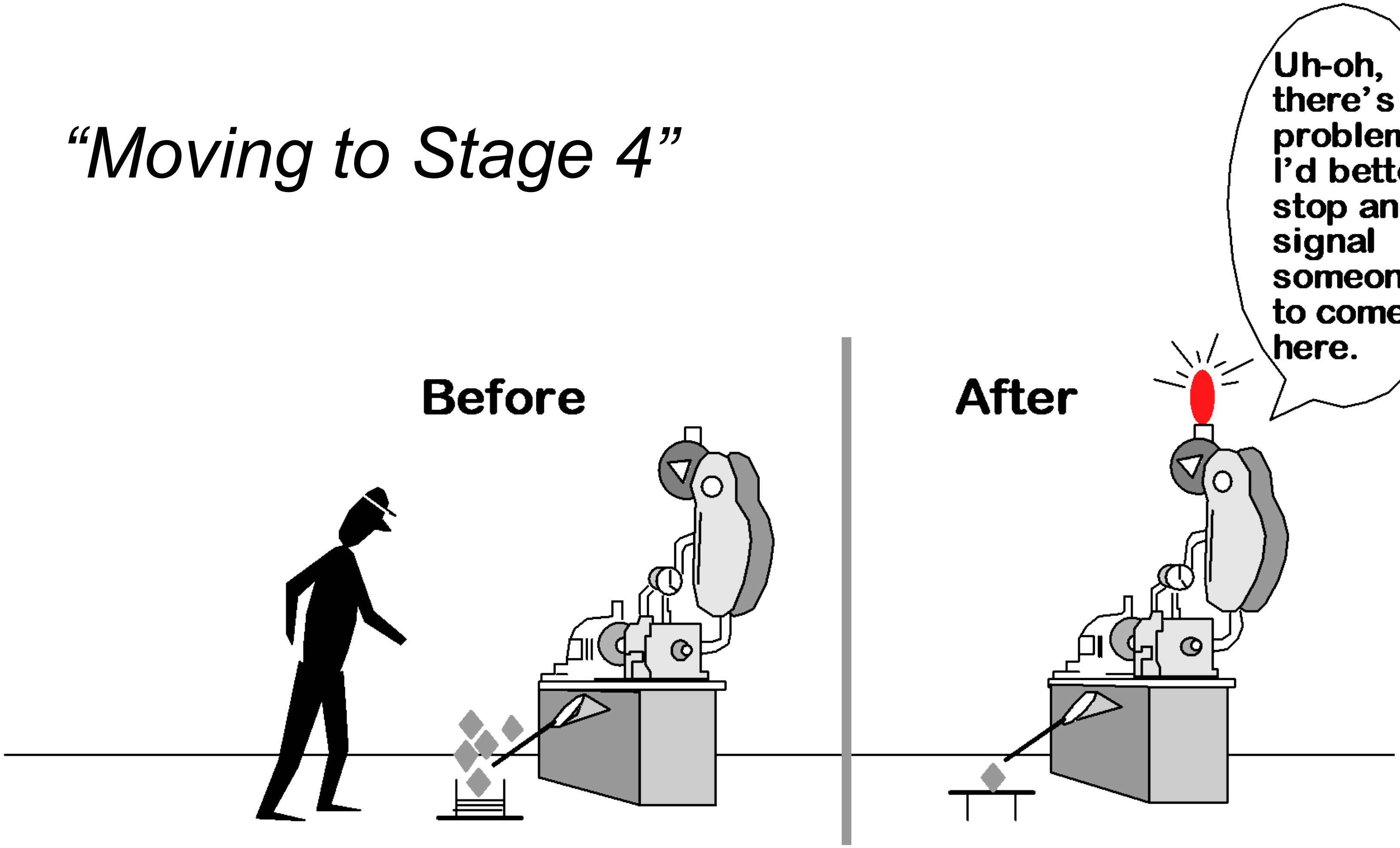
- Total working time per day = 960 minutes
- Time per day for breaks and other manufacturing activities = 160 minutes
- Monthly Customer Demand = 1600 pieces
- Working days per month = 20

Process	Machine Cycle Time
A	10 min
B	10 min
C	3 min
D	2 min
E	5 min

What is takt time?
Do we have capacity? How many operators?

Step 6: Separate People from Machines

"Moving to Stage 4"



Step 6: Separate People from Machines

Apply autonomation (automation with a human touch)

Install devices to stop machine when finished or problem occurs (Jidoka or autonomation)

Install mistake-proofing devices (poka-yoke)

Eliminate watching machines and waiting

- Enable people to leave machine and move to next process
- Perform another value-adding task while machine is working

Allowing People to Separate from Machines

Autonomation (Jidoka)

- Machines and assembly operations can stop production when errors are detected or at the end of a production cycle

Mistake-proofing (Poka-Yoke)

- Methods for error detection and (especially) prevention

Step 7: Train People to Operate Multiple Processes

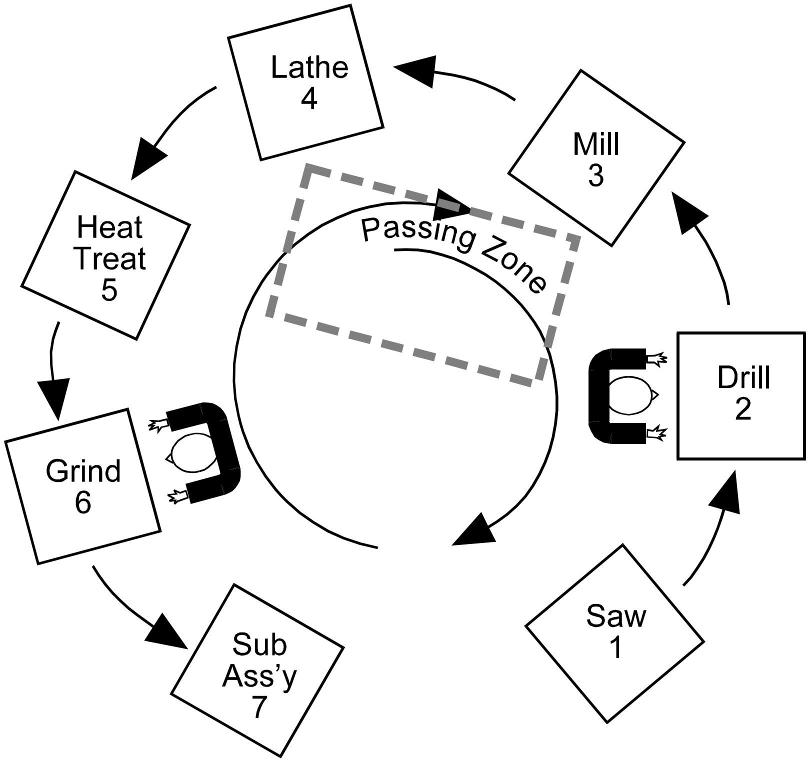
What skills are needed to operate the cell?

Who performs what tasks?

How will we work together in the cell?

Design for mutual assistance and use defined "passing zones"

People	Process 1	2	3	4	5	6	7
John	✓	✓	✓	✓	✓	✓	✓
Mary	✓	✓	✓	✓			
Frank			✓	✓	✓	✓	✓



Step 8: Balance Operations in the Cell

Make cycle time = takt time

- Tasks
- Machines
- People

Smooth production

- Level schedule
- Mixed lot production

Determine Number of People Required

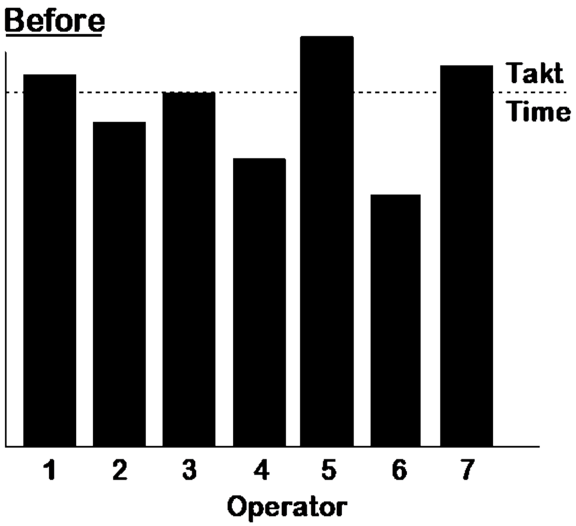
$$\boxed{\text{Number of People Required} = \frac{\text{Sum of Cycle Times}}{\text{Takt Time}}}$$

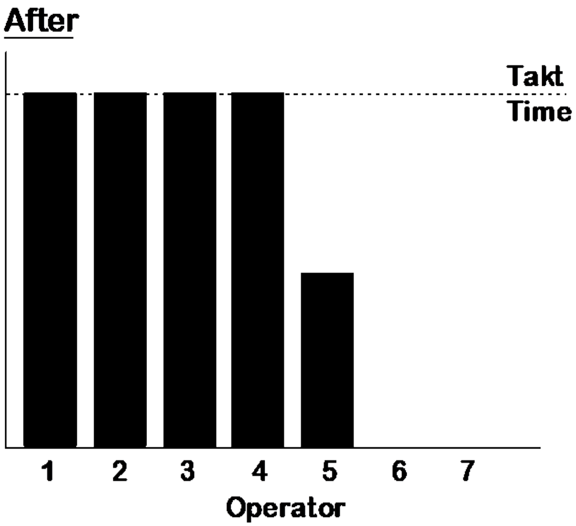
Example:

Sum of Cycle Times = 50.40 seconds

Takt Time = 11.35 seconds

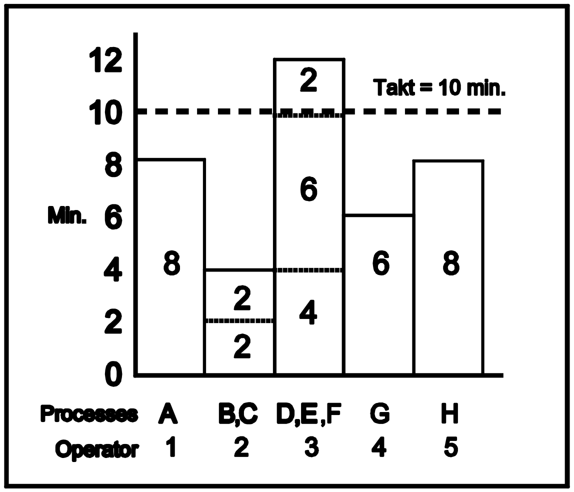
$$\text{Number of People Required} = \frac{\text{50.40 seconds}}{\text{11.35 seconds}} = 4.4$$



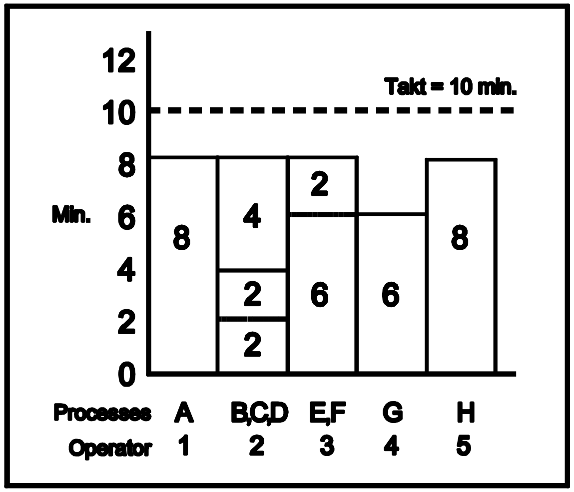


Examples of Using Work Balancing Analysis

DATA
Cycle Time (min.)
A = 8
B = 2
C = 2
D = 4
E = 6
F = 2
G = 6
H = 8

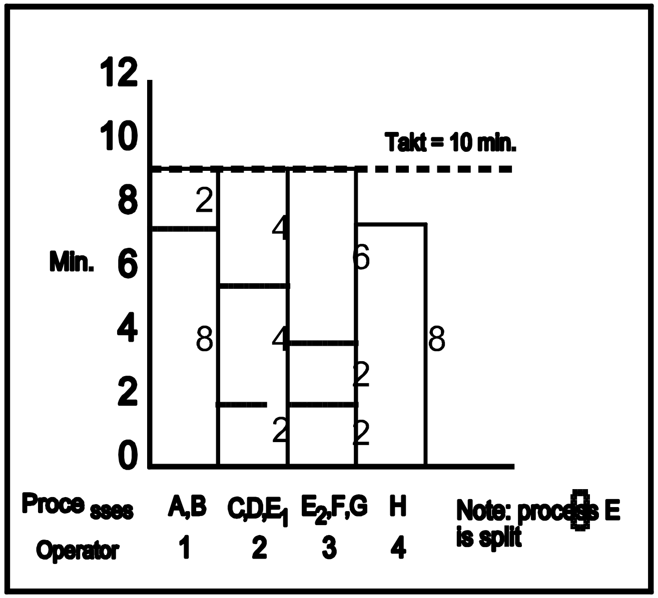


Identify Bottlenecks

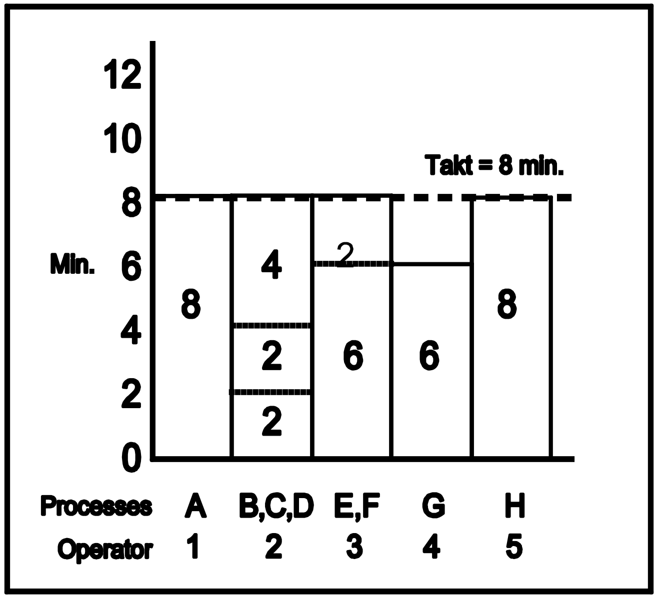


Redistribute to eliminate bottlenecks

Examples of Using Work Balancing Analysis



Identify opportunities
to increase productivity —
reduce from 5 to 4 people



Adjust production line
to decrease in takt time —
increase the number
of people or improve processes
to meet the
8-min. takt time

Mixed-Lot Production

Weekly

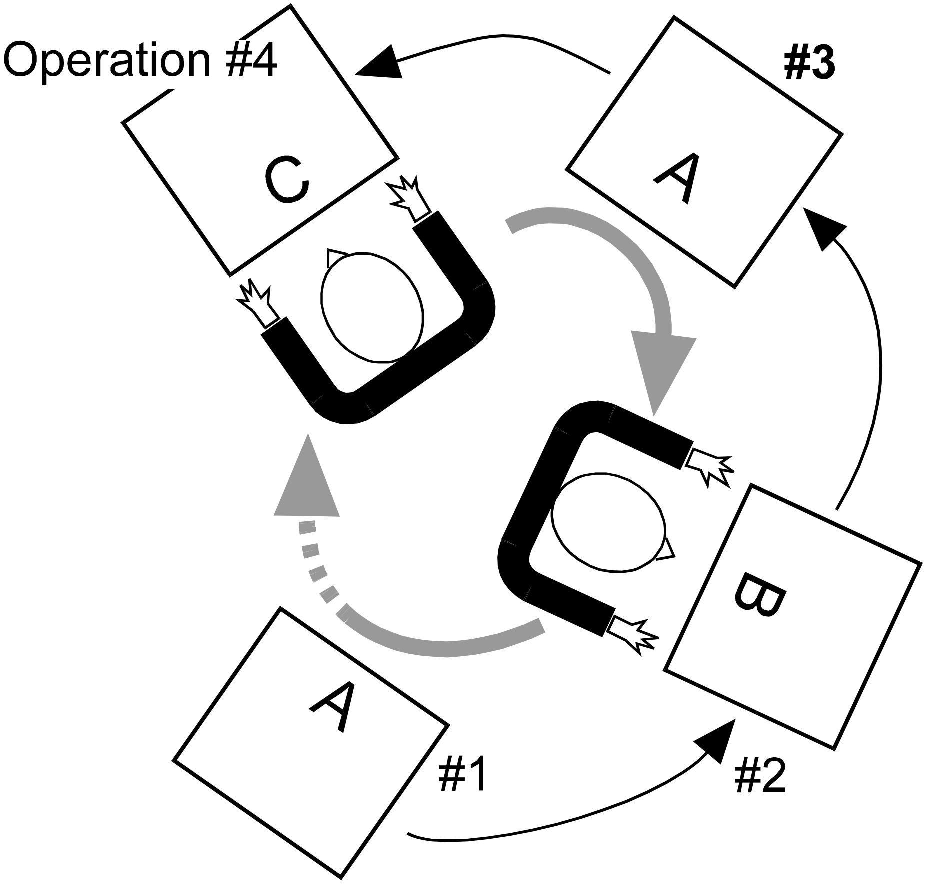
Production Rate = 1000
A 500
B 250
C 250

Daily

Production Rate = 200
A 100
B 50
C 50

Mixed Lot Sequence

A B A C
Repeat this sequence
50 times daily



Standard
Work

Standard Work

Defines and standardizes the best current work practices

Provides consistency in the operation, and low variation in the output

Provides a basis for improvement

Three Requirements of Standard Work

Takt time

Work sequence

Standard quantity (WIP)

Time Definitions - review

Takt time

- The pace at which an operation should complete products or transactions to meet customer demand during the Available Working Time.
- Available working time during a period divided by the number of products or transactions *required* during that same period

Cycle time

- The fastest repeatable time between part or transaction completions using the current processes and resources
- Shows how a process is capable of performing
- Combines with AWT to determine capacity

Time Definitions - review

Lead time

- The total elapsed time to produce one defect free product or transaction
- The time difference between when a part or transaction enters and leaves a process

Processing time

- The actual value-added component of lead time

Takt Time: Produce at Rate of *Customer's* Consumption

$$\text{Takt Time} = \frac{\text{Net Working Time per Day}}{\text{Daily Quantity Required}}$$

"Heartbeat" or "Drumbeat" of Production

Example: Net Working Time per Day = 7 hours

Daily Quantity Required = 56 pieces per day

$$\text{Takt Time} = \frac{(7\text{ hours})\ (60\text{ min/hour})}{56\text{ pieces}} = 7.5\text{ minutes}$$

- Some equipment may need to be slowed down to produce at takt time!!.
- Takt time is expressed as **time**!
- Takt time is always **calculated** from rate of customer demand

Standard Work Sequence

The sequence of ***operations*** *to produce a product (e.g., #1 cut, #2 bend, #3 drill, #4 assemble)*

The sequence of ***activities*** *necessary to accomplish a single* ***operation*** *(e.g., sequence of tasks to bend a part)*

Standard Work Tools

Time Observation Form

Standard Work Analysis Sheet

Standard Work Combination Chart

Line Balance Analysis Chart

EXAMPLE:
Time Observation

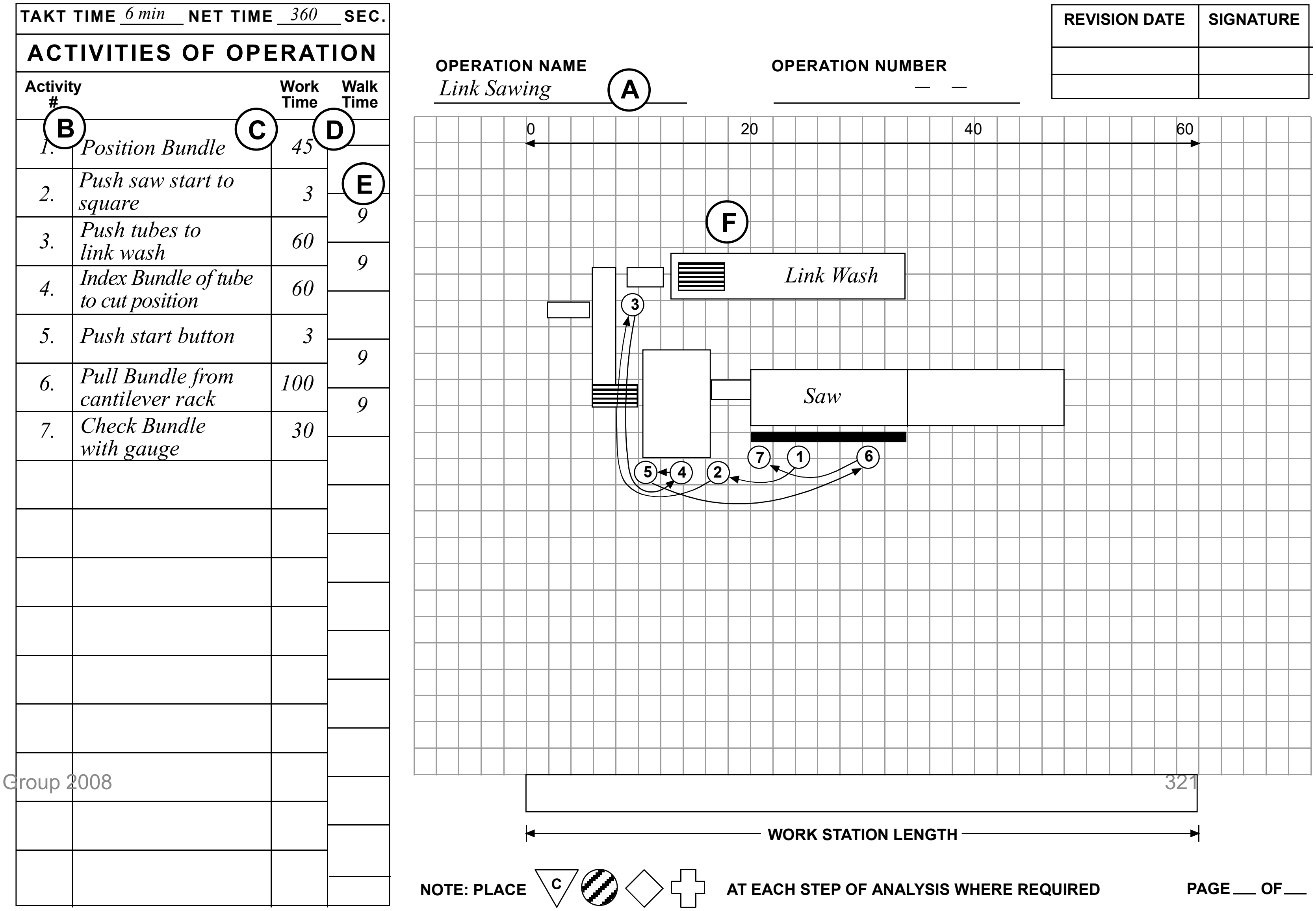
Process *Plate Fab* Ⓐ **Observer** *DS* **Date** *2/20/96* Ⓑ

Ⓓ

No.	Operation/Activity	1	2	3	4	5	6	7	8	9	10	11	12	Average	Range	Comments
1	*Cut* Ⓒ	*15.0*	*14.8*	*14.8*	*15.4*	*15.1*	*15.2*	*14.7*	*15.0*	*15.0*	*15.1*	*15.2*	*14.8*	*15.0* Ⓕ	*.7* Ⓖ	
2	*Bend*	*14.8*	*14.5*	*15.5*	*15.2*	*15.1*	*15.5*	*14.8*	*14.7*	*15.1*	*15.0*	*14.9*	*14.7*	*15.0*	*1.0*	
3	*Drill*	*20.5*	*20.0*	*19.8*	*19.7*	*19.2*	*20.5*	*20.0*	*21.0*	*20.2*	*19.5*	*20.1*	*20.2*	*20.1*	*1.8*	
4	*Tap*	*15.2*	*15.0*	*15.0*	*15.1*	*15.1*	*14.9*	*14.9*	*14.8*	*14.8*	*14.8*	*15.0*	*15.0*	*15.0*	*.4*	
5	*Clean/Deburr*	*15.5*	*16.0*	*16.0*	*14.0*	*14.0*	*15.0*	*15.5*	*16.0*	*15.0*	*14.0*	*14.2*	*15.7*	*15.1*	*2.0*	*Variation in burr removal time*
Time for Cycle Ⓔ		*81.0*	*80.3*	*81.1*	*79.4*	*78.5*	*81.1*	*79.9*	*81.5*	*80.1*	*78.4*	*79.4*	*80.4*	*80.1*	*3.1*	

Standard Work Tools

EXAMPLE:
Standard Work Analysis Sheet



TAKT TIME *6 min* **NET TIME** *360* **SEC.**

ACTIVITIES OF OPERATION

Activity #		Work Time	Walk Time
1.	*Position Bundle*	*45*	
2.	*Push saw start to square*	*3*	*9*
3.	*Push tubes to link wash*	*60*	*9*
4.	*Index Bundle of tube to cut position*	*60*	
5.	*Push start button*	*3*	*9*
6.	*Pull Bundle from cantilever rack*	*100*	*9*
7.	*Check Bundle with gauge*	*30*	

OPERATION NAME *Link Sawing*

OPERATION NUMBER — —

REVISION DATE	SIGNATURE

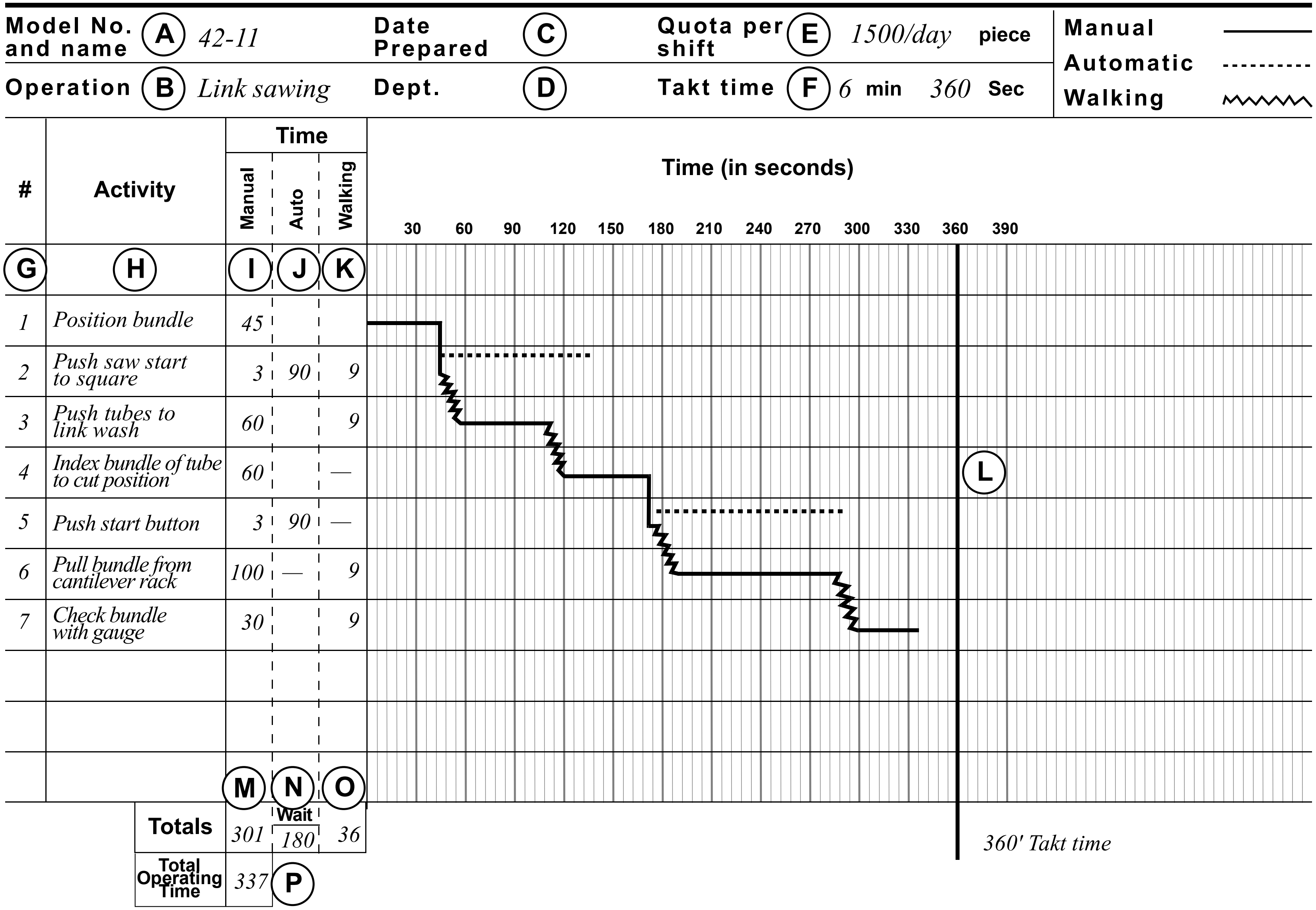
WORK STATION LENGTH

NOTE: PLACE ▽C ▨ ◇ ✚ **AT EACH STEP OF ANALYSIS WHERE REQUIRED**

PAGE __ **OF** __

Standard Work Tools

EXAMPLE:
Standard Work Combination Sheet



Model No. and name	Ⓐ 42-11	Date Prepared	Ⓒ	Quota per shift	Ⓔ 1500/day piece
Operation	Ⓑ Link sawing	Dept.	Ⓓ	Takt time	Ⓕ 6 min 360 Sec

Manual ——————
Automatic ----------
Walking ∿∿∿∿

#	Activity	Time		
		Manual	Auto	Walking
Ⓖ	Ⓗ	Ⓘ	Ⓙ	Ⓚ
1	Position bundle	45		
2	Push saw start to square	3	90	9
3	Push tubes to link wash	60		9
4	Index bundle of tube to cut position	60		—
5	Push start button	3	90	—
6	Pull bundle from cantilever rack	100	—	9
7	Check bundle with gauge	30		9
		Ⓜ	Ⓝ	Ⓞ
	Totals	301	Wait 180	36
	Total Operating Time	337	Ⓟ	

EXAMPLE:
Line Balance Analysis Chart

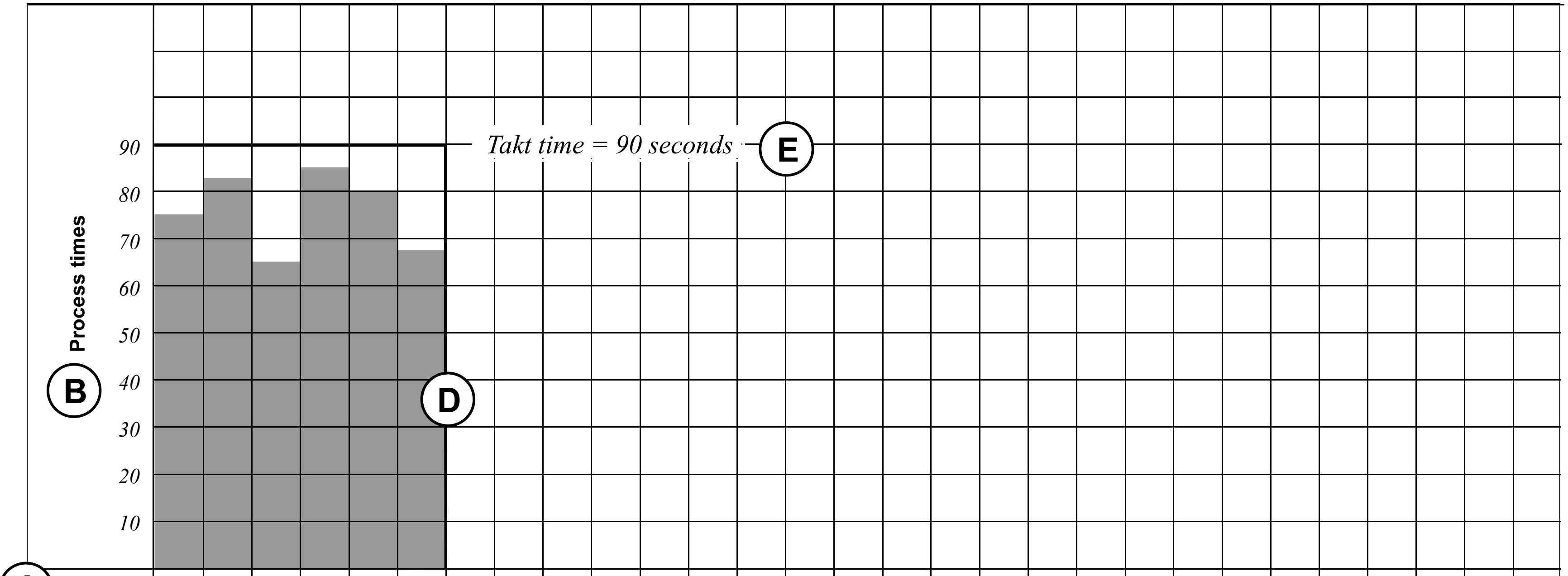
Product name: *Connector Assembly*	**Line name:** *Premier*	**By:** *D. Smith*	**Date:** *2/20/96*
Lot size: *10*	**Units/day:** *300*	**Operating time/day:** *450 minutes*	**Takt time:** *90 seconds*

Line balance loss =

100 – line balance efficiency = *100 – 84 = 16%*

Ⓕ **Line balance efficiency =**

$$\frac{\text{Total of process times}}{\text{Takt time X number of workers}} \text{ X 100} = \frac{455}{(90)\ (6)} \text{ X 100} = 84\%$$



Ⓐ **Time**	*75*	*82*	*65*	*85*	*80*	*68*
Ⓒ **Operation Name**	*Shear/ Punch*	*Slot*	*Clean/ Deburr*	*Ass'y*	*Paint/ Label*	*Package*
Ⓒ **NO**	*1*	*2*	*3*	*4*	*5*	*6*

The 5S Vision

A Workplace that is:

- Clean, organized, orderly
- Safe
- Efficient and pleasant
- The foundation for all other improvement activities

Resulting In:

- Fewer accidents
- Improved efficiency
- Improved quality
- Workplace control

And therefore:

- Reduced waste
- Reduced cost

5S

Sort – Sort through and Sort out

- Keep what is needed – Eliminate what is not
- Reduce quantity of items to what is needed

Set in Order – A place for everything and everything in its place

- Identify best location and relocate out-of-place items
- Make locations visually identified – easy to see missing items
- Set height, quantity, and size limits
- Organize for safety

Shine – Shine and Inspect through cleaning

- Filthy work environments lead to poor morale
- Spills and debris are safety hazards
- Its easier to identify a maintenance need on clean equipment

Standardize

- Build the framework for maintaining Sort, Set in Order, and Shine
- Clarity about what is and is not normal with simple action plans

Sustain

- Incorporate 5S into the daily work cycle

Pull systems for supply replenishment

- Material usage should be first-in-first-out (FIFO)
- Supply orders are triggered by *kanbans* (cards, empty bins, or other signals)
- The objective is to minimize stock-outs without keeping excessive supply quantities on hand

Kanban card for supply items

- An order is triggered when the minimum quantity is reached[*]

- A kanban card goes with the order, returns with the delivery

- The minimum quantity should represent what is needed to span the delivery cycle time

Item Name ____________________

Max. Quantity __________

Min. Quantity __________

Re-order Qty. __________ **(Max – Min)**

Vendor ______________________

Catalog Pg. No. ________

- The maximum quantity should represent a desired upper bound for supply quantity on hand

[*] What can cause this system to fail?

Example: two-bin kanban system

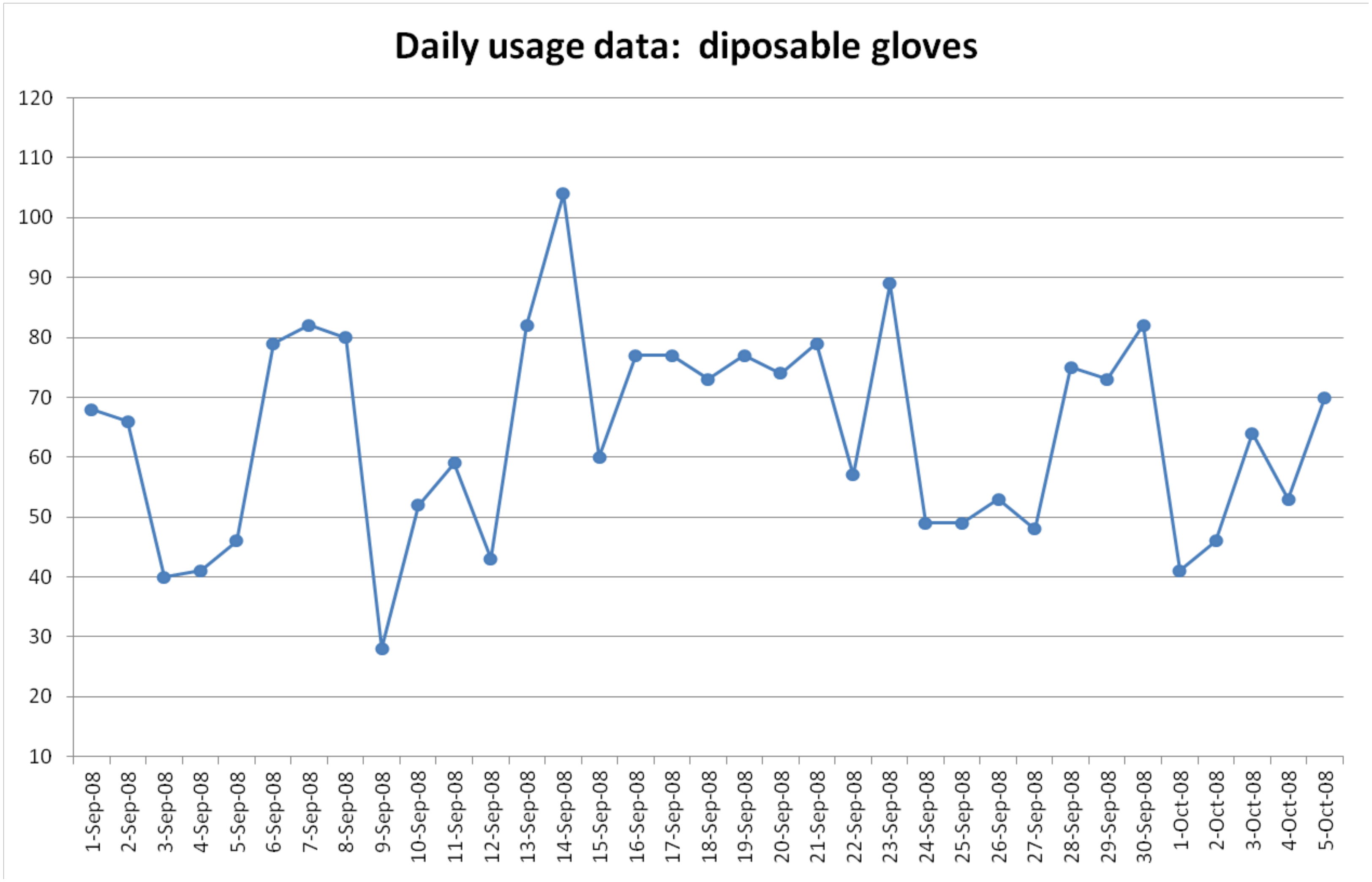
- Two bins for each item (see next slide)
- Amount in each bin = min. quantity = order quantity
- Order when top bin is empty, move bottom bin to top
- Visual system, easy to use
- The max and min quantities can be determined by trial and error
- If usage data is available, there is a better way

Two-bin system (cont'd)

Using data to set max/min values

- Required inputs
  - ✓ Time basis for usage data (hourly, each shift, daily, weekly, . . .)
  - ✓ Average usage per time period
  - ✓ Standard deviation of usage per time period
  - ✓ Minimum order quantity
  - ✓ Min. value (number of orders)
  - ✓ Max. value (number of orders)
- Values calculated in the simulation
  - ✓ Starting quantity for each period
  - ✓ Quantity received during each period
  - ✓ Quantity used during each period
  - ✓ Ending quantity for each period
  - ✓ Quantity ordered during each period

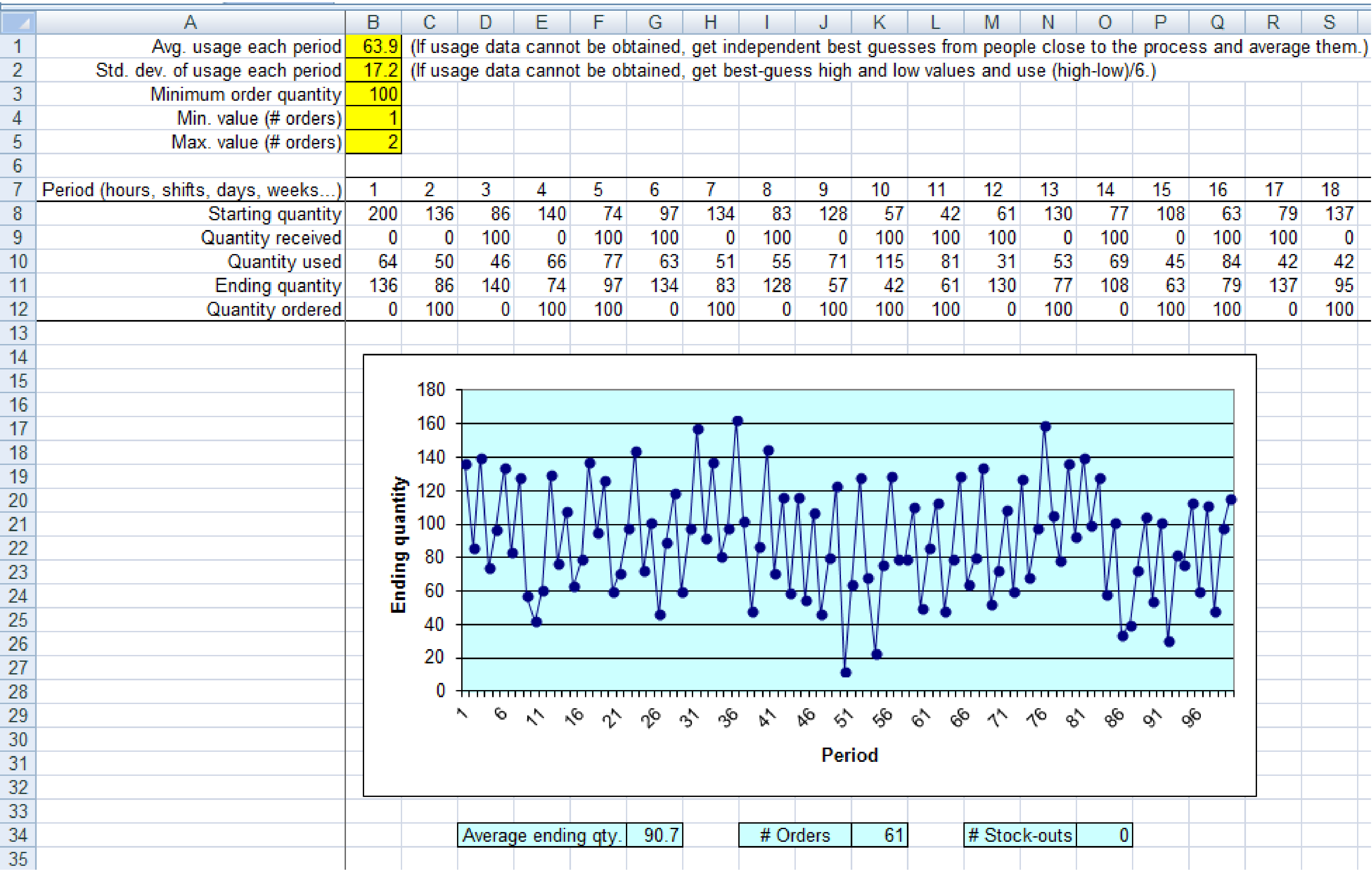
Setting max/min values (cont’d)



Average = 63.9

Std. dev. = 17.2

Setting max/min values (cont'd)



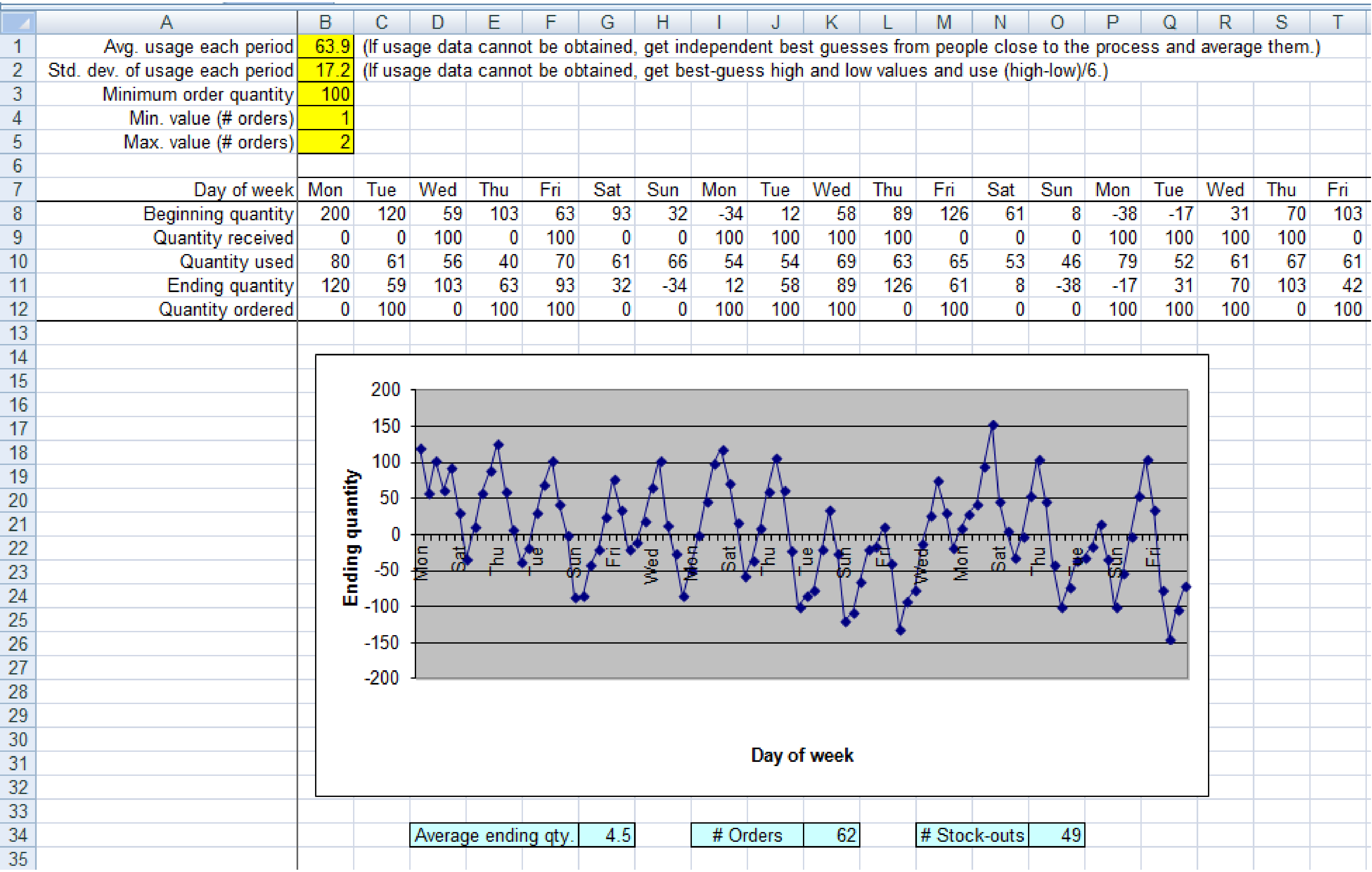
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Avg. usage each period	63.9	(If usage data cannot be obtained, get independent best guesses from people close to the process and average them.)																
2	Std. dev. of usage each period	17.2	(If usage data cannot be obtained, get best-guess high and low values and use (high-low)/6.)																
3	Minimum order quantity	100																	
4	Min. value (# orders)	1																	
5	Max. value (# orders)	2																	
6																			
7	Period (hours, shifts, days, weeks...)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
8	Starting quantity	200	136	86	140	74	97	134	83	128	57	42	61	130	77	108	63	79	137
9	Quantity received	0	0	100	0	100	100	0	100	0	100	100	100	0	100	0	100	100	0
10	Quantity used	64	50	46	66	77	63	51	55	71	115	81	31	53	69	45	84	42	42
11	Ending quantity	136	86	140	74	97	134	83	128	57	42	61	130	77	108	63	79	137	95
12	Quantity ordered	0	100	0	100	100	0	100	0	100	100	100	0	100	0	100	100	0	100

Average ending qty. 90.7

\# Orders 61

\# Stock-outs 0

Setting max/min values (cont'd)



Avg. usage each period	63.9
Std. dev. of usage each period	17.2
Minimum order quantity	100
Min. value (# orders)	1
Max. value (# orders)	2

(If usage data cannot be obtained, get independent best guesses from people close to the process and average them.)

(If usage data cannot be obtained, get best-guess high and low values and use (high-low)/6.)

Day of week	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri
Beginning quantity	200	120	59	103	63	93	32	-34	12	58	89	126	61	8	-38	-17	31	70	103
Quantity received	0	0	100	0	100	0	0	100	100	100	100	0	0	0	100	100	100	100	0
Quantity used	80	61	56	40	70	61	66	54	54	69	63	65	53	46	79	52	61	67	61
Ending quantity	120	59	103	63	93	32	-34	12	58	89	126	61	8	-38	-17	31	70	103	42
Quantity ordered	0	100	0	100	100	0	0	100	100	100	0	100	0	0	100	100	100	0	100

Average ending qty.	4.5	# Orders	62	# Stock-outs	49

Mistake-proofing (Poke Yoke) examples

- Designing connecting cables and ports so that a cable cannot be plugged into the wrong port
- Programming software so that the user cannot proceed unless necessary information is filled in
- Auto fill of previously entered information on electronic forms
- Pull down menus in computer programs — especially for data entry
- Using feedback control systems and alarms on equipment
- Fixturing to prevent incorrect placement and hold things in place

Reduce batch sizes (keep the work moving)

Don't do things in batches.
The ideal is to do one thing at a time.
Come as close to this as you can.

- Wait a minute — batching is supposed to be "efficient"
- Maybe, but here are some problems with batching:
  - ✓ A customer who wants just one item has to wait for a whole batch to be completed
  - ✓ Reduces flexibility in building different products.
  - ✓ Items accumulate until the batch quantity is reached — wastes space, creates opportunities for defects

Reduce batch sizes (cont'd)

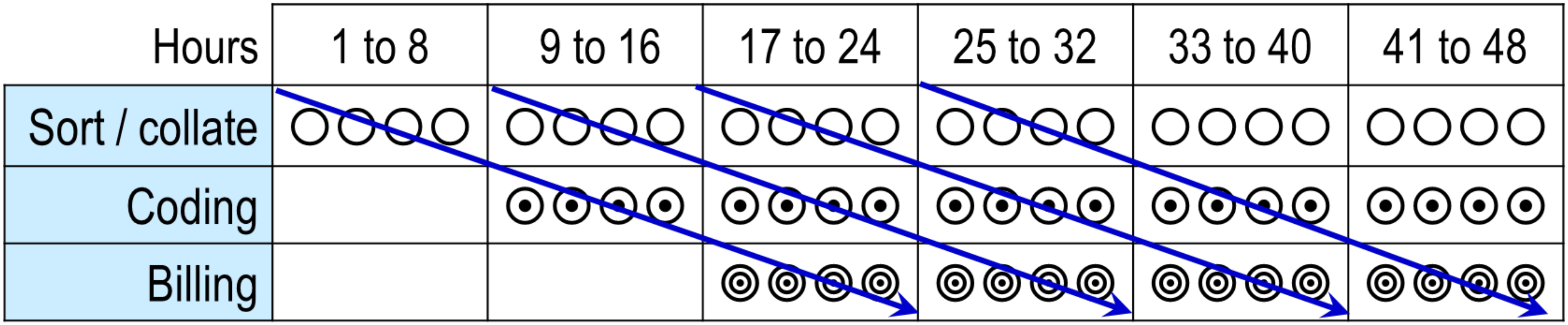
Of course, there can be a legitimate problem with reducing batch sizes: it increases the number of changeovers.

Fortunately, this is a problem for which Lean has excellent solutions. Lean projects have reduced changeover times by 80% or more.

Current state: daily batching

3 operations

2 hours per transaction per operation



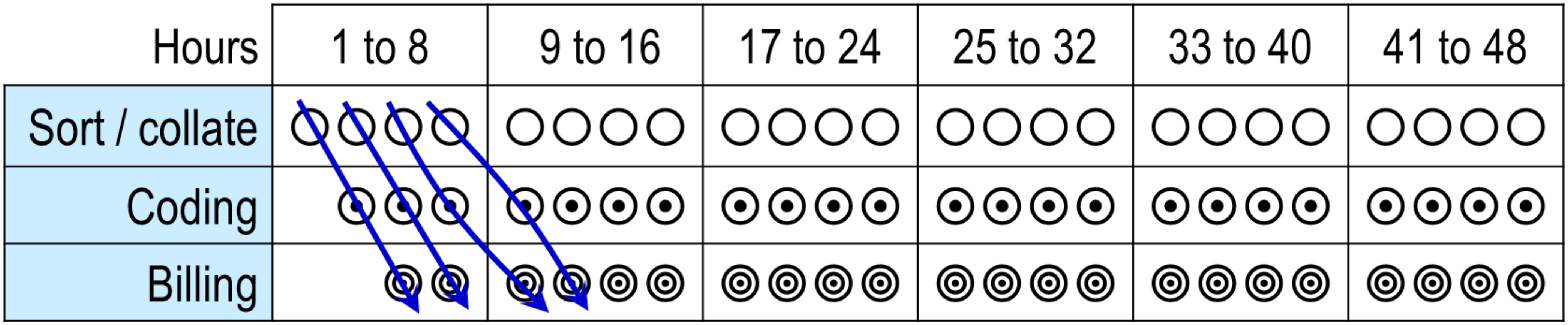
Hours	1 to 8	9 to 16	17 to 24	25 to 32	33 to 40	41 to 48
Sort / collate	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Coding		⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙
Billing			◎◎◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎

Lead time = 24 hours (3 days)

Future state: continuous flow

3 operations

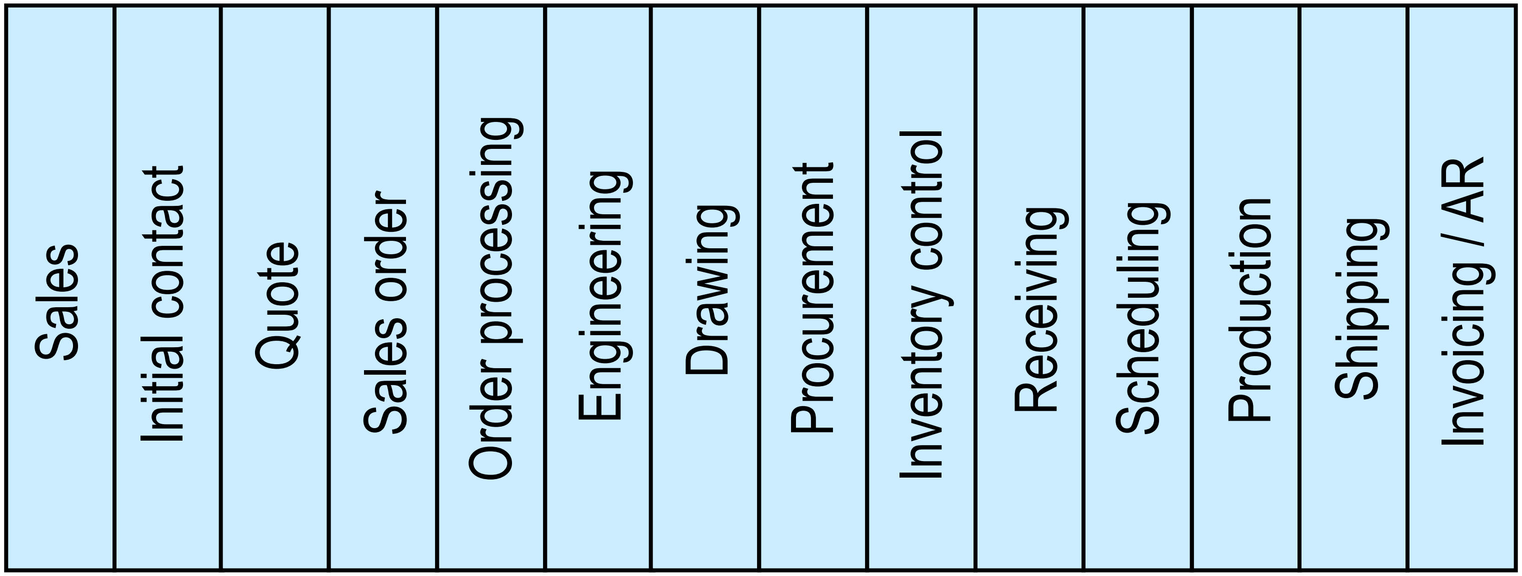
2 hours per transaction per operation



Hours	1 to 8	9 to 16	17 to 24	25 to 32	33 to 40	41 to 48
Sort / collate	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Coding	⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙	⊙⊙⊙⊙
Billing	◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎	◎◎◎◎

Lead time = 6 hours (less than one day)

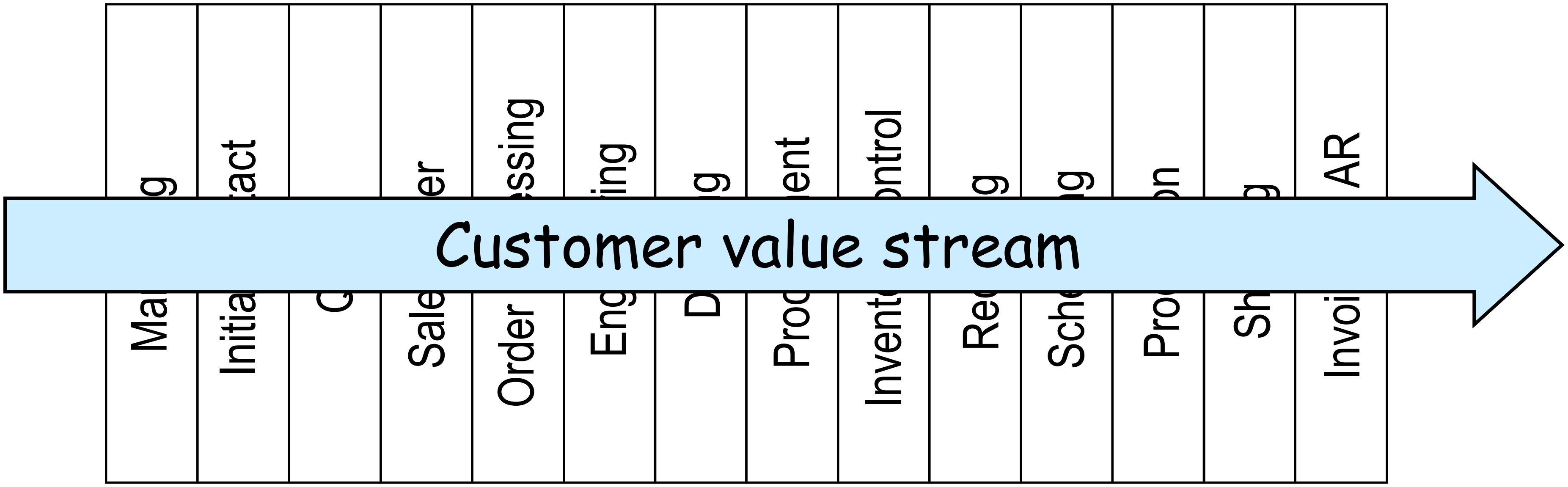
Organizing by value stream



Sales
Initial contact
Quote
Sales order
Order processing
Engineering
Drawing
Procurement
Inventory control
Receiving
Scheduling
Production
Shipping
Invoicing / AR

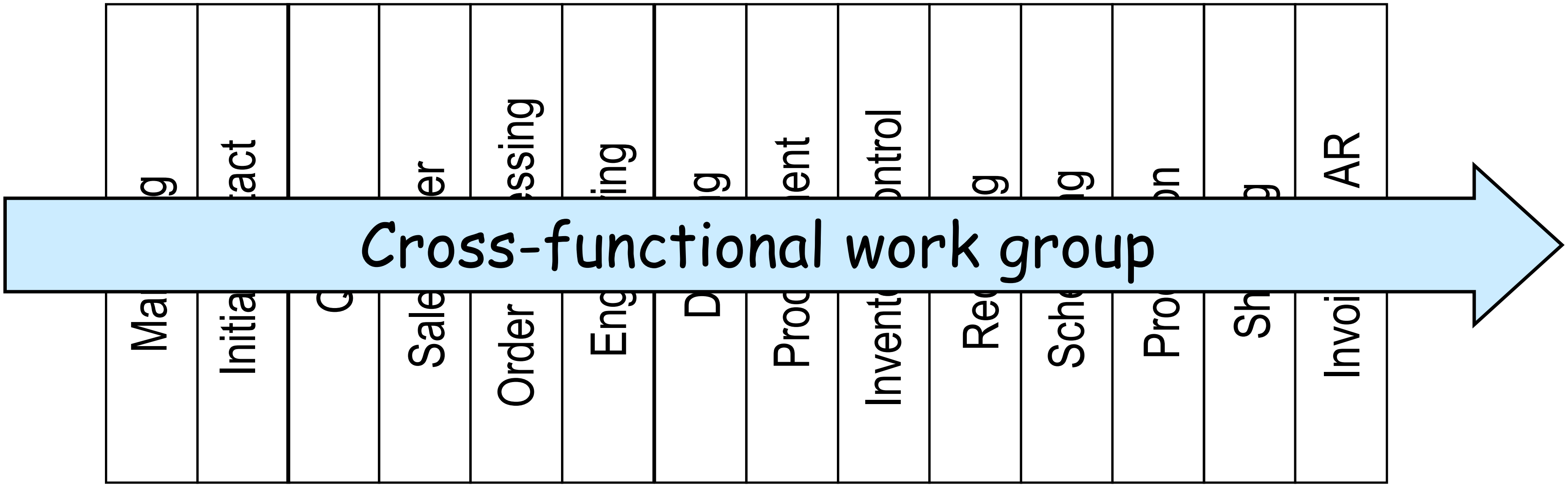
- Departmental boundaries create “silos”
- Vestige of industrial revolution — need for specialization
- Silos are “islands” of responsibility
- Hand offs between silos are opportunities for poor communication and lack of coordination

Organizing by value stream (cont'd)



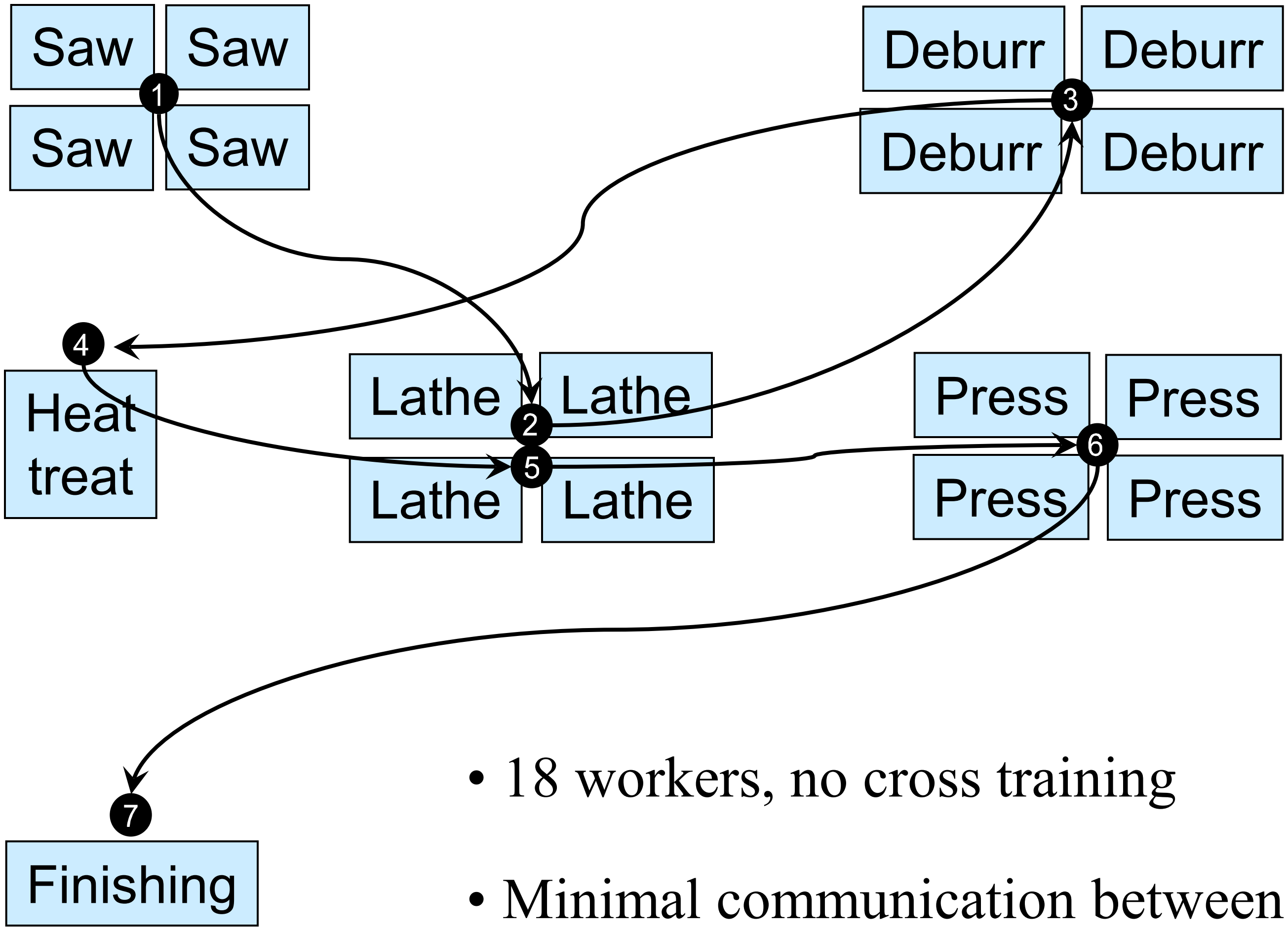
- Customer value stream spans all silos
- Often, no single entity has overall responsibility for customer satisfaction

Organizing by value stream (cont'd)



- Responsible for entire value stream for a product/service "family"
- Physical co–location is ideal
- Alternative: "value stream team"
- Stand-up meetings: every day, shift, or other frequent interval
- Alternative: virtual meetings

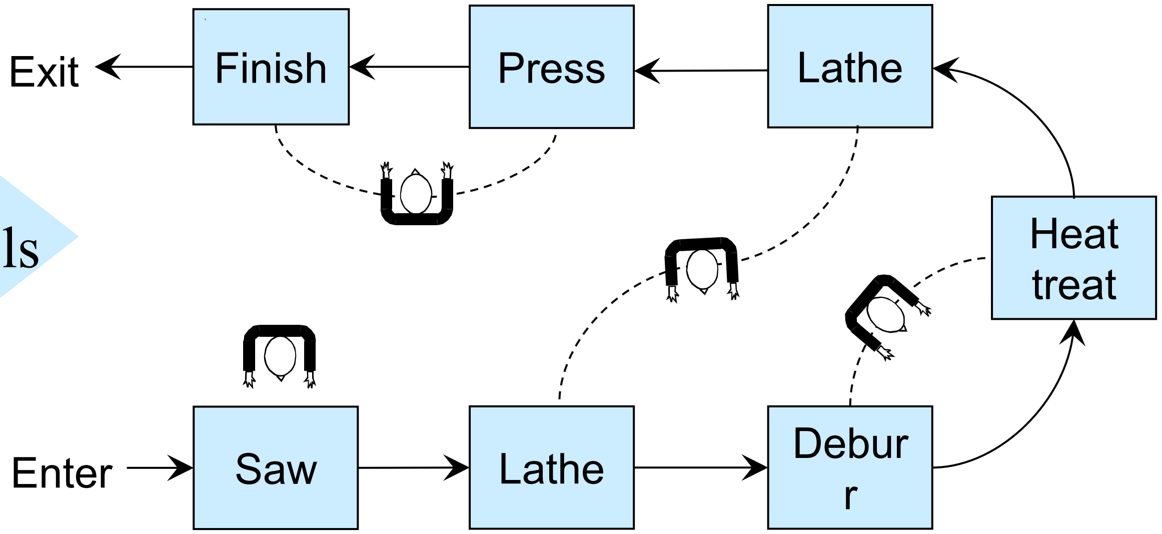
Manufacturing operation in silos



- 18 workers, no cross training
- Minimal communication between silos
- Each silo handles all products
- Silos produce as much as possible, all the time (push system)
- WIP moves between silos in large batches → long lead time

Manufacturing operation in U-shaped work cells*

One of 4 cells



Exit

Finish

Press

Lathe

Heat treat

Enter

Saw

Lathe

Debur
r

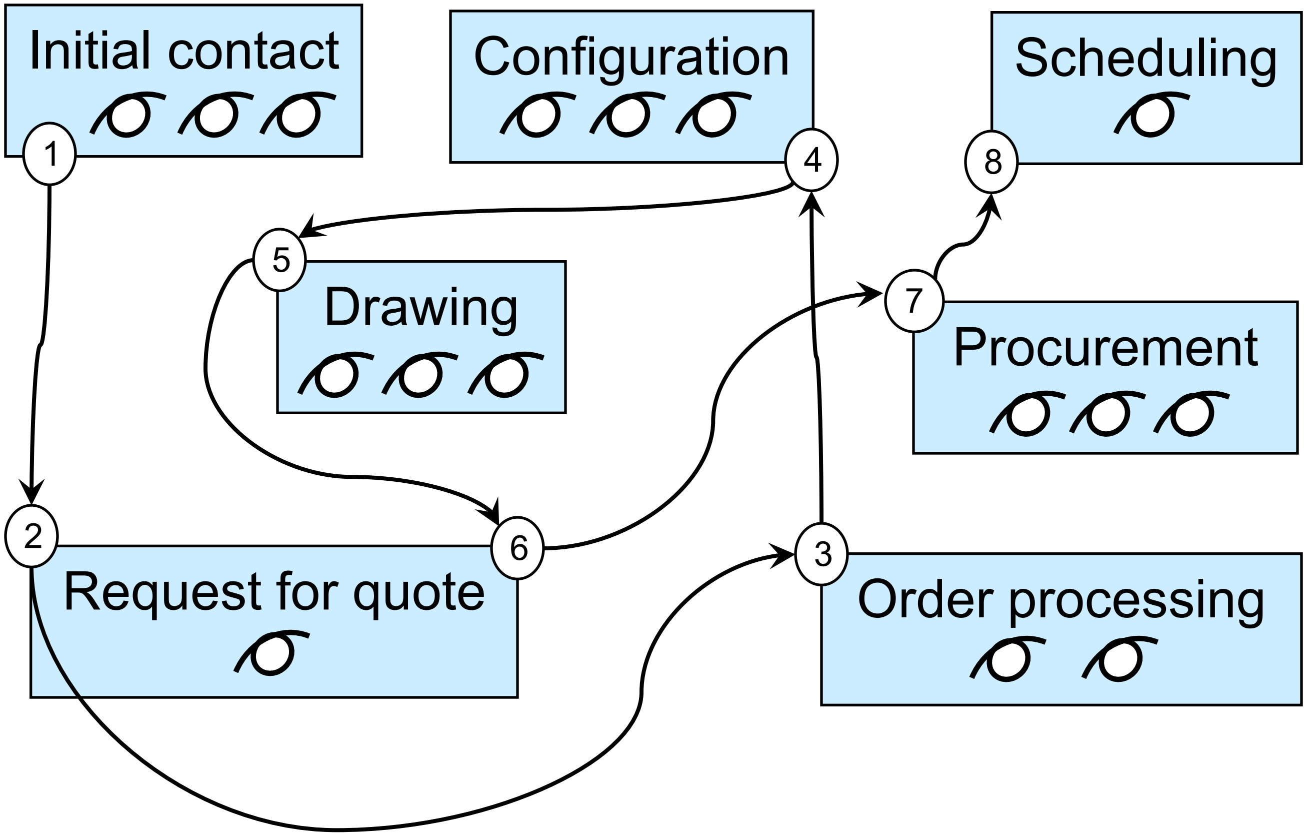
"Right size"
equipment for
each cell

- Each cell handles all operations for one product family, and produces just what is needed to meet current demand (pull system)
- Continuous flow → minimal WIP → short lead time
- Rapid response to workflow or quality problems
- 16 workers instead of 18 — what happened to the other 2?

---

*Physical co-location is not always possible in process industries, where equipment determines capacity and is difficult or impossible to relocate. See **Lean for the Process Industries** by Peter King for ideas on how to apply Lean in this situation.

Transactional process in silos



Initial contact σσσ

Configuration σσσ

Scheduling σ

Drawing σσσ

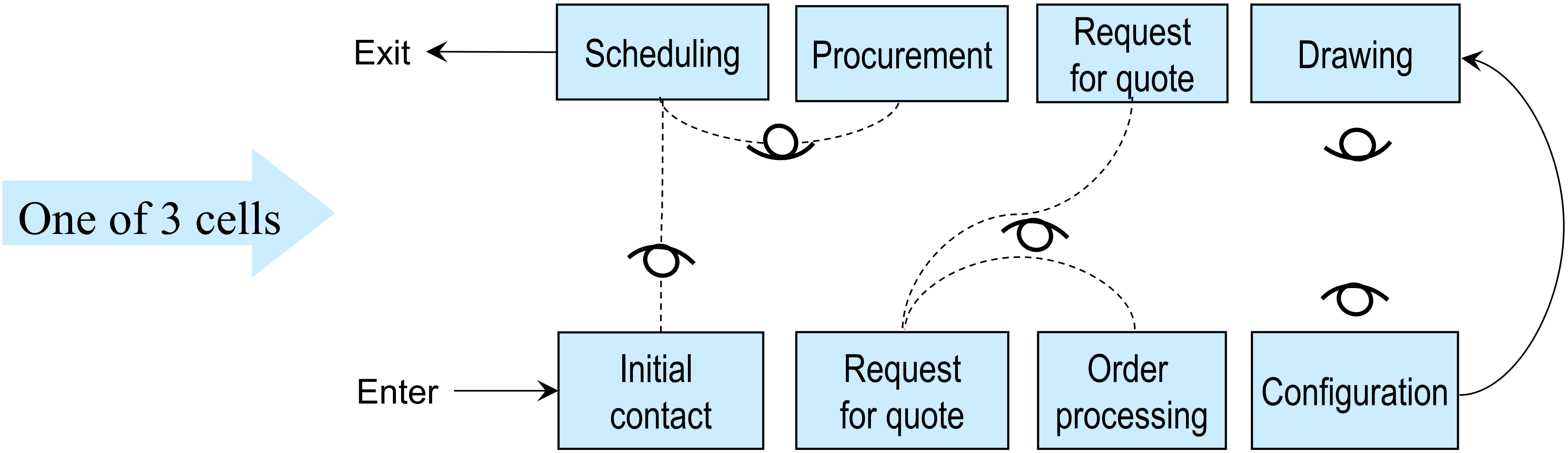
Procurement σσσ

Request for quote σ

Order processing σ σ

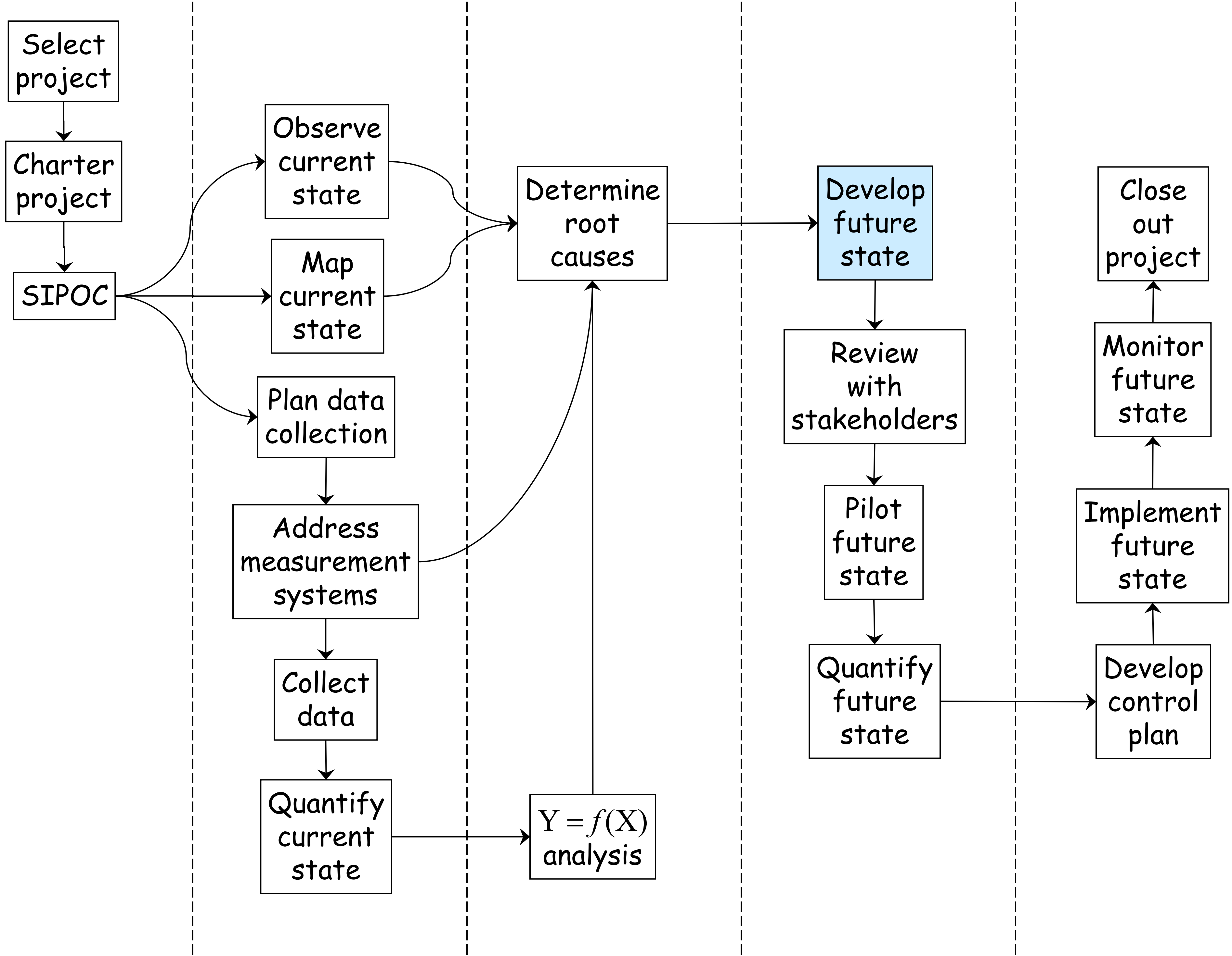
- 16 workers (σ), no cross training
- Each silo handles all transactions
- Minimal communication between silos
- Lots of do overs (not shown in diagram)
- Lots of WIP → long turnaround time

Transactional process in U-shaped work cells


One of 3 cells

- Each cell handles all steps for one transaction family
- Continuous flow → minimal WIP→ short turnaround time
- Rapid response to errors or workflow problems
- 15 workers instead of 16 — what happened to the other one?

18 Theory of Constraints (TOC)



Select project

Charter project

SIPOC

Observe current state

Map current state

Plan data collection

Address measurement systems

Collect data

Quantify current state

Determine root causes

$Y = f(X)$ analysis

Develop future state

Review with stakeholders

Pilot future state

Quantify future state

Develop control plan

Implement future state

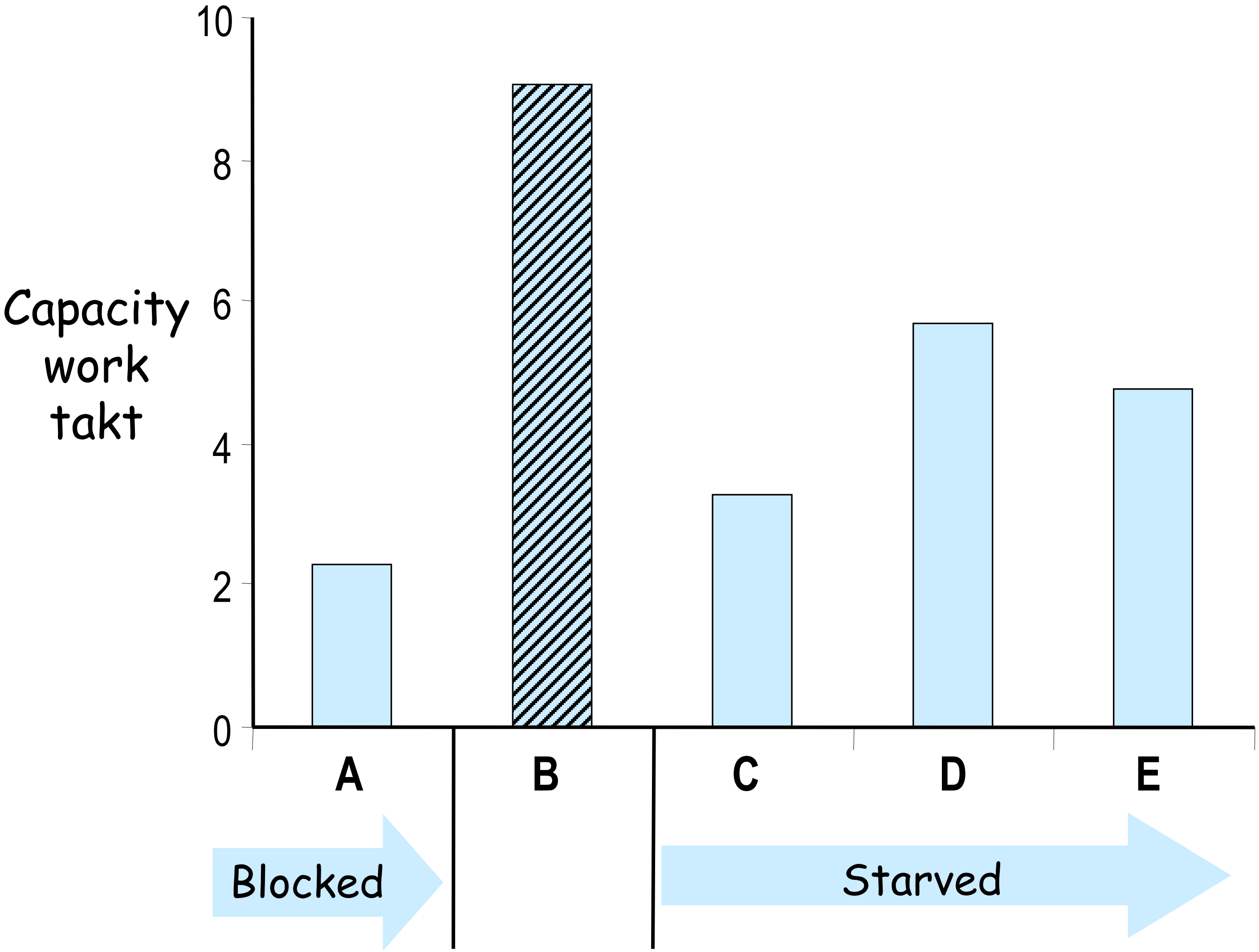
Monitor future state

Close out project

TOC (cont’d)

What if cross training is not feasible?

What if the bottleneck is machine capacity?



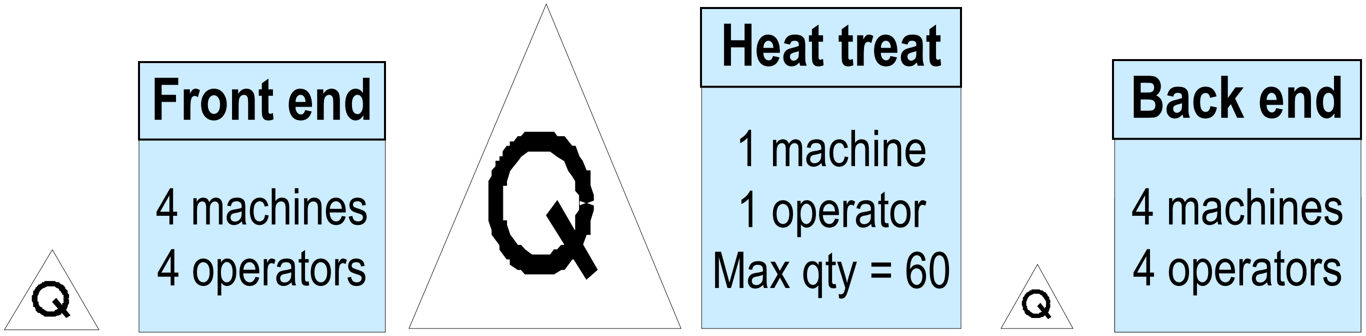
TOC (cont'd)

TOC improvement cycle	Lean terminology
1. *Identify* the system constraint (the "drum")	Find the bottleneck ("pacemaker")
2. *Exploit* the identified constraint (includes establishing the "buffer")	• Move resources to the bottleneck • Minimize NVA at the bottleneck • Maintain needed level of "safety" WIP
3. *Subordinate* everything else to the constraint (establish the "rope")	Pull system synchronized with the takt time of the bottleneck
4. *Elevate* the constraint	Add enough resources to eliminate the bottleneck
5. Return to step #1	Find the new bottleneck, repeat same steps

Ways to identify the constraint

- Greatest WIP
- Longest cycle time
- Longest process time
- Highest % utilization

Example: current state



Front end

4 machines
4 operators

Heat treat

1 machine
1 operator
Max qty = 60

Back end

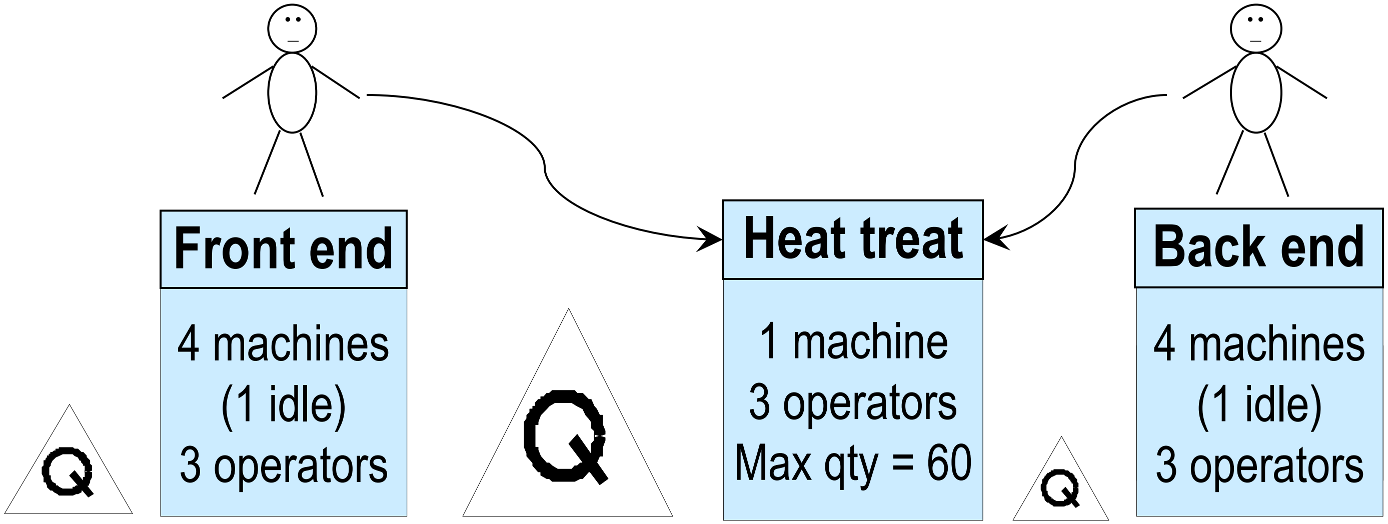
4 machines
4 operators

Lead time				120 mins		
“process” time	0	4 min	0	90 mins (load change = 30 mins)	0	4 min
Cycle time		4 mins/4 pcs = 1 min		120/60 = 2 mins		4 mins/4 pcs = 1 min
Constrained cycle time		1 min		2 mins		2 mins

Blocked

Starved

Future state #1: reallocate resources



Front end

4 machines
(1 idle)
3 operators

Heat treat

1 machine
3 operators
Max qty = 60

Back end

4 machines
(1 idle)
3 operators

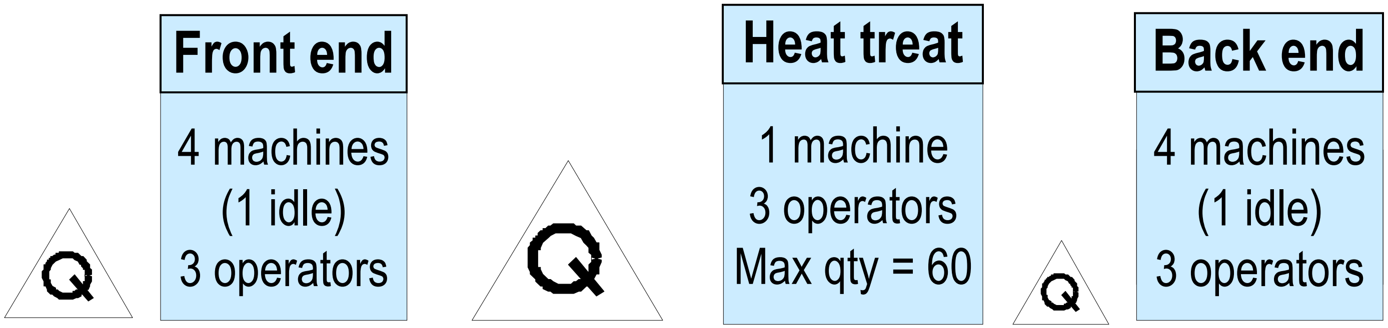
Lead time				100 mins		
"process" time	0	4 min	0	90 mins (load change = 10 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		100/60 = 1.67 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.33 mins		1.67 mins		1.67 mins

Less over-production

Less WIP

Faster load change

Future state #2: improve load change process



Front end

4 machines
(1 idle)
3 operators

Heat treat

1 machine
3 operators
Max qty = 60

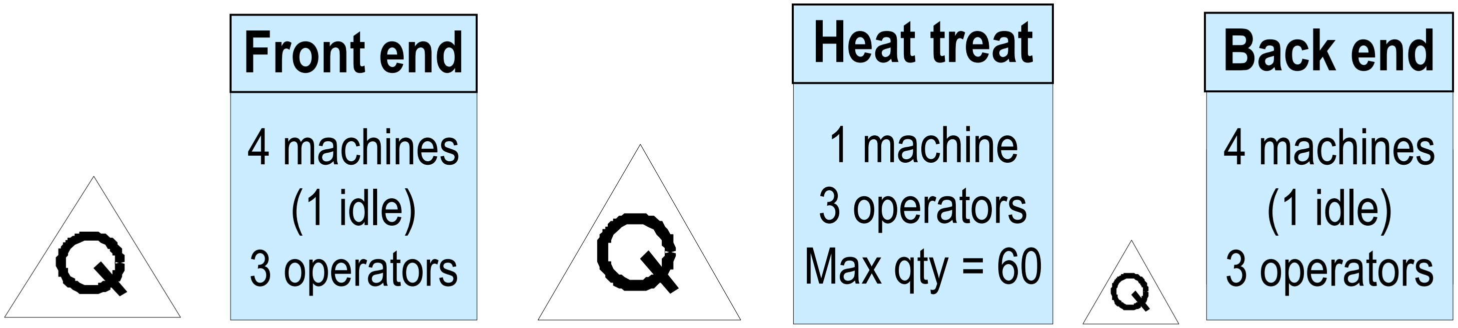
Back end

4 machines
(1 idle)
3 operators

Lead time				95 mins		
“process” time	0	4 min	0	90 mins (load change = 5 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		95/60 = 1.58 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.33 mins		1.58 mins		1.58 mins

Even faster
load change

Future state #3: pull system in front end



Front end

4 machines
(1 idle)
3 operators

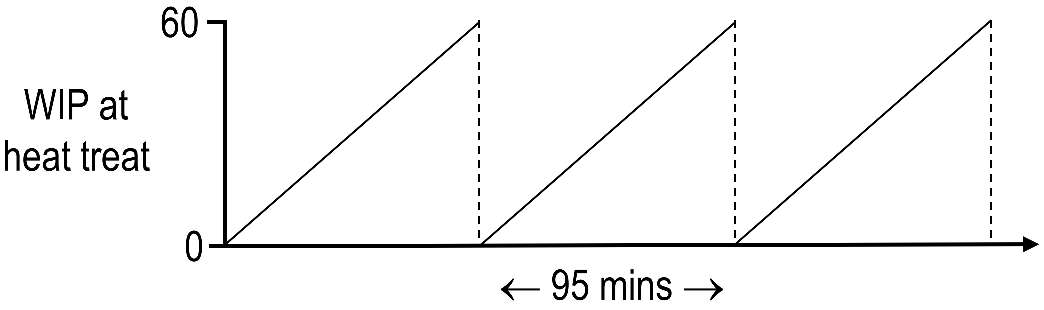
Heat treat

1 machine
3 operators
Max qty = 60

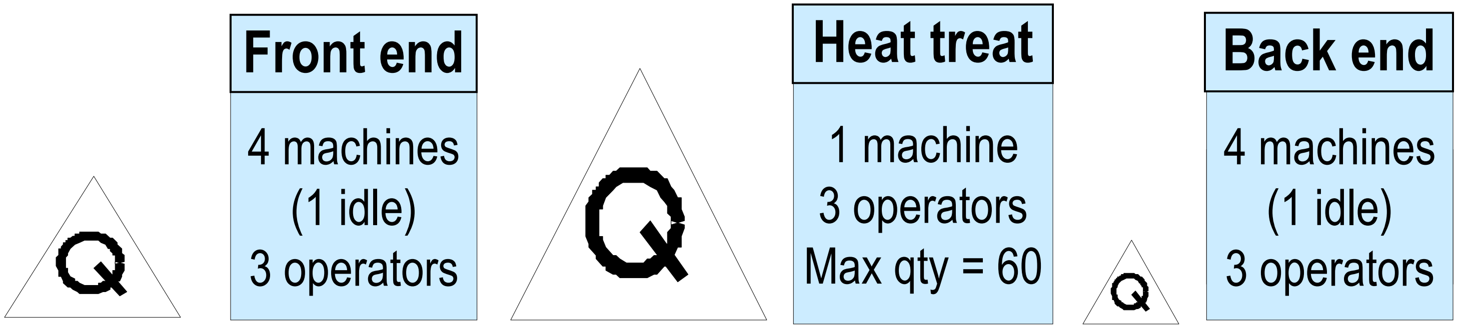
Back end

4 machines
(1 idle)
3 operators

Lead time				95 mins		
“process” time	0	4 min	0	90 mins (load change = 5 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		95/60 = 1.58 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.58 mins		1.58 mins		1.58 mins



Future state #4: establish and maintain safety WIP



Front end

4 machines
(1 idle)
3 operators

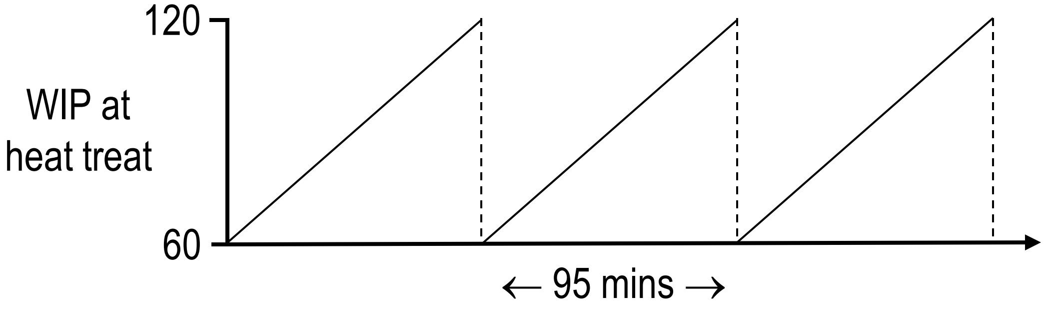
Heat treat

1 machine
3 operators
Max qty = 60

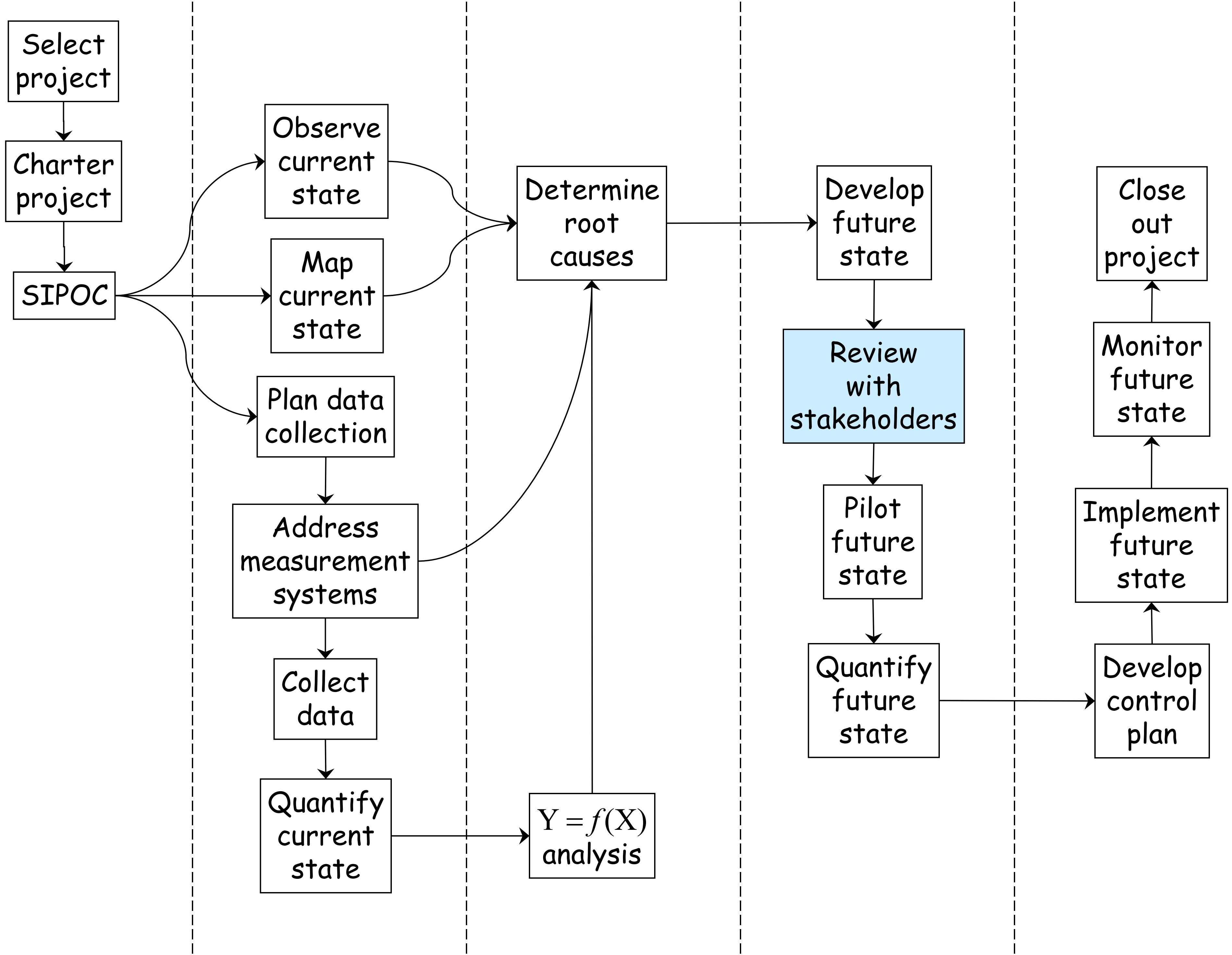
Back end

4 machines
(1 idle)
3 operators

Lead time				95 mins		
“process” time	0	4 min	0	90 mins (load change = 5 mins)	0	4 min
Cycle time		4 mins/3 pcs = 1.33 mins		95/60 = 1.58 mins		4 mins/3 pcs = 1.33 mins
Constrained cycle time		1.58 mins		1.58 mins		1.58 mins



19 Reviewing the Proposed Future State



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$Y = f(X)$ analysis

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Quantify future state

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Implement future state

Monitor future state

Close out project

Reviewing the Future State

- Use *Failure Modes and Effects Analysis* to identify problems (failure modes) that could occur in your new process and their impact (effects)
- Put things in place in the new process, to prevent or mitigate these failure modes, before they happen
- After you develop your proposed future state, the next step is to review it with stakeholders
    - Give them an opportunity to voice concerns or suggest enhancements prior to piloting
    - This can be an informal process of presentation and discussion

FMEA: Design vs. Process

- *Principles and steps are the same*
  - *Purpose and objectives differ*
- *Rating scale definitions will differ*

Design

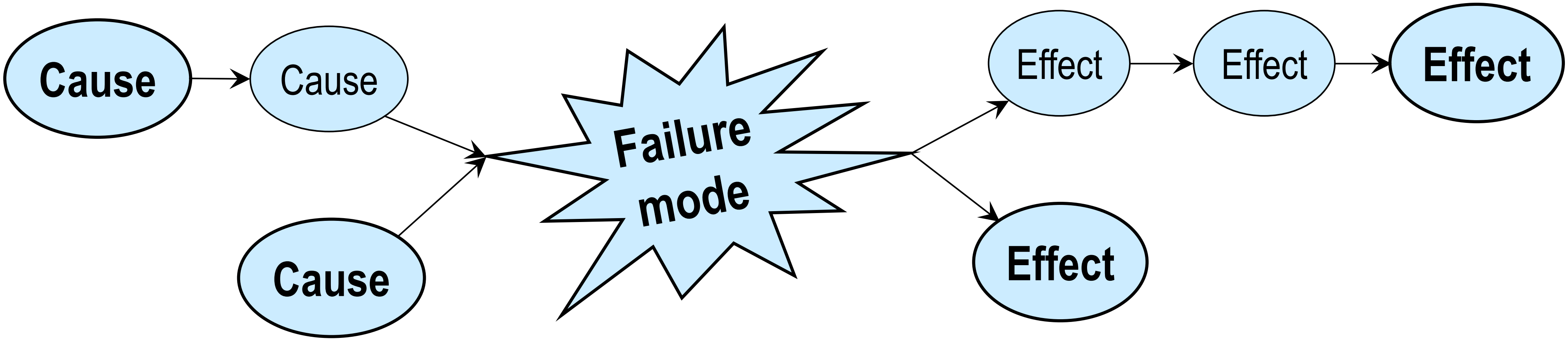
✓ Discover potential problems with the design of the product that will result in safety concerns, malfunctions, or shortened life

Process

✓ Discover potential problems related to the manufacture of the product that will affect the product, safety, or processing efficiency

Failure Modes & Effects Analysis (FMEA)

1. Identify potential failure modes before deploying a new product, service, or process



3. Identify and prioritize root causes of potential failure modes

2. Identify and evaluate ultimate effects of potential failure modes

4. Identify and take corrective actions to eliminate or reduce the occurrence of root causes

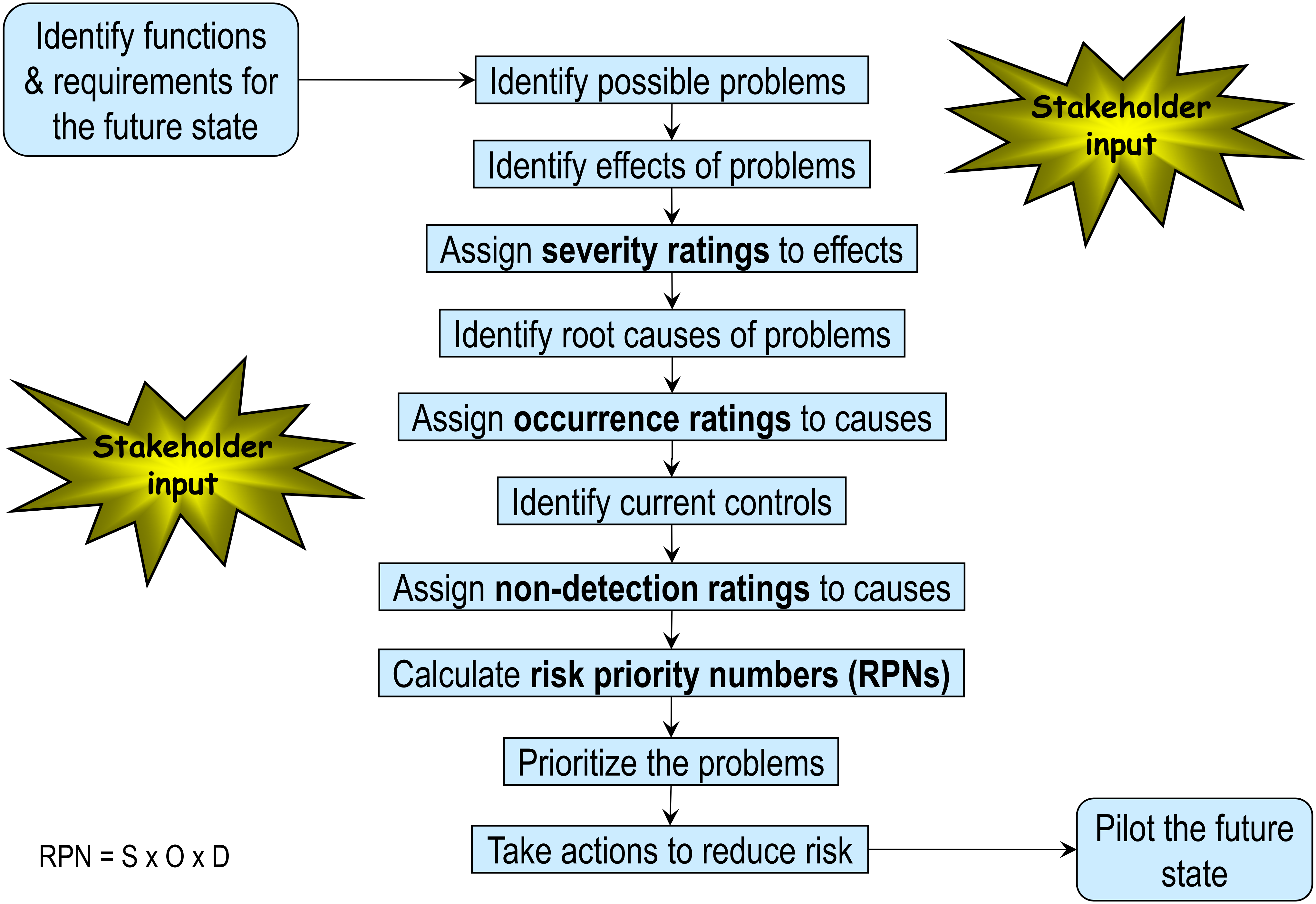
The role of FMEA in a LSS project

- Identify and prioritize stakeholder concerns with the proposed future state

- Take appropriate corrective action prior to piloting the future state

- Use results to strengthen the control plan for the future state

Detailed FMEA process



Identify functions & requirements for the future state

Identify possible problems

Identify effects of problems

Assign **severity ratings** to effects

Identify root causes of problems

Assign **occurrence ratings** to causes

Identify current controls

Assign **non-detection ratings** to causes

Calculate **risk priority numbers (RPNs)**

Prioritize the problems

Take actions to reduce risk

Pilot the future state

RPN = S x O x D

Example of a Severity rating

Level		*Description*
10	Hazardous, no warning	May endanger machine or assembly operator. Failure causes unsafe product operation or noncompliance with government regulation. Failure will occur without warning.
9	Hazardous, warning	May endanger machine or assembly operator. Failure causes unsafe product operation or noncompliance with government regulation. Failure will occur with warning.
8	Very high	Major disruption to production line. 100% of product may have to be scrapped. Product is inoperable with loss of Primary Function.
7	High	Minor disruption to production line. Product may have to be sorted and a portion scrapped. Product is operable but at a reduced level of performance.
6	Moderate	Minor disruption to production line. A portion of the product may have to be scrapped (no sorting). Product is operable but comfort or convenience item(s) are inoperable.
5	Low	Minor disruption to production line. 100% of the product may have to be reworked. Product is operable but comfort or convenience item(s) operate at a reduced level of performance.
4	Very low	Minor disruption to production line. Product may have to be sorted and a portion reworked. Fit/finish or squeak/rattle item does not conform. Most customers notice defect.
3	Minor	Minor disruption to production line. Some product may require rework on-line but out-of-station. Fit/finish or squeak/rattle item does not conform. Average customers notice defect.
2	Very minor	Minor disruption to production line. Some product may require rework on-line but in-station. Fit/finish or squeak/rattle item does not conform. Discriminating customers notice defect.
1	None	No effect.

Example of an Occurrence rating

Level		*Description*	*Failure Rate*
10	Very high	Failure is almost inevitable.	≥□ 1 in 2
9			1 in 3
8	High	Generally associated with processes similar to previous processes that have often failed.	1 in 8
7			1 in 20
6	Moderate	Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions.	1 in 80
5			1 in 400
4			1 in 2000
3	Low	Isolated failures associated with similar processes.	1 in 15,000
2	Very low	Only isolated failures associated with almost identical processes.	1 in 150,000
1	Remote	Failure is unlikely. No failures ever associated with almost identical processes.	≤ 1 in 1,500,000

Example of a Detection rating

Level		*Description*
10	Almost impossible	No known controls available to detect failure mode or cause.
9	Very remote	Very remote likelihood current controls will detect failure mode or cause.
8	Remote	Remote likelihood current controls will detect failure mode or cause.
7	Very low	Very low likelihood current controls will detect failure mode or cause.
6	Low	Low likelihood current controls will detect failure mode or cause.
5	Moderate	Moderate likelihood current controls will detect failure mode or cause.
4	Moderately high	Moderately high likelihood current controls will detect failure mode or cause.
3	High	High likelihood current controls will detect failure mode or cause.
2	Very high	Very high likelihood current controls will detect failure mode or cause.
1	Almost certain	Current controls almost certain to detect failure mode or cause. Reliable detection controls are known with similar processes.

FMEA ratings

- The previous three slides give examples of traditional 1–10 ratings for severity, occurrence, and non–detection

- Note the detailed quantitative operational definitions

- Customers or regulatory agencies may require this level of detail

- For the application to LSS projects, qualitative 1–5 ratings are often sufficient:

1. Very low
2. Low
3. Moderate
4. High
5. Very high

PFMEA Example

Process Functions	Requirements	Failure Modes	Effects	SEV	Causes	OCC	CN	Current Controls	DET	RPN	Actions Planned	Responsible	Due Date	Actions Taken
Reagent lot creation	New lot information distributed to OPS team	Printer malfunction	Delay in distribution to the OPS team	1	Electrical	1	**1**	One printer	1	**1**				
Reagent creation	New reagent created based on processing demand	Operator error during manufacture of reagent	Processing delay, wasted sub-reagents, time lost, labor money	5	Did not use trained witness	1	**5**	SOP requires trained witness for procedure	1	**5**				
Reagent storage	Storage of new reagent at point of use (laboratory)	Insufficent storage space in freezer or fridge	Reagent stock-out	4	Freezer space not reconciled	5	**20**	No control.	5	**100**				
Material storage	Stocking of materials and reagents in designated location within the functional laboratory	Insufficient shelf space for materials.	Material stock-out	3	Too many items on shelving	3	**9**	Shelving units with four shelves	5	**45**				
		Staff is unclear where material items should be stored	Materials not stocked in designated location within the functional area	2	Insufficent labeling system to designate material and reagent locations	3	**6**	Labels on shelving only	3	**18**				
Material Distribution	Distribution of materials based on MIN/MAX forecasting	MIN/MAX values not accurate	Material shortage	2	Forecasting not accurate	3	**6**	Master Science Forecasting	5	**30**				

Project example

Problem statement

Operations staff within the Gene Expression Lab (GEL) are experiencing frequent material stock outs while performing procedures. They have to stop processing samples until the missing material is delivered. This increases process cycle time and reduces the quality of the data deliverables. Other labs directly affected by this problem are:

- ✓ Tissue Homogenization
- ✓ Experiment Processing
- ✓ Sample Processing

Goal statement

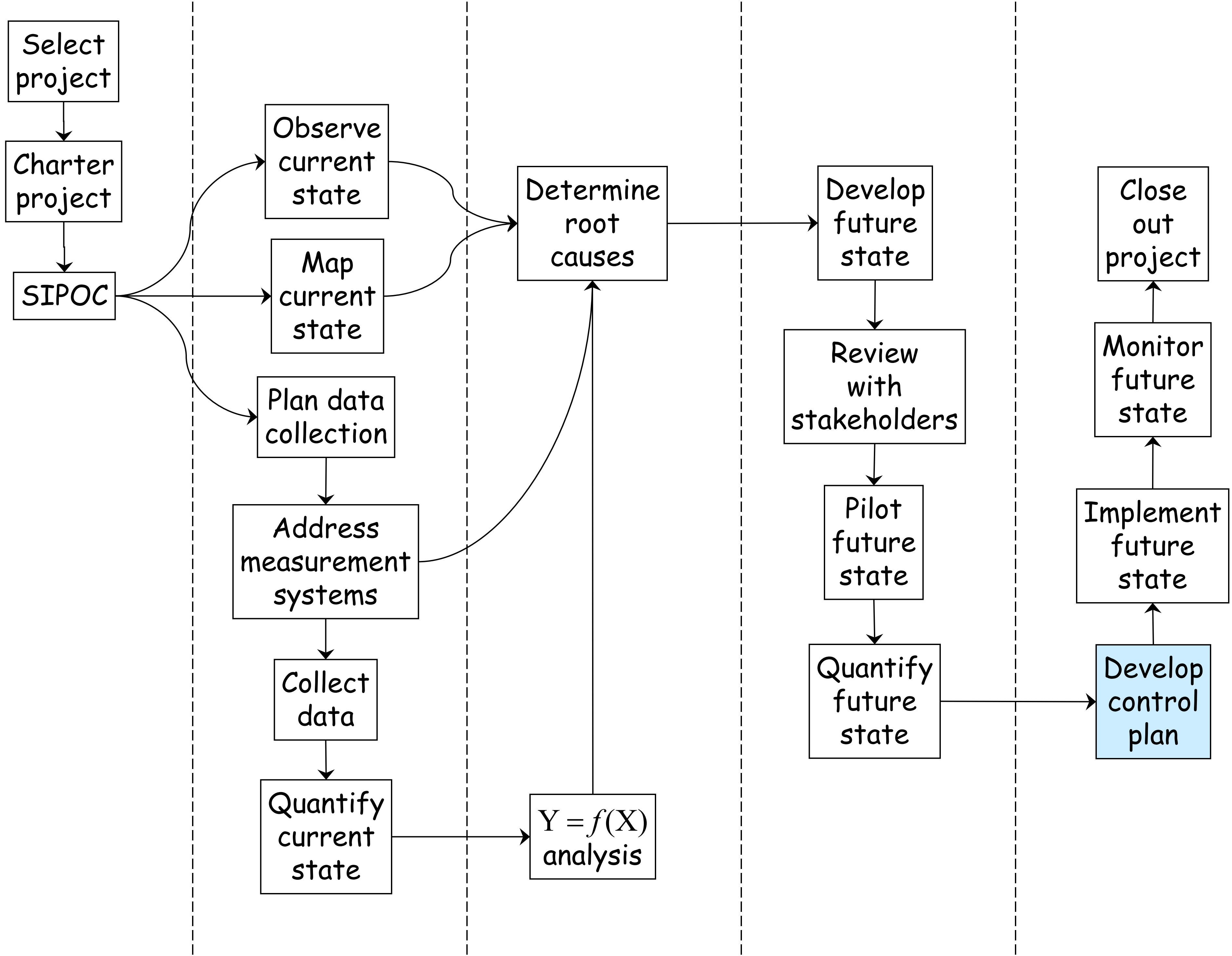
- Reduce frequency of stock outs by 50%.
- Reduce time lost due to stock outs by 50%.

Constraint

No increase in labor cost.

Control Phase

20 Control Plan



What is a control plan?

- A summary of the plan to sustain the gains from a LSS project
- The project team helps the in–scope process owner and participants develop the plan
- Project team advises the in–scope process owner and participants on statistical monitoring issues
- Most common control methods: training, auditing, control chart
- Most common control chart quantities: *individual measurements*, *averages*, and *percentages*

Student Files → blank control plan

Process name:

Process owner:

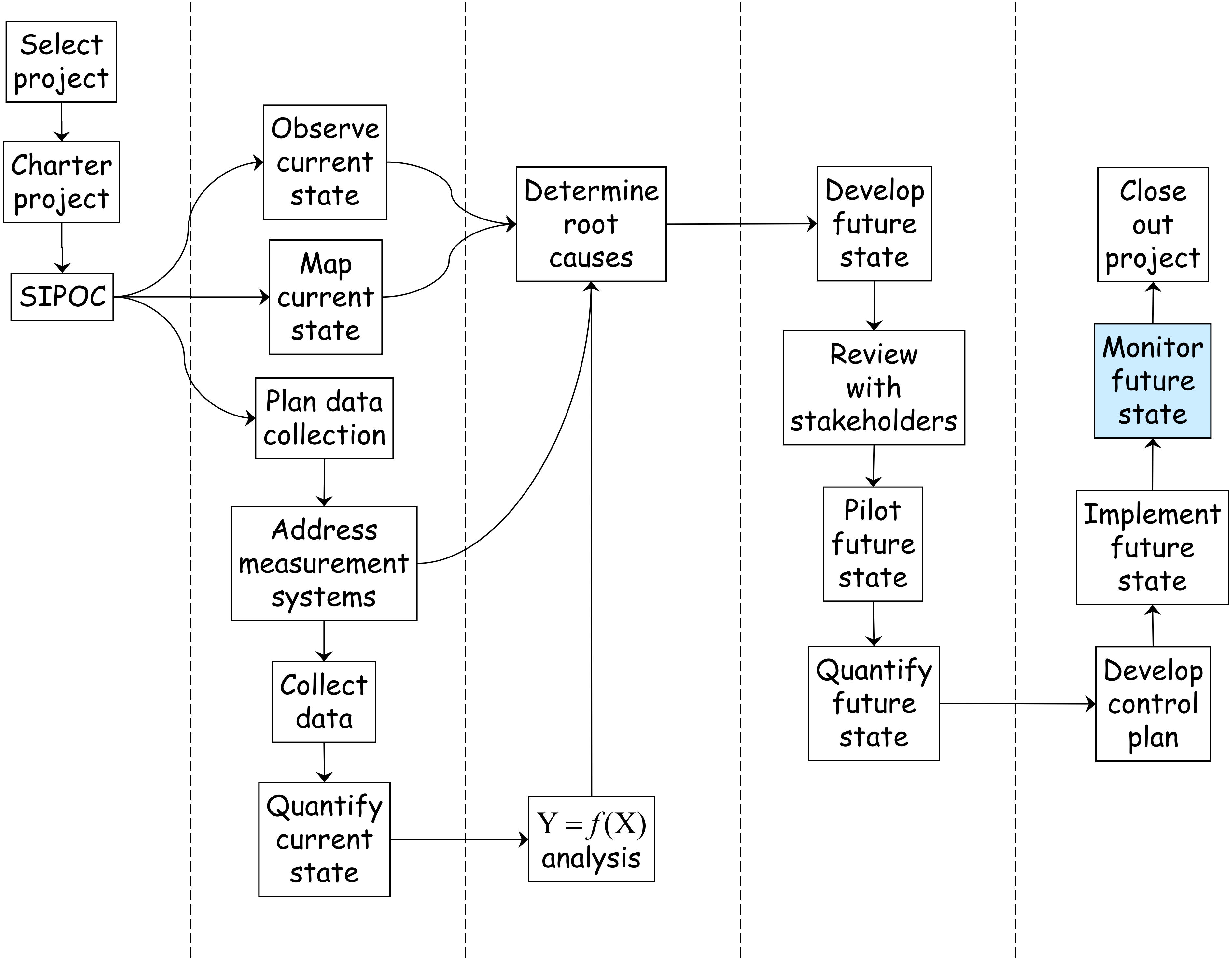
Revision date:

Process step	Control method	Frequency	Data variable	Meas. system	Metric to monitor	Control limits		Response plan owner	Response plan location
						Lower	Upper		

Student Files → tool development control plan

Process name:	Tool Testing Process
Process owner:	Testing Area Manager
Revision date:	

Process step	**Control method**	**Frequency**	**Data variable**	**Meas. system**	**Metric to monitor**	**Control limits**		**Response plan owner**	**Response plan location**
						Lower	**Upper**		
Determine run conditions	Audit compliance with new procedure requiring special approval to change weight or line speed	Monthly, then Quarterly	Run conditions						
Determine run conditions	Disable weight and line speed controls on test line								
Release to manufacturing	Control chart	Weekly	Number of days in testing	Database	Average		TBD	Testing area manager	TBD
Release to manufacturing	Control chart	Weekly	Number of rework cycles	Database	Average		TBD	Testing area manager	TBD
Dimensional inspection	Install DVT gage and train testers to use it								
Dimensional inspection	Periodic gage R&R	TBD	Spec dimensions	DVT	% of Tolerance		TBD	Testing Engineer	TBD



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Statistical monitoring*

- Two kinds of variation
- Quantifying common cause variation
- Establishing control limits
- Commonly used control charts
- Interpreting control charts
- Response plans
- Relationship to Process Capability

*The more commonly used term is Statistical Process Control (SPC), even though it has nothing to do with "control" in the usual sense.

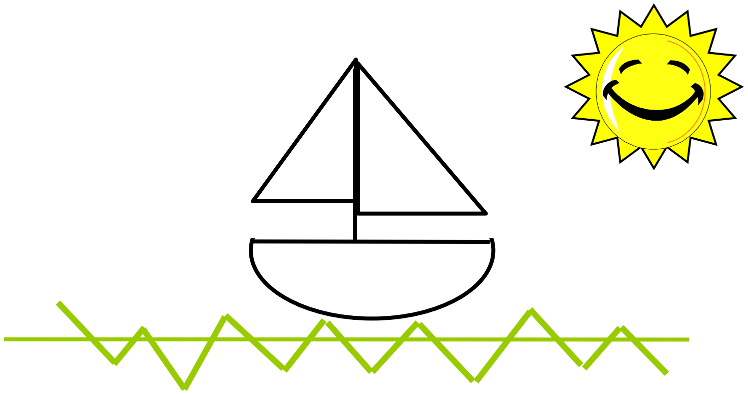
Exercise 21.1

a) Sign your name five times in the space provided below.

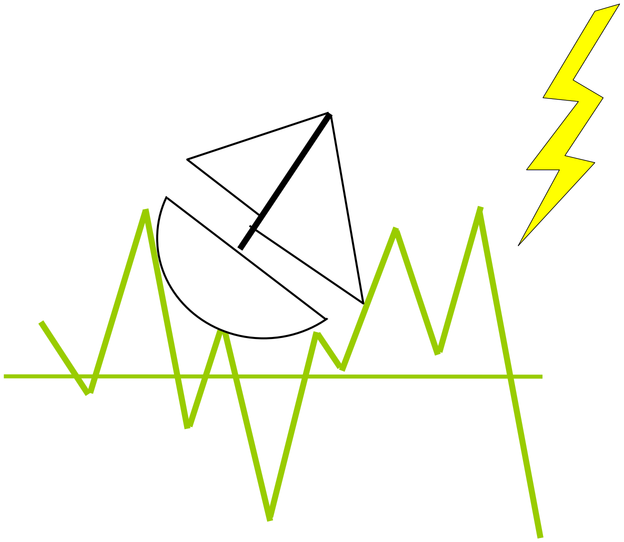
b) Put your pencil or pen into the other hand. Sign your name once in the space provided below.

Two kinds of variation

Variation due to *common causes*



Variation due to *assignable causes*



Common causes

- Random variation
- Inherent in the process as currently defined
- Many small fluctuations
- Outcomes are statistically predictable
- Causes for individual fluctuations cannot be determined

Assignable causes

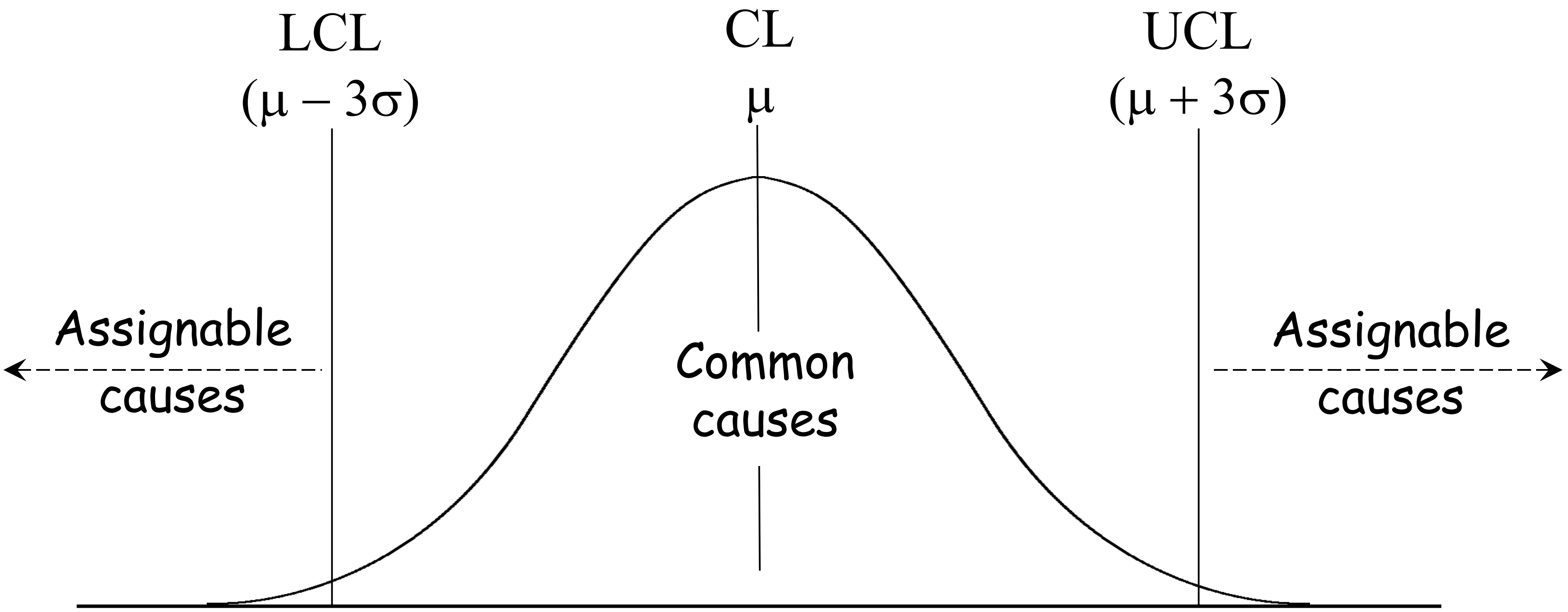
- Systematic variation
- Mistakes, malfunctions, miscommunications, external factors . . .
- Relatively few large fluctuations
- Outcomes are not predictable
- Causes of individual fluctuations *can* be determined

Quantifying common cause variation

- Common cause variation is usually represented by upper and lower *control limits*
- Upper control limit (UCL) = $\mu + 3\sigma$
- Lower control limit (LCL) = $\mu - 3\sigma$
- These are also called *three-sigma limits*
- Center Line (CL) = μ

Common cause variation (cont'd)

Control limits provide an *operational definition*
of common cause variation

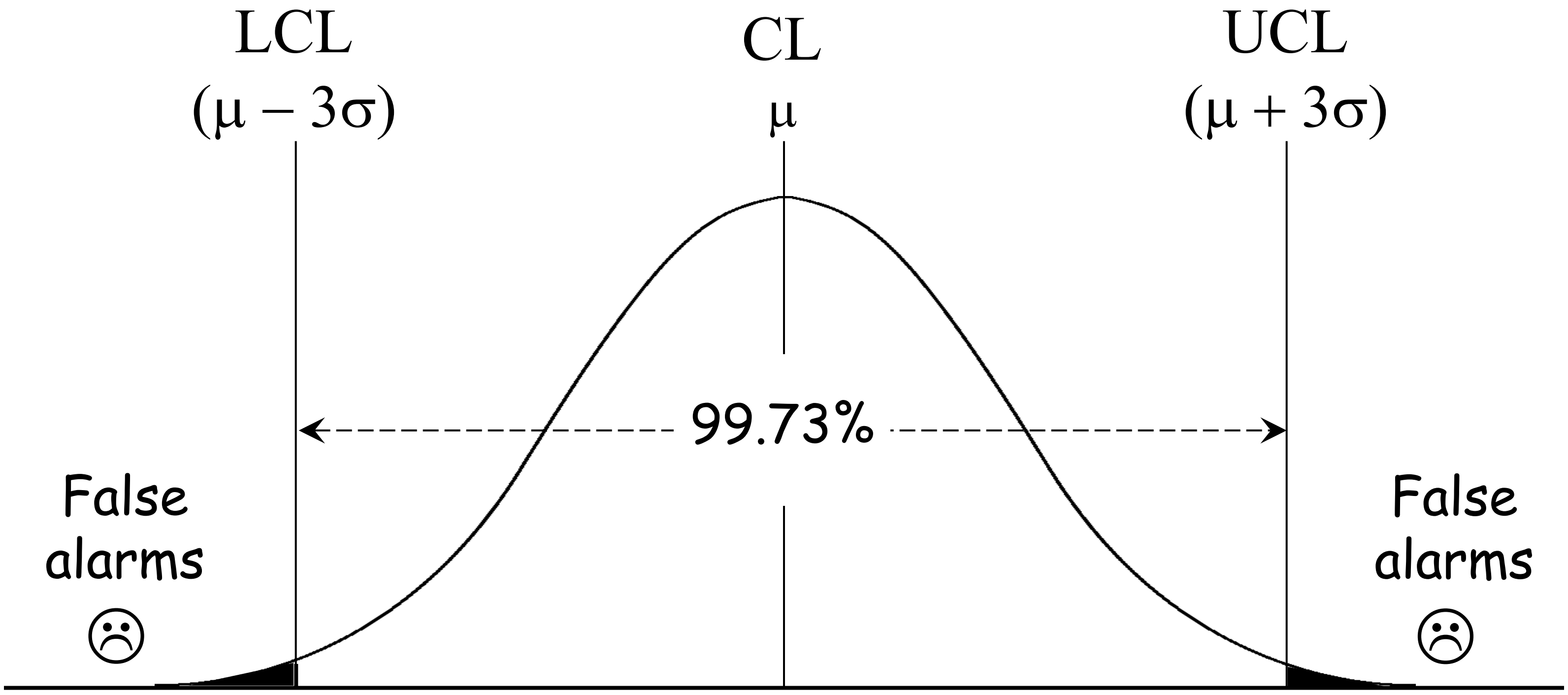


Baseline variation in the quantity to be monitored

μ = average
σ = standard deviation

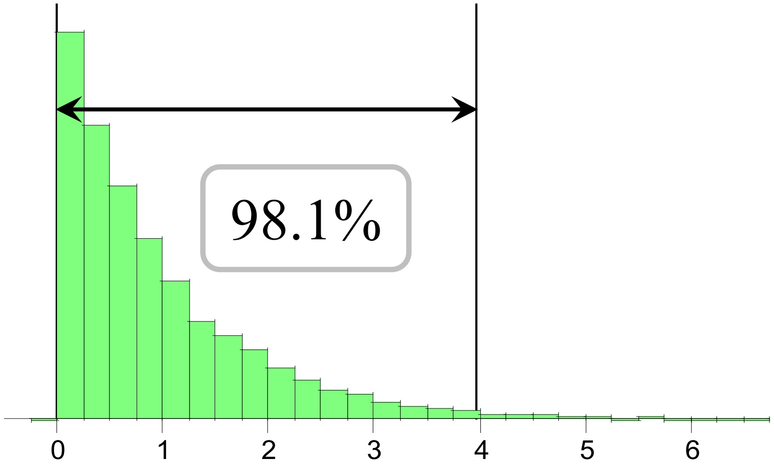
Common cause variation (cont'd)

If the quantity to be monitored follows a Normal distribution, the chance of a *false alarm* is 0.27%

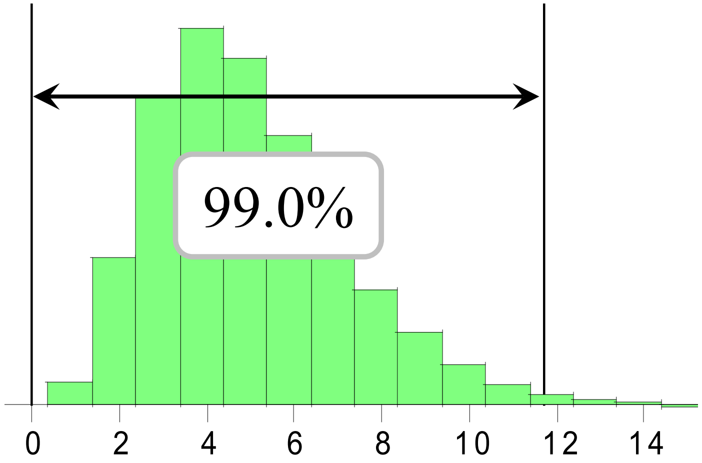


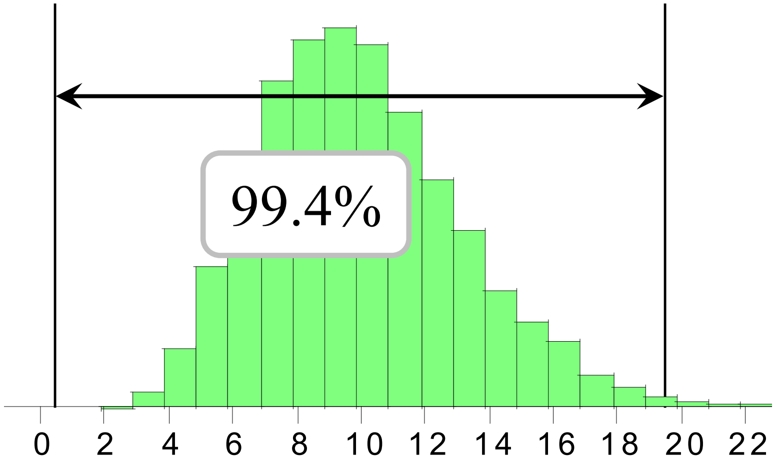
Baseline variation in the quantity to be monitored

Common cause variation (cont'd)



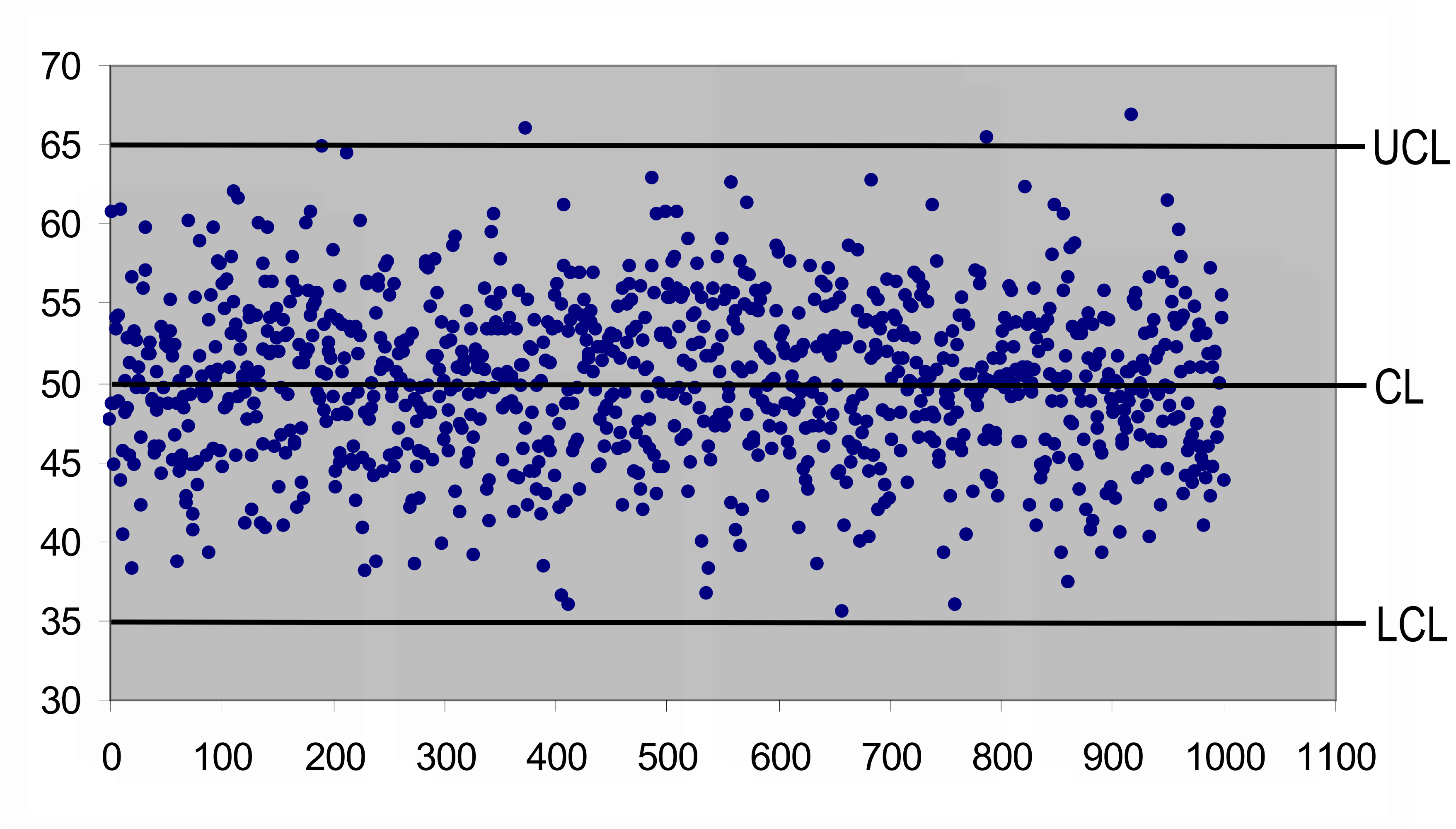
- 3σ limits are shown for three non–Normal distributions
- Data doesn't need to be Normally distributed for most charts
- The *Central Limit Theorem* also greatly reduces the effect of non-Normality when samples are used
- 3σ limits are an economic compromise between *false alarms* and *missed signals*





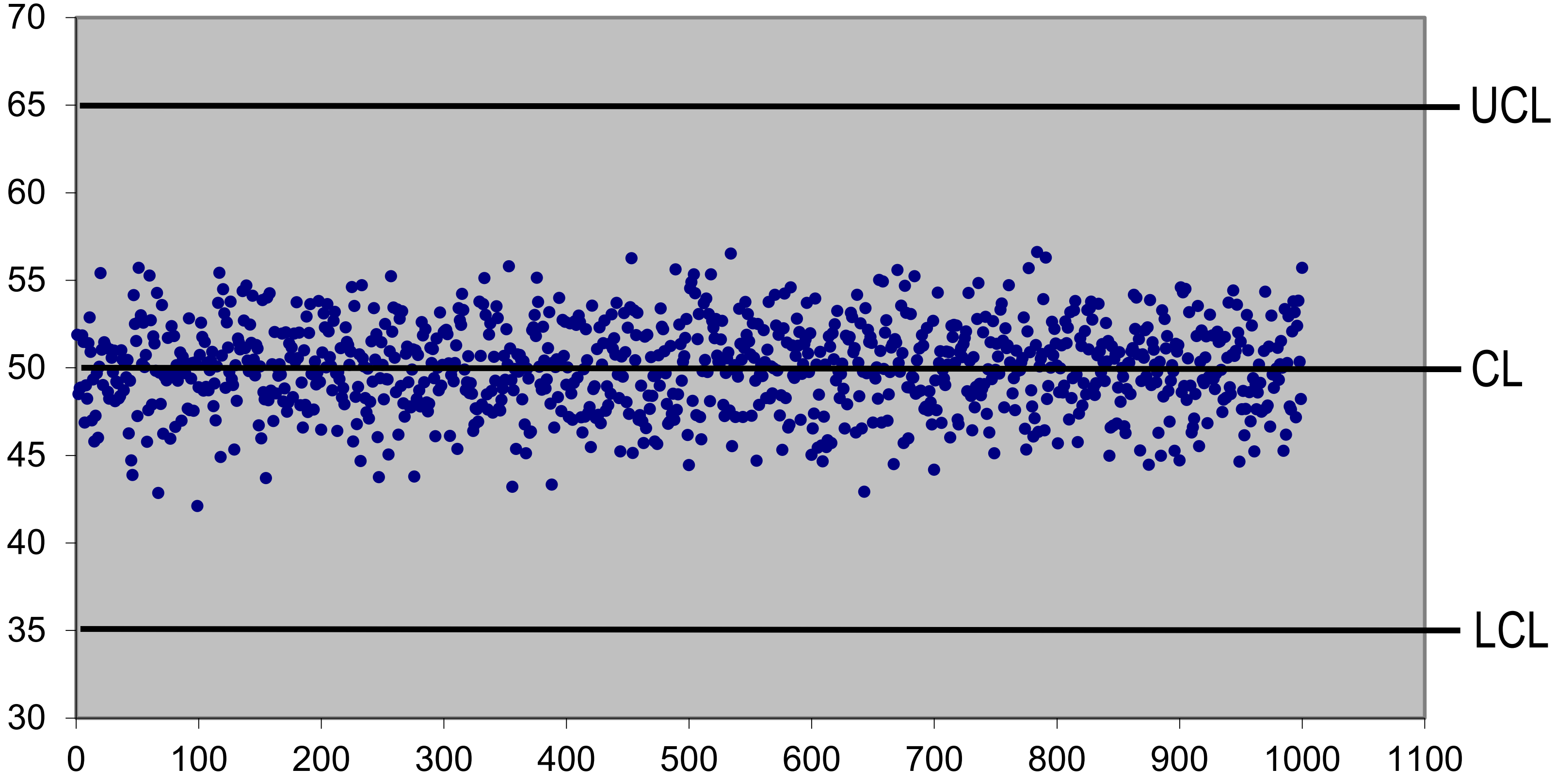
Behavior of Averages: the “Central Limit” effect

Individual data values sampled from a population
with $\mu = 50$ and $\sigma = 5$



Behavior of Averages: the “Central Limit” effect (cont’d)

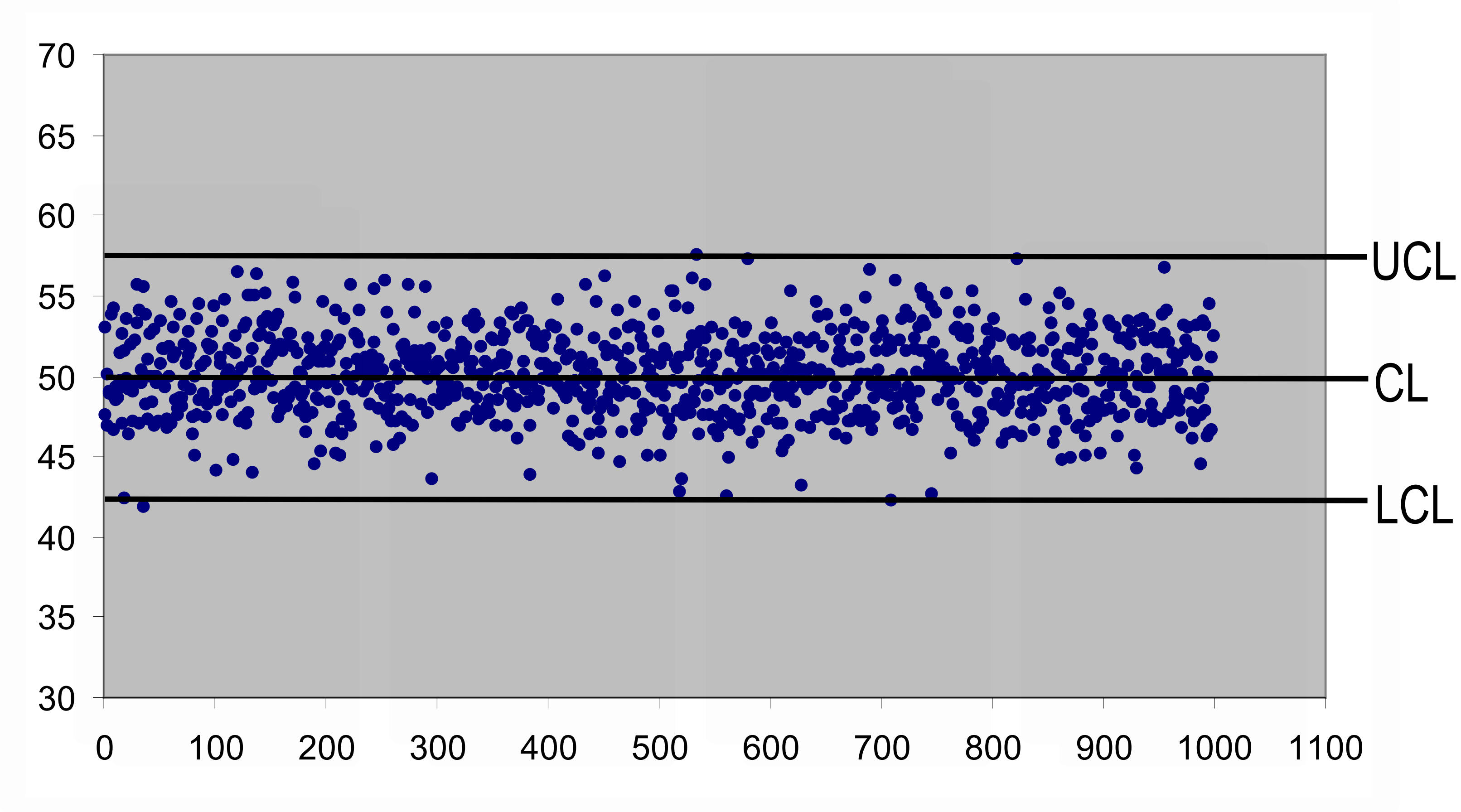
Averages of 4 data values sampled from the same population
with $\mu = 50$ and $\sigma = 5$



- Why would the limits shown above be ineffective for statistical monitoring of the averages?
- Control limits for a distribution of averages must be calculated a different way.

Behavior of Averages: the “Central Limit” effect (cont’d)

Averages of 4 data values sampled from the same population
with $\mu = 50$ and $\sigma = 5$



- These are the true control limits for the averages.
- In addition to the obvious narrowing of the distribution, the Central Limit Theorem (stated simply), concludes that subgroup averages converge to a Normal distribution, even if the underlying distribution is non-Normal.

The Standard Deviation of Averages

If we repeatedly sample sets of N individual data values from a population with mean μ and standard deviation σ, and calculate the average in each case, the *standard deviation of the averages* is:

$$\boxed{\frac{\sigma}{\sqrt{N}}}$$

Control Limits for Averages

If we repeatedly sample sets of N individual data values from a population with mean μ and standard deviation σ, and calculate the average in each case, the *three-sigma limits for the averages* are:

$$\mathrm{UCL} = \mu + 3\frac{\sigma}{\sqrt{\mathrm{N}}}$$

$$\mathrm{LCL} = \mu - 3\frac{\sigma}{\sqrt{\mathrm{N}}}$$

Establishing Control Limits

- Control Limits are calculated using data *representative* of day-to-day process operation
- The exact calculation for three sigma limits depends on the type of control chart being used
- The type of control chart used depends on the type of data and the sampling method
- At least 20 – 25 sample subgroups should be used to set control limits
- Data from a pilot run can be used to set control limits for the "future state" process, if the pilot is representative of the process that will be implemented.
    - If not, run the "future state" process long enough to gather a sufficient sample.

Control limits are *not* the same as specification limits!

Sampling for control charts

To detect process shifts, we need to take a *reasonable* sample of the process.

- Samples should estimate, or try to represent, the population.
- Samples need to be taken in the order of production and as soon as possible in an operation to get an early warning of defects.
- The chance of variation from assignable causes should be *minimized within* an individual sample set (pull parts for a sample close together in time).
- The chance of variation from assignable causes should be *maximized between* samples (time separation between samples).
- Pulling subgroups of parts at a predetermined interval works best.
  - Do not pre-identify which parts will form the SPC sample before they are manufactured (avoid bias).
  - Do not adjust the process during sampling.

Common Shewhart control charts

Quantitative measurement:

- $\overline{X}$ & s (sample average and standard deviation)
- $\overline{X}$ & R (sample average and range)
- IX and MR (individual values and moving range

Categorical classification:

- p (fraction defective)

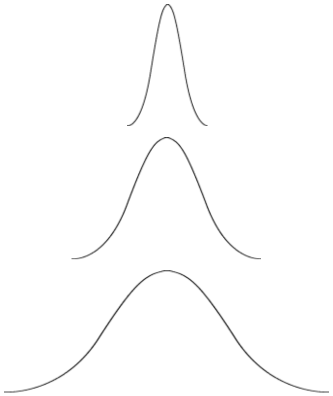
Quantitative control charts

With quantitative control charts, we pull samples from the process and use them to estimate how the process as a whole is performing.

We can then answer two important questions using two graphs:

1. Is the process staying centered?
2. Is the process staying consistent?

SCENARIO A



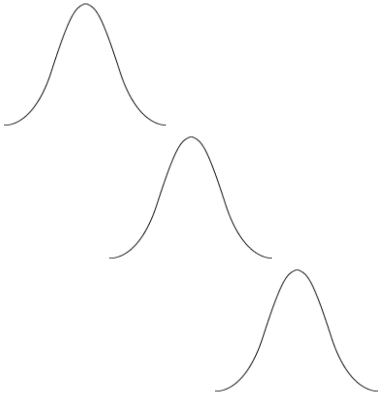
The centering is ______________

____

The consistency is ______________

____

SCENARIO B



The centering is ______________

____

The consistency is ______________

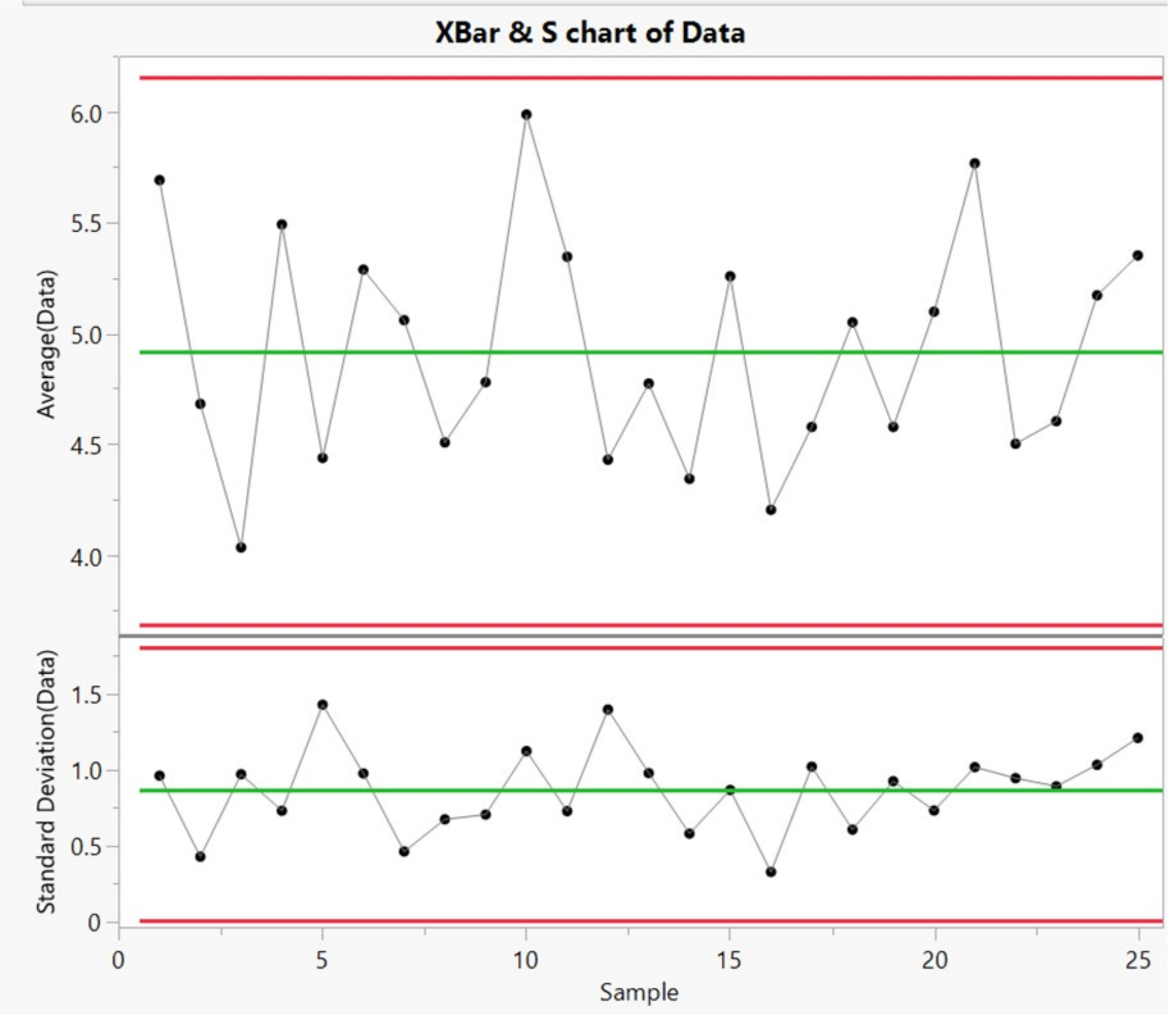
____

Quantitative control charts (cont'd)

Control Chart	Statistics Plotted	Sample Size	Description
X-bar & R	Average & Range	2–5	The X-bar and R chart was the first and most common quantitative control chart used in SPC, only because in the days before calculators and statistical software, Range was easier to calculate than Standard Deviation. The X-bar and R chart can be useful for monitoring product, process or environmental characteristics when the sample size is fairly small (say 5 or less). But given the prevalence of software tools available, it should really be replaced by the X-bar and s chart unless there is a particular need for spotting "outlier" range values.
X-bar & s	Average & Standard Deviation	5–15	The X-bar and s chart is useful for monitoring product, process or environmental characteristics, especially when the sample size is larger (say, more than 5). Again, the standard deviation chart will be more robust than range because all data are used, not just the highest and lowest numbers.
IX & MR	Individual & Moving Range	1	The IX and MR chart is used when the sample size is one. A single sample may need to be taken because: • It is expensive to take samples. • The measurement method is destructive. • It is the only sample size that makes sense for that process. Because an average cannot be calculated for a sample size of one, the individual data points are used. When there is only one number, standard deviation and range cannot be calculated. Instead, we use what is called the *Moving Range*.

Example: $\overline{X}$ and s chart

For each sample, the average is plotted on the $\overline{X}$ chart (centering) and the standard deviation (consistency) is plotted below on the s chart.



JMP Output of $\overline{X}$s Chart of *control chart diameter*

Control limit calculations for X–bar and s charts

Monitoring frequency	*Metric to monitor*	*Statistic(s) Needed*	*Control limits*
Hourly Daily Weekly Monthly Quarterly etc.	*$\bar{X}$ chart:* Average	Average (μ)	$\text{UCL} = \mu + 3\frac{\sigma}{\sqrt{N}}$ $\text{CL} = \mu$ $\text{LCL} = \mu - 3\frac{\sigma}{\sqrt{N}}$
		Standard deviation (σ)	
	s chart: Standard Deviation	Standard deviation (σ)	$\text{UCL} = \bar{\sigma} + 3\frac{\sigma}{\sqrt{2(N-1)}}$ $\text{CL} = \bar{\sigma}$ $\text{LCL} = \bar{\sigma} - 3\frac{\sigma}{\sqrt{2(N-1)}}$

Exercise 21.2

We want to use $\overline{X}$ and s control charts to monitor a critical dimension, diameter, of the parts we are producing. Open *Data Sets → control chart diameter*. Does the baseline data appear to be adequate to represent process variation?
Use Excel formulas for the following:

a) Calculate the average ($\overline{x}$) and standard deviation (s) for each subgroup of five parts.

b) Calculate the overall average, which will be the center line (CL) of the $\overline{x}$ chart. There are two ways to do so: take the average of all the data points or take the average of the subgroup averages. The name given to the statistic from the second method is $\overline{\overline{X}}$ (X-double bar) or the Grand Average.

c) Calculate the average of the subgroup standard deviations, ($\overline{s}$), which will be the Center Line (CL) for the standard deviation chart.

Exercise 21.2 (cont’d)

d) The estimates of the standard deviation of the distribution of averages and the distribution of standard deviations have been calculated for you. They are used in the “3-sigma” quantities that are added to and subtracted from the Center Lines.

e) Use the numbers found above to calculate the upper and lower control limits for each chart.

$\mathrm{UCL}_{\bar{\mathrm{x}}} =$

$\mathrm{CL}_{\bar{\mathrm{x}}} =$

$\mathrm{LCL}_{\bar{\mathrm{x}}} =$

$\mathrm{UCL}_{\mathrm{s}} =$

$\mathrm{CL}_{\mathrm{s}} =$

$\mathrm{LCL}_{\mathrm{s}} =$

Control limits for X–bar and R charts

$\overline{\mathrm{X}}$ Chart Control Limits:

$$\mathrm{UCL} = \bar{\bar{x}} + A_2\bar{R}$$

$$\mathrm{CL} = \bar{\bar{x}}$$

$$\mathrm{LCL} = \bar{\bar{x}} - A_2\bar{R}$$

R Chart Control Limits:

$$\mathrm{UCL} = \bar{R}D_4$$

$$\mathrm{CL} = \bar{R}$$

$$\mathrm{LCL} = \bar{R}D_3$$

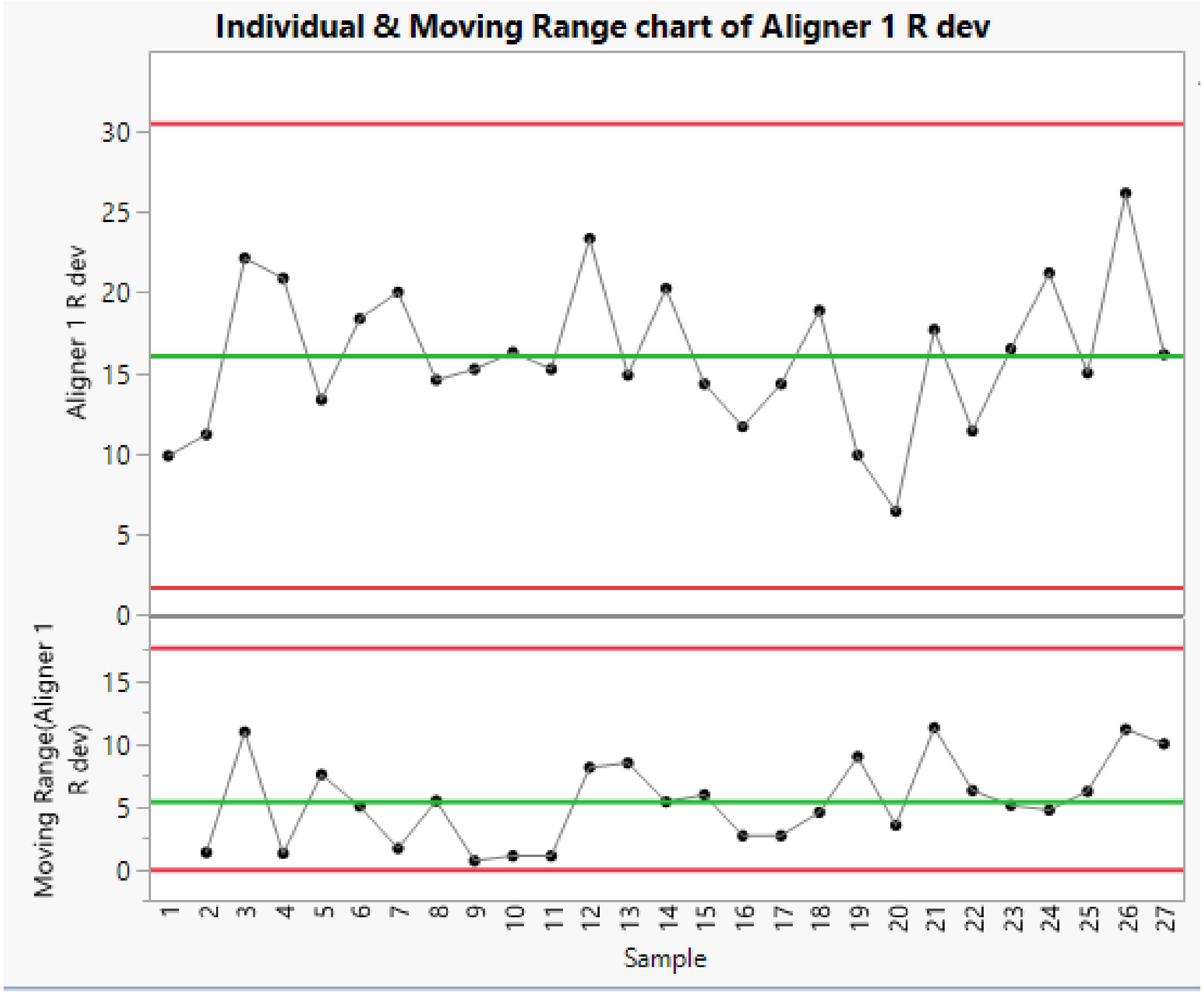
Constants for sample size n

n	A_2	D_3	D_4	d_2
2	1.880	0.000	3.267	1.128
3	1.023	0.000	2.574	1.693
4	0.729	0.000	2.282	2.059
5	0.577	0.000	2.114	2.326
6	0.483	0.000	2.004	2.534
7	0.419	0.076	1.924	2.704
8	0.373	0.136	1.864	2.847
9	0.377	0.184	1.816	2.97
10	0.308	0.223	1.777	3.078

From Introduction to Statistical Quality Control by Douglas C. Montgomery

Example: Individual and Moving Range chart

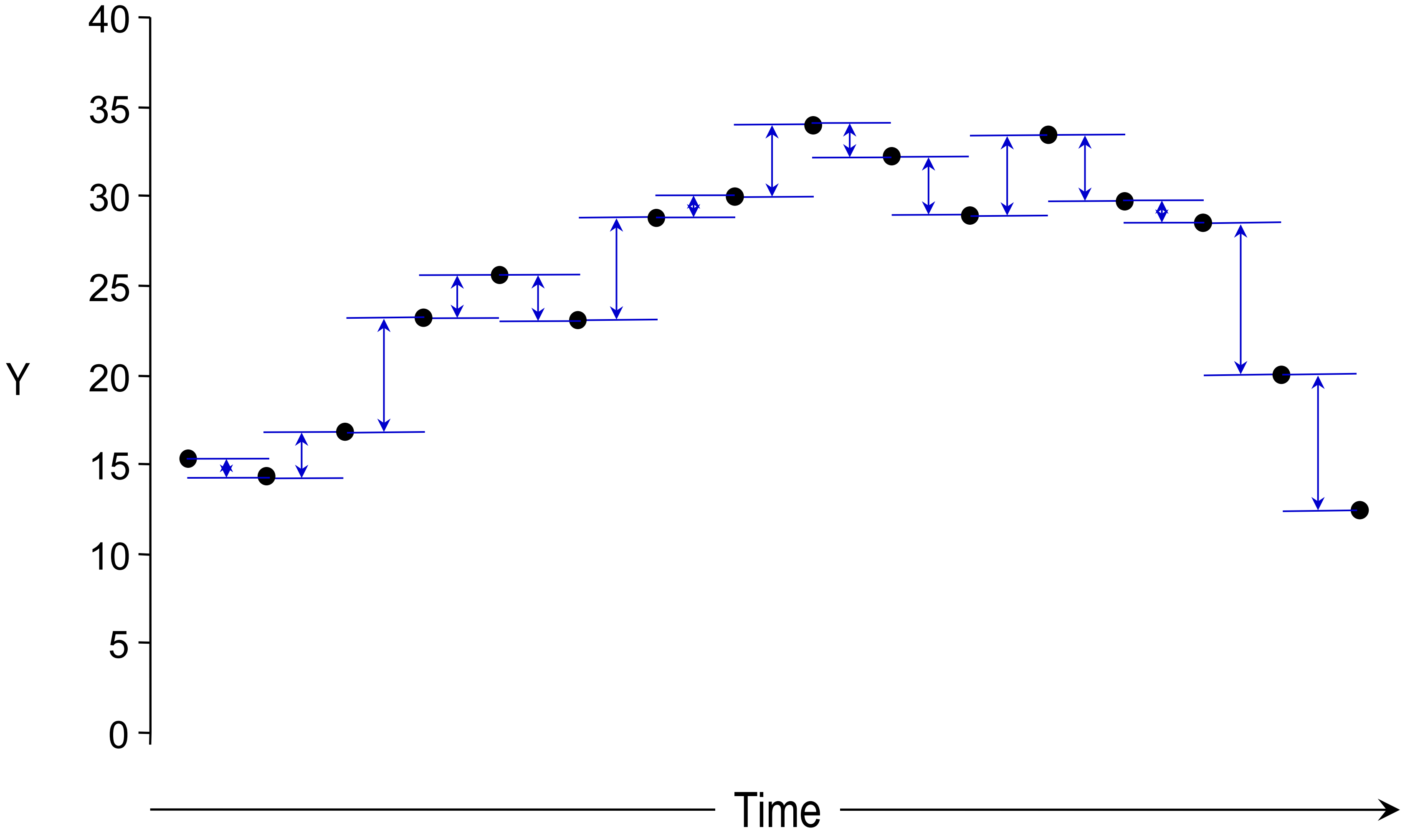
For each unit, the measurement is plotted on the Individual chart and the Moving Range is plotted below.



Why is the first point missing on the MR chart?

Estimating standard deviation using the moving range method

Each moving range is the absolute value of the difference between consecutive data points.



Control limit calculations for Individual and Moving Range chart

Individual Chart Control Limits:

$$\mathrm{UCL} = \bar{\mathrm{x}} + 3\frac{\overline{\mathrm{MR}}}{\mathrm{d}_2}$$

$$\mathrm{CL} = \bar{\mathrm{x}}$$

$$\mathrm{MR} = |\mathrm{x}_\mathrm{i} - \mathrm{x}_{\mathrm{i}-1}|$$

$$\mathrm{LCL} = \bar{\mathrm{x}} - 3\frac{\overline{\mathrm{MR}}}{\mathrm{d}_2}$$

The value of d_2 is 1.128 since the range is between two consecutive points.

Moving Range Chart Control Limits:

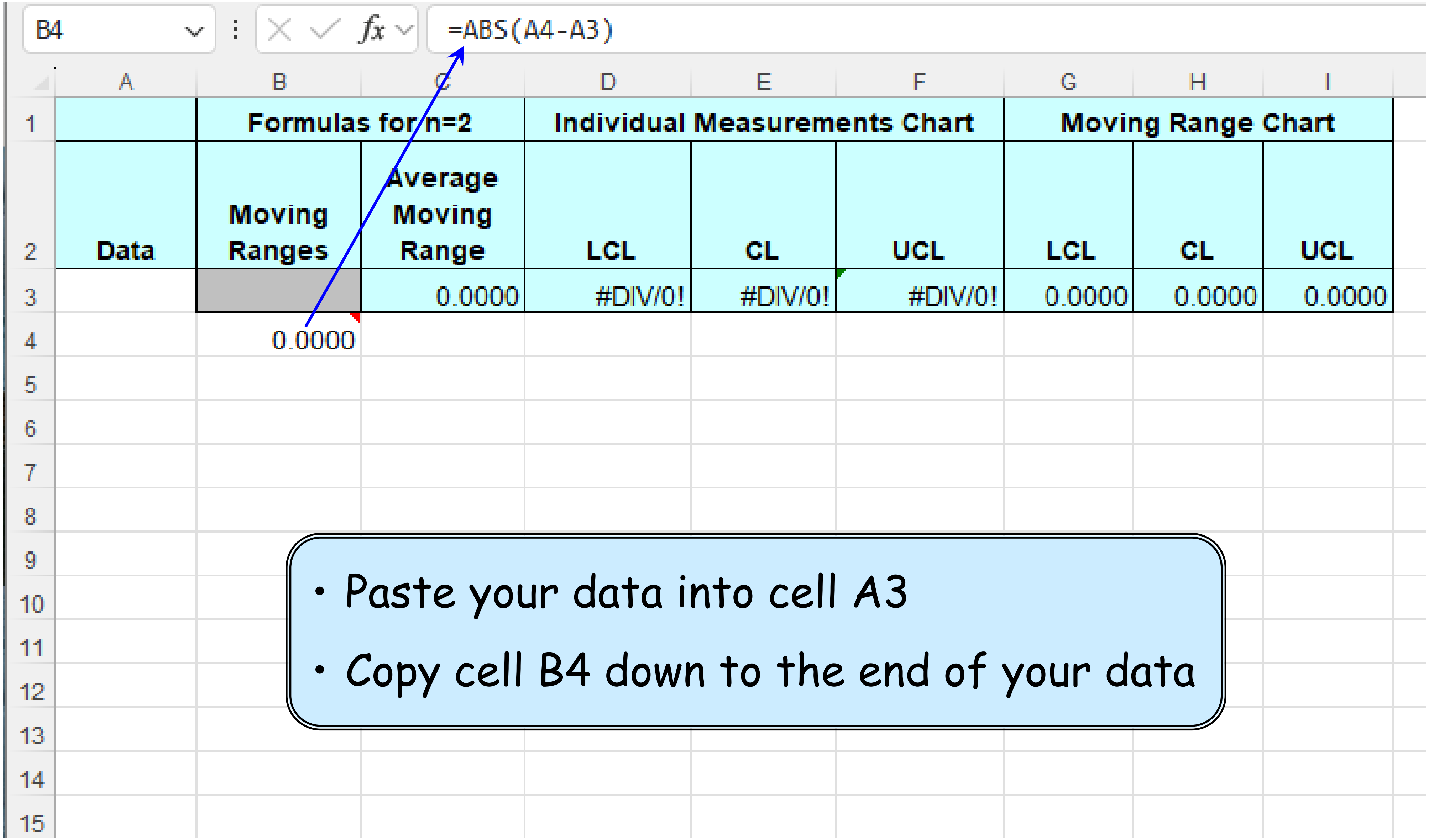
$$\mathrm{UCL} = \mathrm{D}_4\overline{\mathrm{MR}} = 3.267\overline{\mathrm{MR}}$$

$$\mathrm{CL} = \overline{\mathrm{MR}}$$

$$\mathrm{LCL} = \mathrm{D}_3\overline{\mathrm{MR}} = 0$$

Individual and Moving Range chart calculator

To make it easier to calculate the moving range, open
Student Files → calculator – individual moving range chart



B4

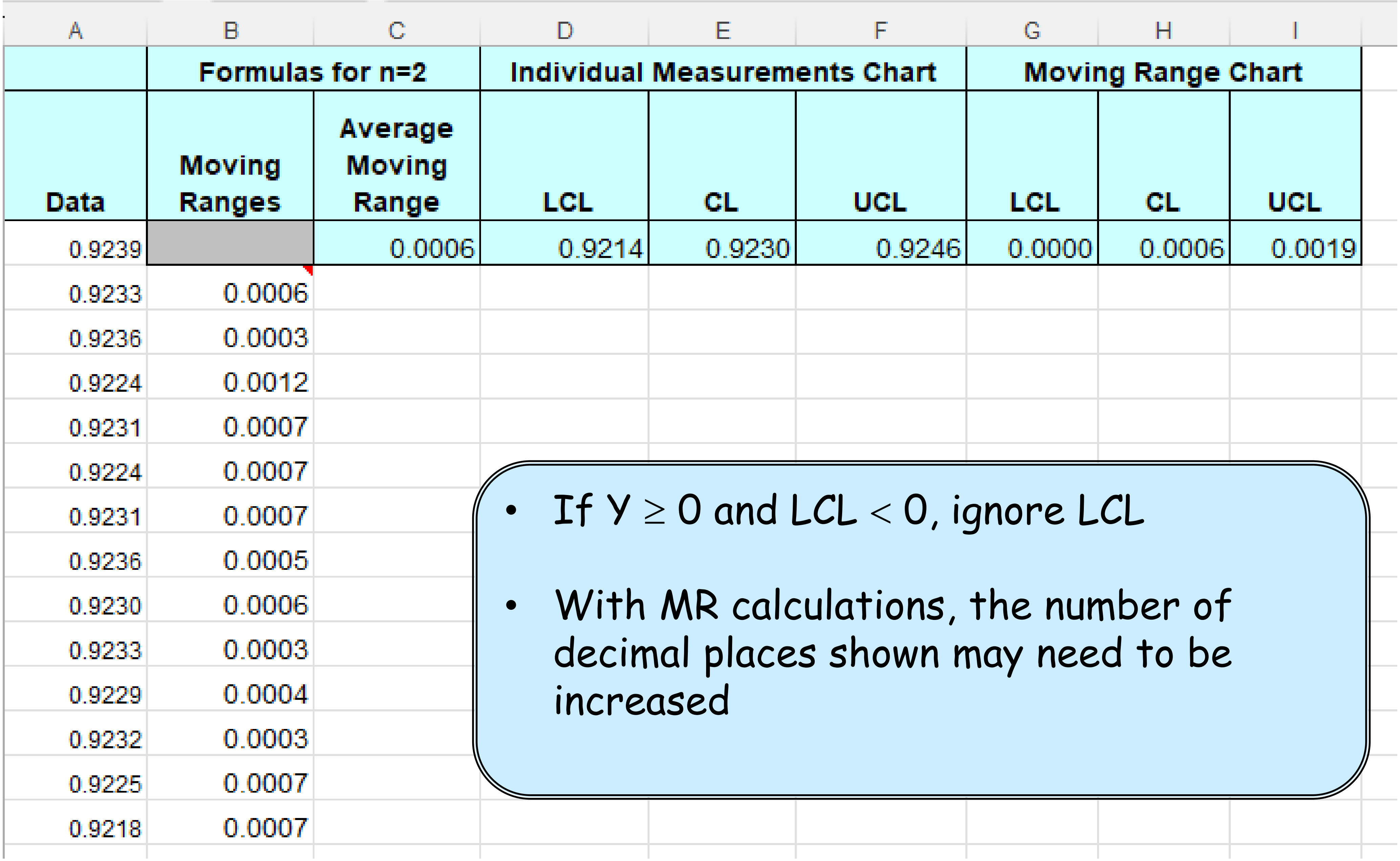
=ABS(A4-A3)

	A	B	C	D	E	F	G	H	I
1		**Formulas for n=2**		**Individual Measurements Chart**			**Moving Range Chart**		
2	**Data**	**Moving Ranges**	**Average Moving Range**	**LCL**	**CL**	**UCL**	**LCL**	**CL**	**UCL**
3			0.0000	#DIV/0!	#DIV/0!	#DIV/0!	0.0000	0.0000	0.0000
4		0.0000							
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

- Paste your data into cell A3
- Copy cell B4 down to the end of your data

Example: Individual and Moving Range chart calculator

Excerpted data from *Data Sets→ solution properties*



A	B	C	D	E	F	G	H	I
	Formulas for n=2		**Individual Measurements Chart**			**Moving Range Chart**		
Data	**Moving Ranges**	**Average Moving Range**	**LCL**	**CL**	**UCL**	**LCL**	**CL**	**UCL**
0.9239		0.0006	0.9214	0.9230	0.9246	0.0000	0.0006	0.0019
0.9233	0.0006							
0.9236	0.0003							
0.9224	0.0012							
0.9231	0.0007							
0.9224	0.0007							
0.9231	0.0007							
0.9236	0.0005							
0.9230	0.0006							
0.9233	0.0003							
0.9229	0.0004							
0.9232	0.0003							
0.9225	0.0007							
0.9218	0.0007							

- If $Y \geq 0$ and $LCL < 0$, ignore LCL
- With MR calculations, the number of decimal places shown may need to be increased

Exercise 21.3

We want to use $\mathrm{I}\overline{\mathrm{X}}$ and MR control charts to monitor radial deviation. This measurement requires special equipment and is very time-consuming, hence the sample size of one.

Open *Data Sets* → *control chart aligner*

Open *Student Files* → *calculator - individual moving range chart*

a) Copy the R dev data into the calculator (Paste Values).

b) Copy the calculation in cell B4 down Column B, in order to calculate the moving range for R dev. What is the average moving range?

$\overline{\mathrm{MR}} =$

Exercise 21.3 (cont'd)

c) What are the control limits for the Individual Chart?

UCL =

CL =

LCL =

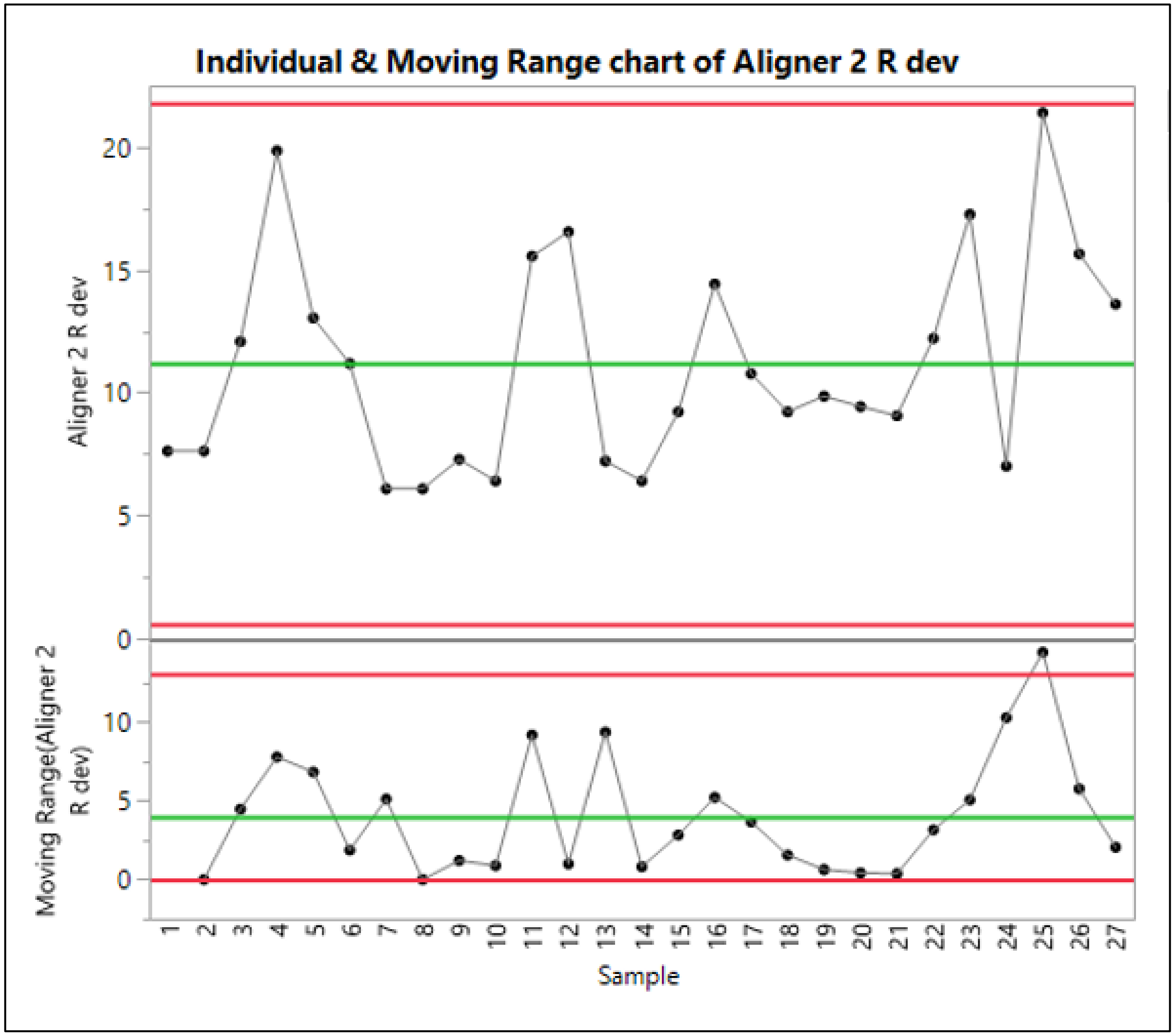
d) What are the control limits for the Moving Range Chart?

UCL =

CL =

LCL =

Individual & Moving Range chart plotted



JMP Output of Individuals & MR Chart of Aligner 2 R dev

Data Sets → control chart aligner

p Chart

The p Chart is used when:

- Samples are periodically taken and it’s determined whether each unit in the sample is good or bad
- The data plotted is fraction or percent defective

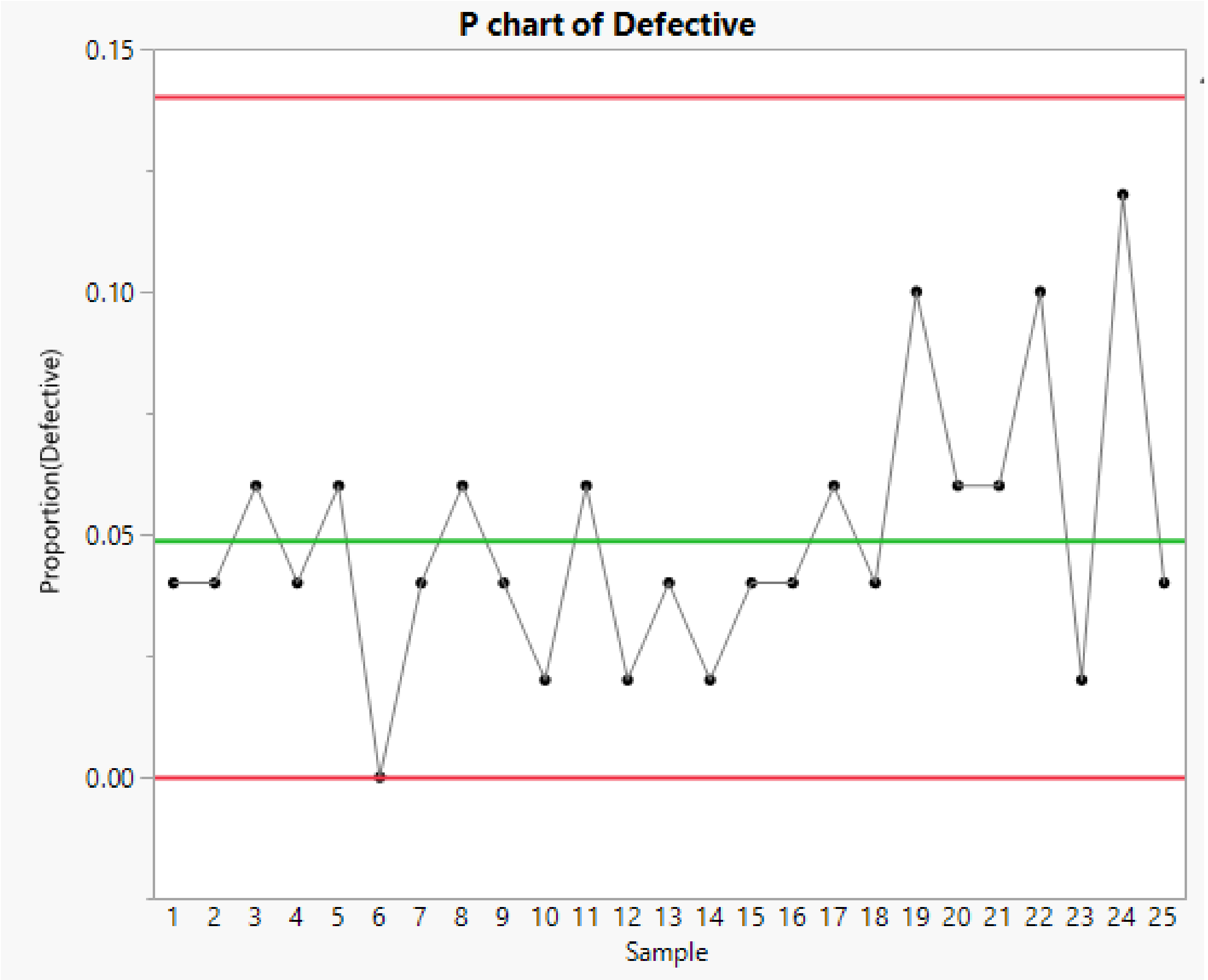
P Chart control limits are based on the Binomial distribution, since pass/fail data is binomial.

- The standard deviation of the Binomial distribution is:

$$\sqrt{\frac{p(1-p)}{n}}$$

p Chart (cont'd)

Example of a p Chart (created in JMP)



In this case, there were 50 units in each sample. Overall percent defective was about 5% for this timeframe.

p Chart (cont'd)

Control Limits for the p Chart

$$\mathrm{UCL} = \bar{\mathrm{p}} + 3\sqrt{\frac{\bar{\mathrm{p}}(1 - \bar{\mathrm{p}})}{\mathrm{n}}}$$

$$\mathrm{CL} = \bar{\mathrm{p}}$$

$$\mathrm{LCL} = \bar{\mathrm{p}} - 3\sqrt{\frac{\bar{\mathrm{p}}(1 - \bar{\mathrm{p}})}{\mathrm{n}}}$$

$$\bar{\mathrm{p}} = \frac{\text{Total number of defective units in the samples}}{\text{Total number of units in the samples}}$$

$$\mathrm{n} = \text{number of items in each sample}$$

These control limits are the mean +/- 3 sigma for this distribution.

Exercise 21.4

We want to use a percent defective (p) control chart to monitor the weekly defects per unit occurring during an in-process assembly inspection.

Open *Data Sets* → *control chart parts inspected & defective*

Use Excel formulas for the following and during calculations, keep the numbers in “fraction defective” form vs percentage:

a) The sample size varies each week, so we’ll use an average sample size for calculating control limits. Calculate the average weekly sample size. What concerns might there be about using this number?

b) Calculate the overall percent defective.

This number will be the center line (CL) for the p chart.

Exercise 21.4 (cont'd)

c) Use the average sample size and $\bar{p}$ found above to calculate the upper and lower control limits for the p chart.

UCL =

CL =

LCL =

d) Optional: Copy the formulas for the control limits down the column for all of the data and use line charts to plot the fraction defective with control chart limits.

Other Shewhart control charts

Categorical classification:

- np chart: number (count) of defective items per sample with a fixed quantity
- u chart: count of defects per unit
- c chart: count of defects) per sample with a fixed quantity

For np, c and u charts, the control limit calculations and chart appearance are similar to the p chart.

Details of these and other specialized control charts are beyond the scope of this course. More information can be found in any basic statistical process control textbook or reference.

Interpreting control charts

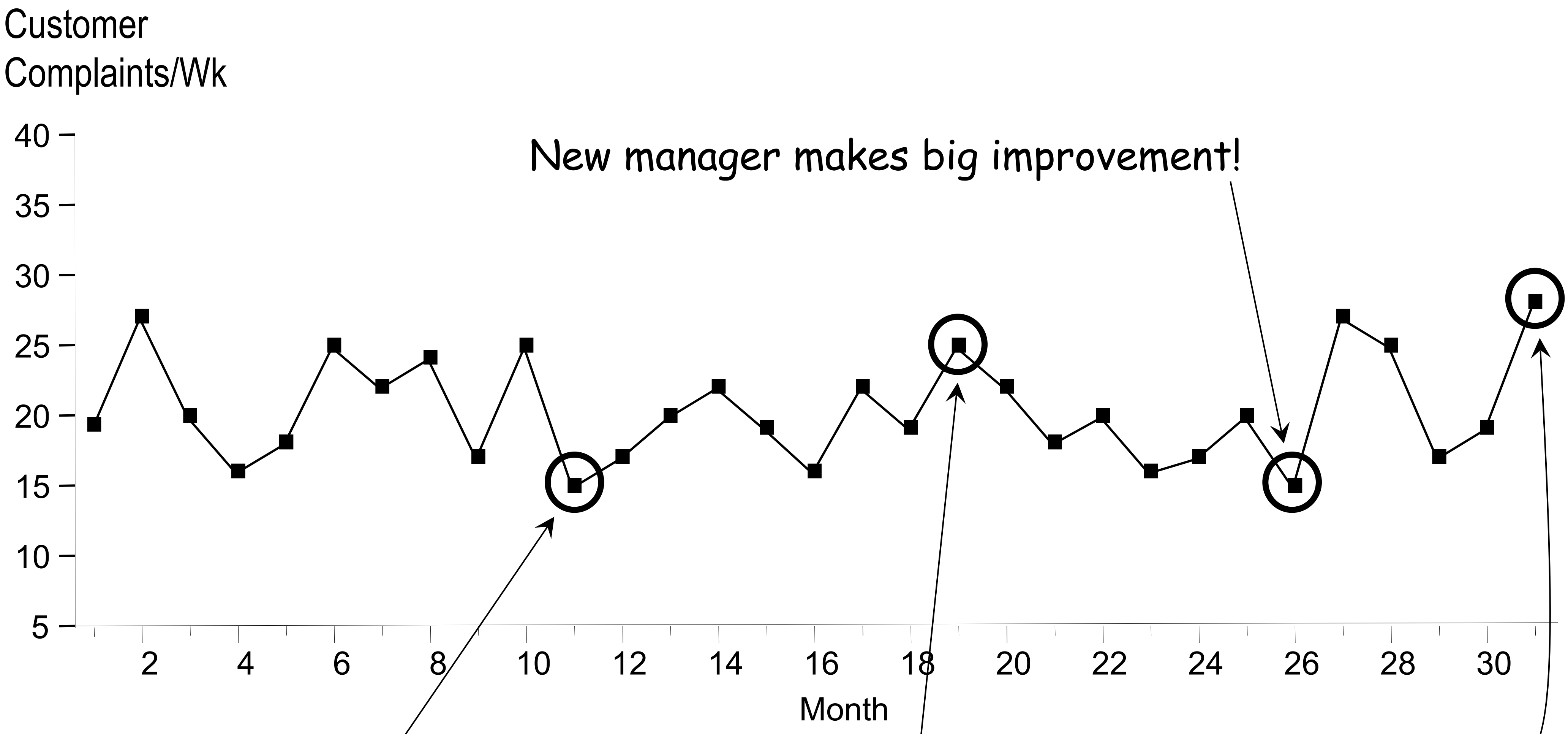
Once the control chart is created, the most valuable work can begin — discerning what the chart is telling us about process variation.

- Is the process “in control” or “out?”
- Are there warning signs that the process may go out of control soon?
- What actions should be take in response to the control chart signals?

The rules we’ll discuss for deciding whether a process is in or out of control work only for control limits — *not* for specification limits.

- Our concern with specification limits is whether an item conforms or not.
- Inspection and testing must be used to screen out bad parts, not control limits.

A hypothetical KPI scenario



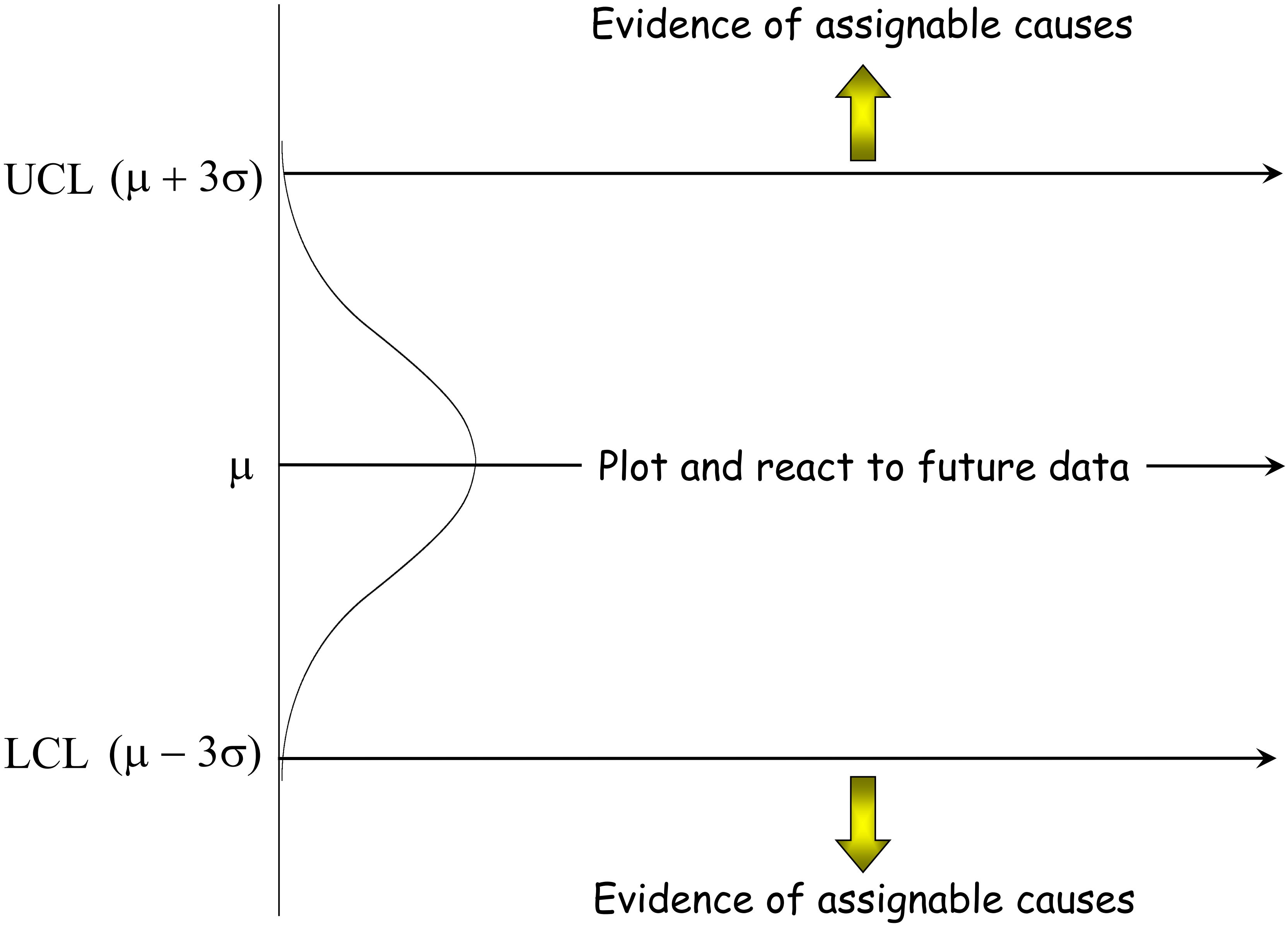
New manager makes big improvement!

Manager gets bonus!

Manager is reassigned!

New manager has "special meeting" with CEO!

Using control limits



Evidence of assignable causes

UCL $(\mu + 3\sigma)$

μ

Plot and react to future data

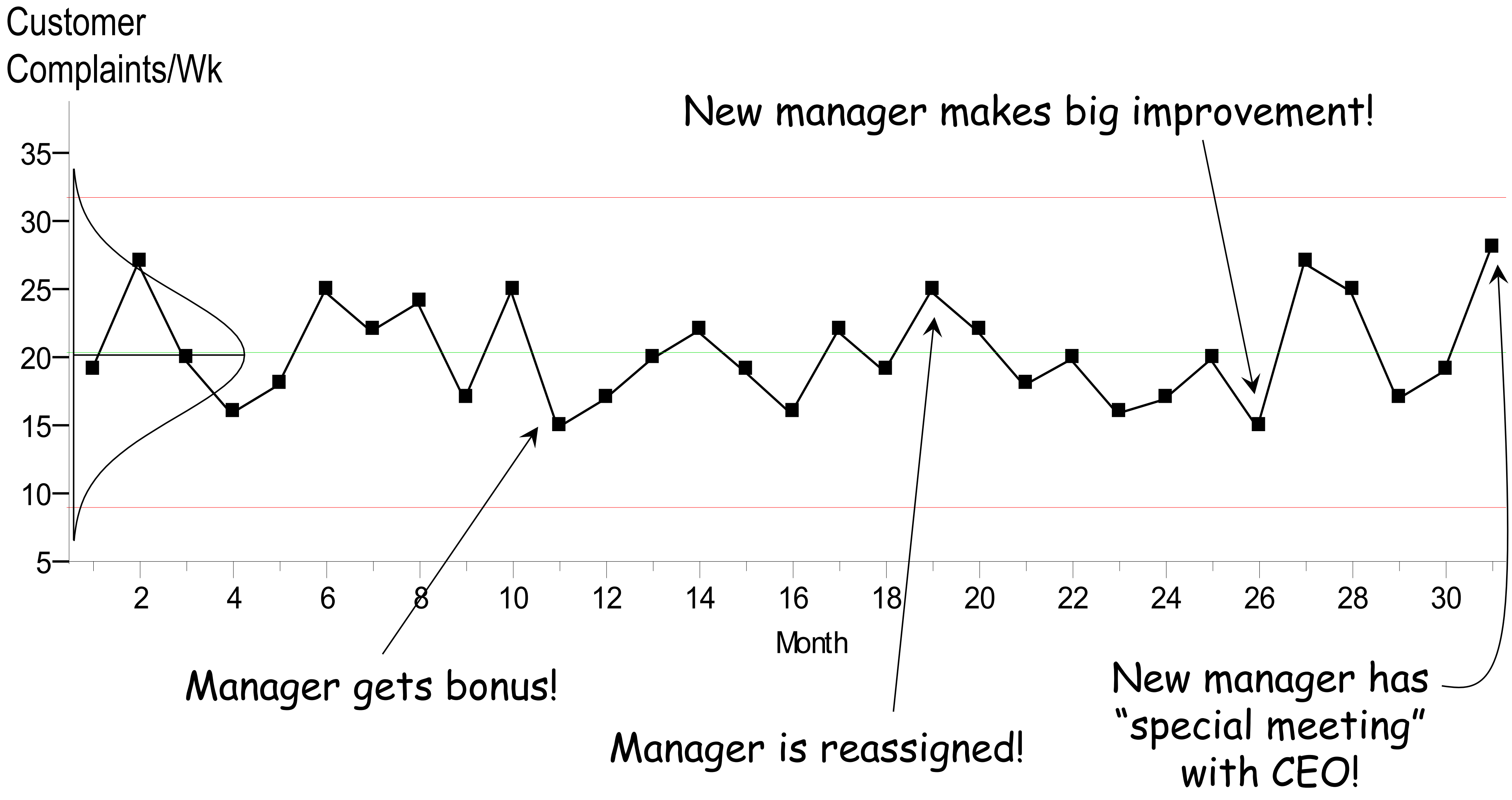
LCL $(\mu - 3\sigma)$

Evidence of assignable causes

Back to our hypothetical scenario

Control Limits show there are no assignable causes!

Run charts can cause us to overreact.



New manager makes big improvement!

Manager gets bonus!

Manager is reassigned!

New manager has "special meeting" with CEO!

Using control limits (cont'd)

- Control limits provide an operational definition of assignable cause variation
- Simplest rule: points inside the limits are common cause variation, points outside the limits have assignable causes
- 27 in 10,000 common cause data points are expected to fall outside the control limits[*] — this is the nominal *false alarm* rate
- Assignable causes may occur without producing points outside the limits — these are *missed signals*
- To reduce missed signals, additional rules are sometimes applied

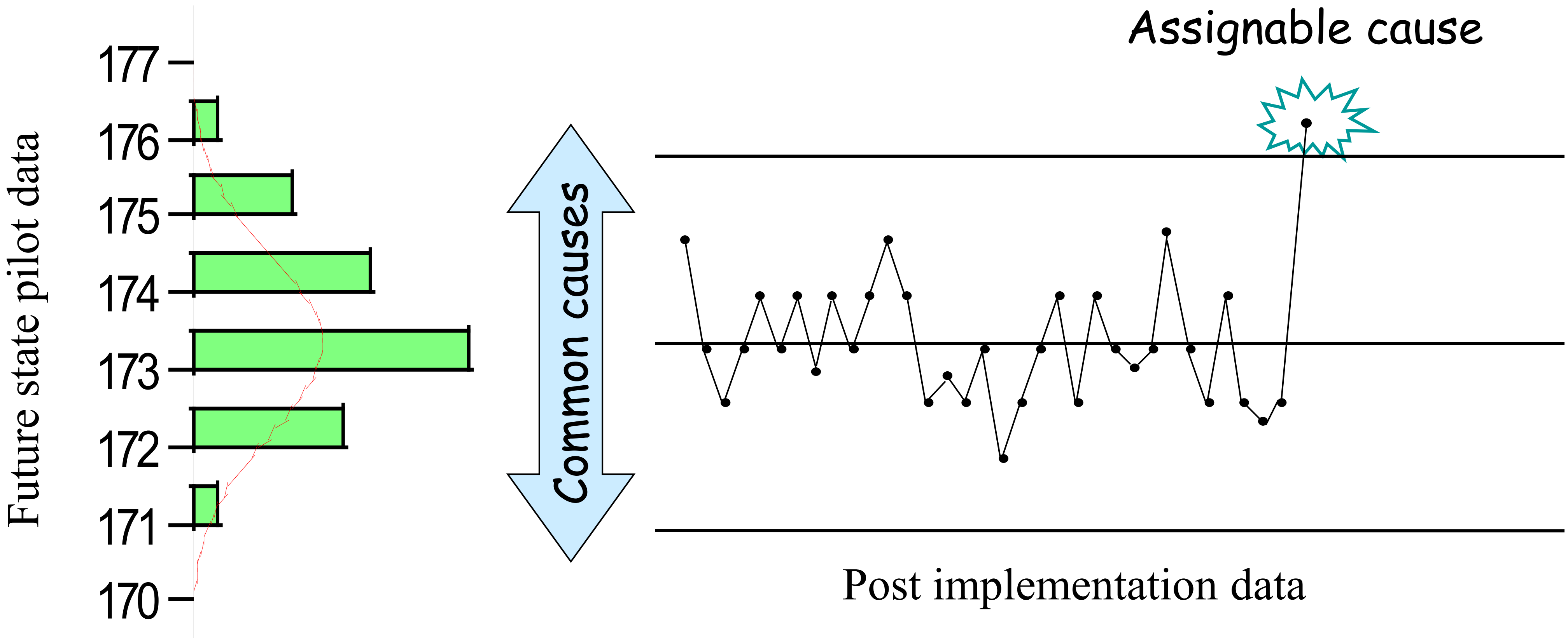
[*] Assuming a Normal distribution

Using control limits (cont'd)

When monitoring a straightforward KPI, such as number of customer complaints/week or monthly on-time delivery, Management may only want to see a chart of the KPI metric itself.

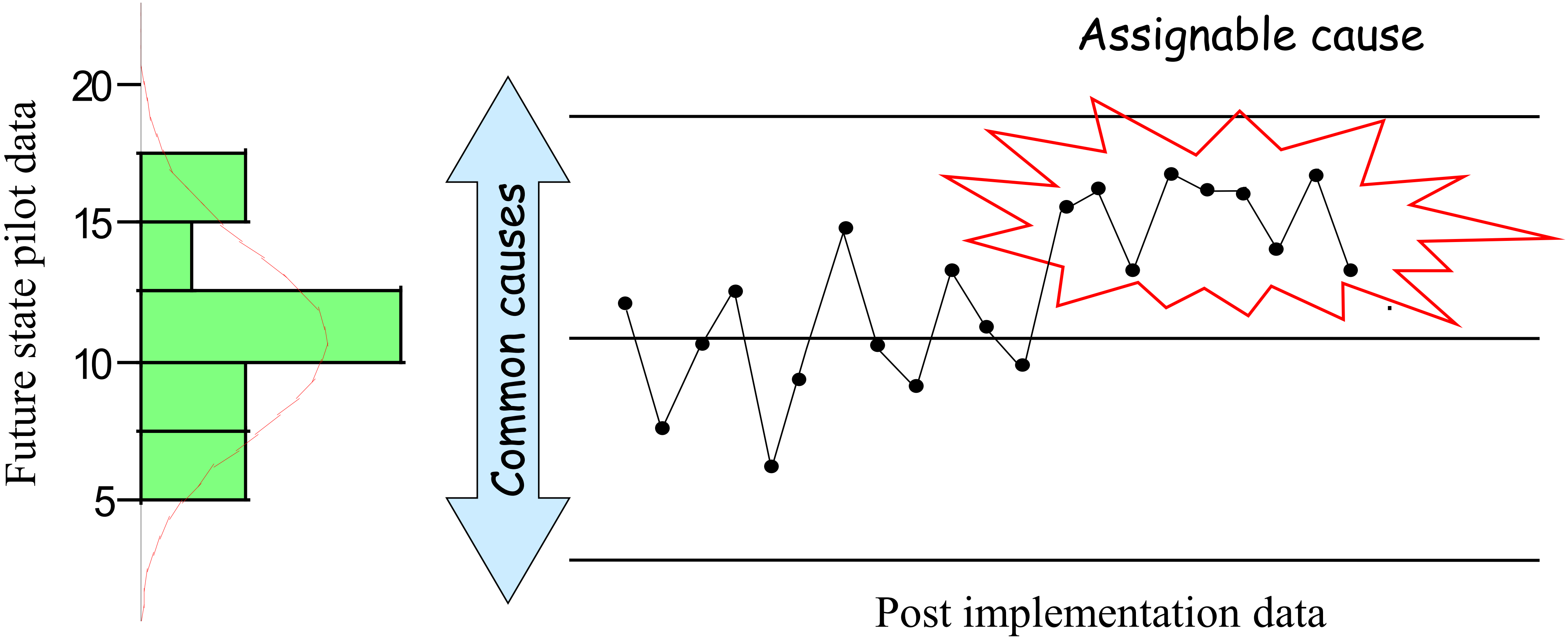
- In this case, it may be sufficient to use an X-bar or IX chart without the associated standard deviation or range chart.
- Adding control limits to the resulting X-bar or IX chart will provide a statistical basis for action.
- It may also be helpful to add a target or goal line to the chart (aligned with the KPI calculation method).
- An associated variation chart could be created for deeper root cause analysis if necessary. For example:
    - ➢ Are late deliveries "normal" for the organization?
    - ➢ Are there inconsistencies between divisions for global KPI charts?

Using control limits (cont'd)



1. This event has probability 0.00135 (0.0027 ÷ 2)
2. Investigate to determine the cause
3. Take corrective action to eliminate the cause

Using control limits (cont'd)



1. This event has probability 0.00195 [$(0.5)^9$]
2. Investigate to determine the cause
3. Take corrective action to eliminate the cause

Additional tests for assignable causes

Control chart zones: A, B, and C

Additional tests for assignable causes (cont’d)

Test 1	One point beyond A (This is the basic test & always used.)
Test 2	9 points in a row on the same side of the average.
Test 3	6 points in a row steadily increasing or decreasing.
Test 4	14 points in a row alternating up and down.
Test 5	Any 2 out of 3 points in a row in A or beyond.
Test 6	Any 4 out of 5 points in B or beyond.
Test 7	15 points in a row in C, above and below the center line.
Test 8	8 points in a row on each side of the average with none in C.

Additional tests for assignable causes (cont’d)

The zone system is based on 3σ limits

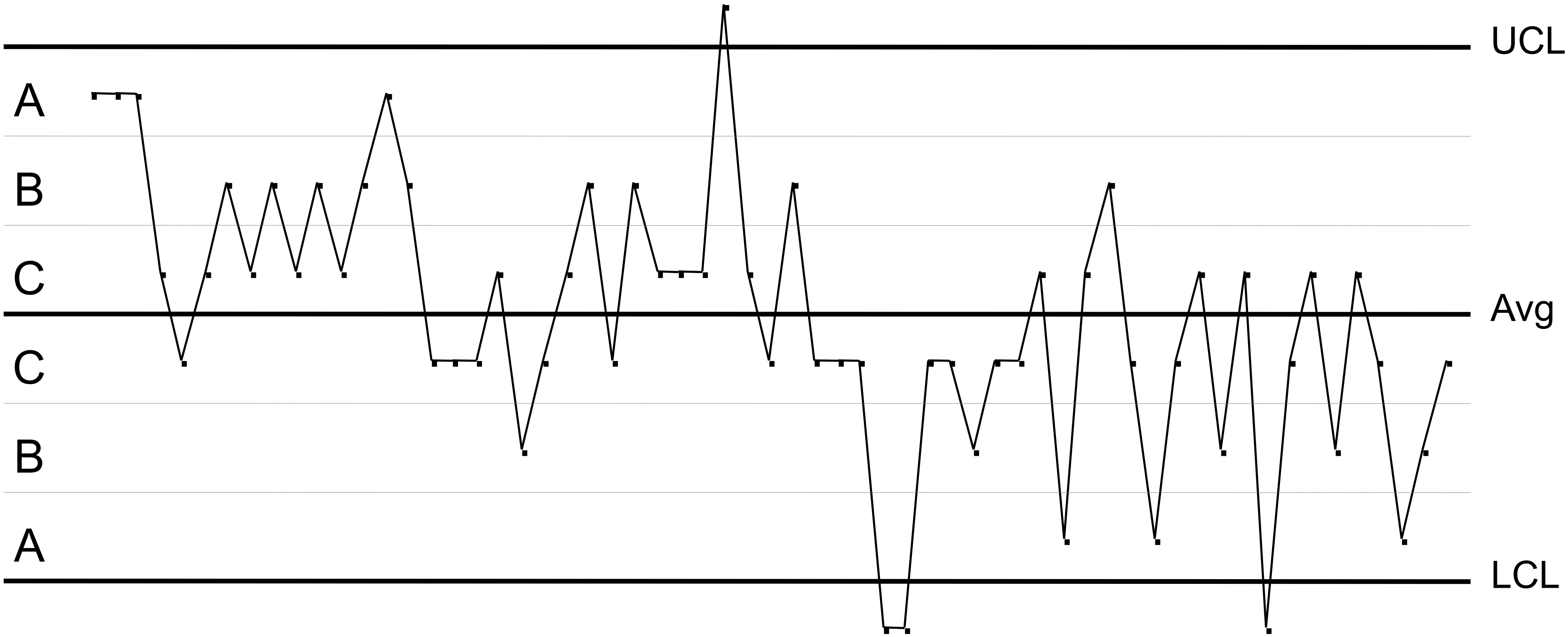
- C is the region within 1 standard deviation of the mean
- B is the region more than 1 but less than 2 standard deviations from the mean
- A is the region more than 2 but less than 3 standard deviations from the mean

Tests most commonly used (and most useful)

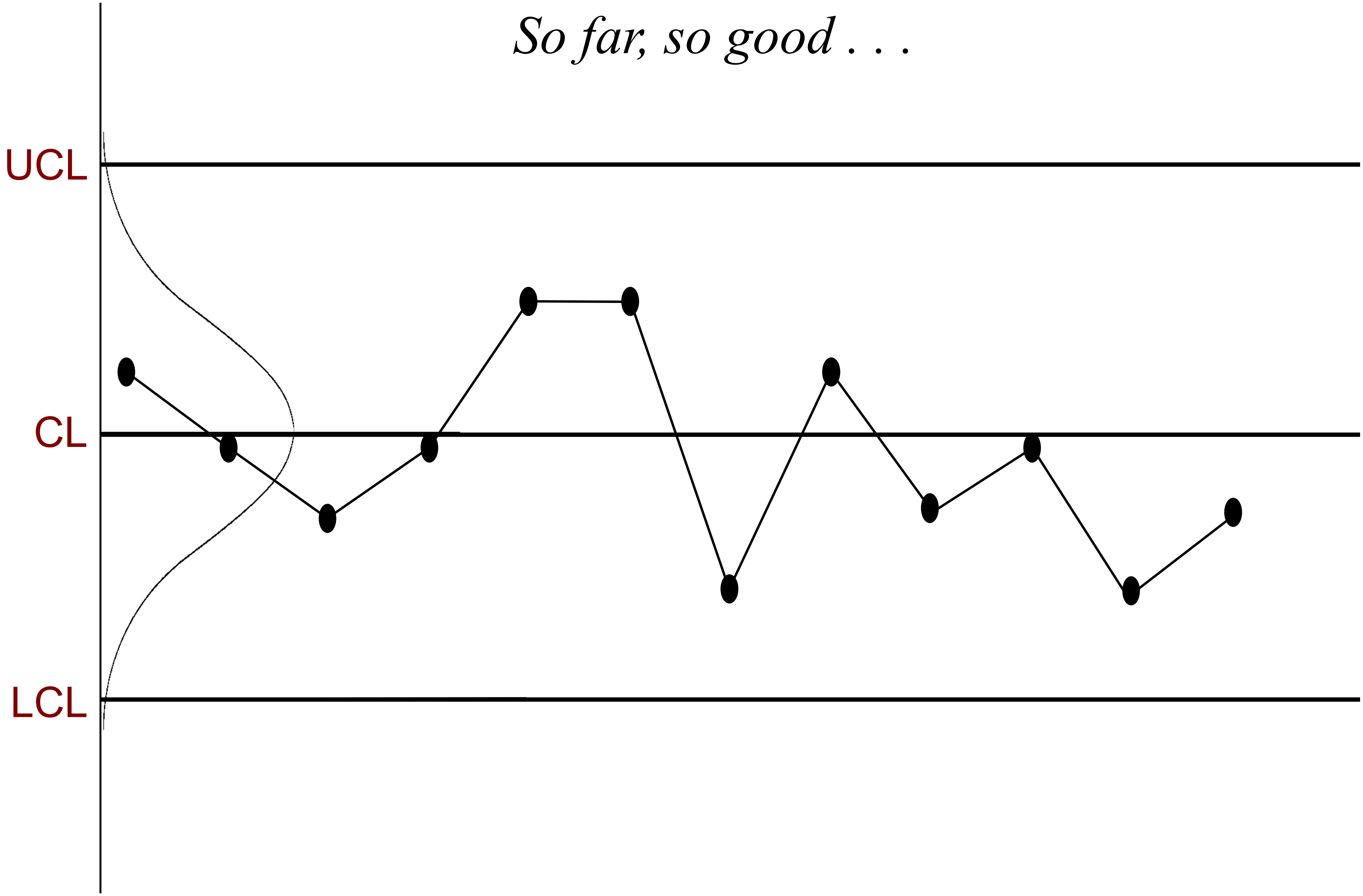
Test #1	One or more points outside the control limits.
Test #2	Nine or more points in a row on one side of the average.

Exercise 21.5

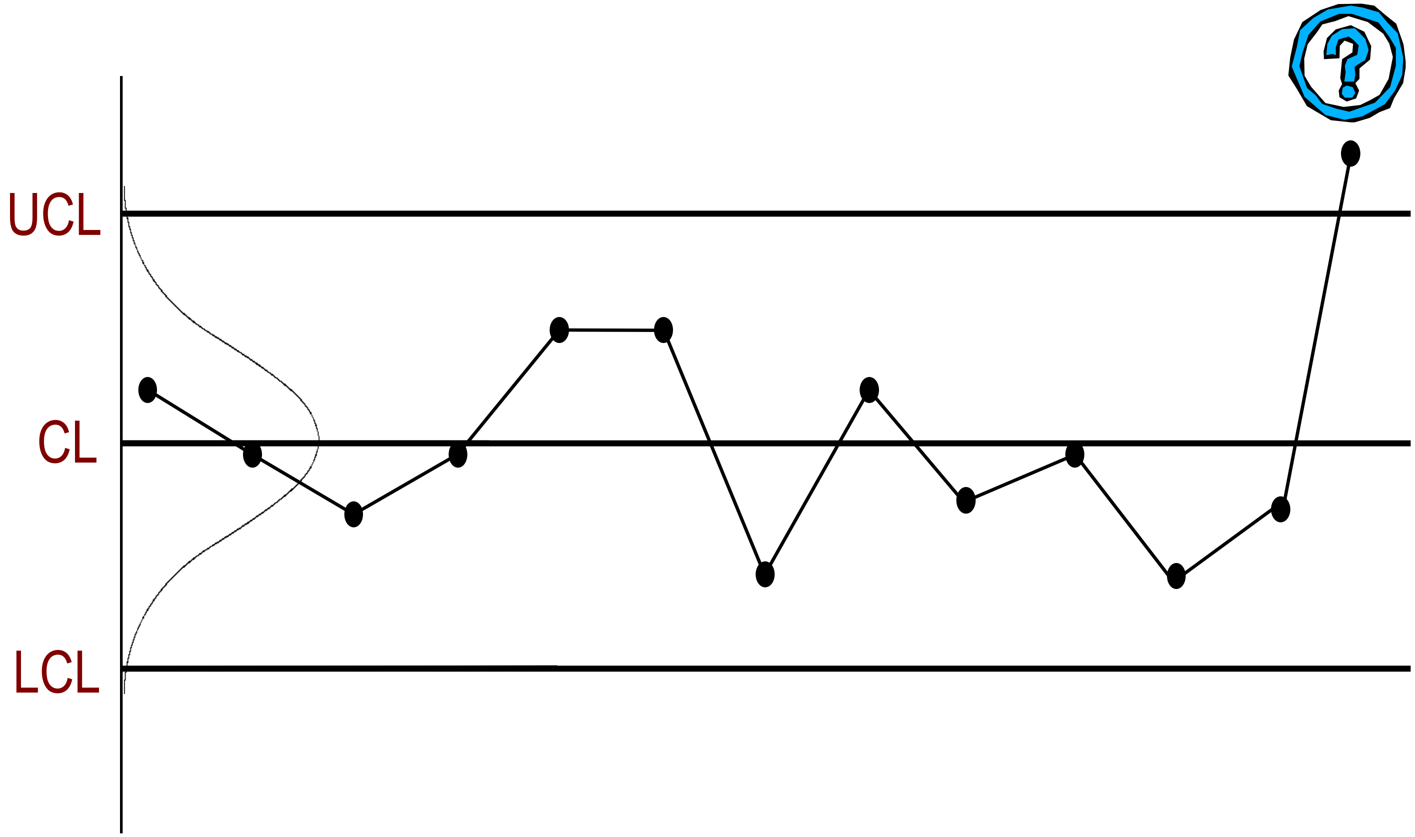
Circle occurrences of Tests 1 and 2 on the control chart shown below. Indicate which is which.



22 Response plans



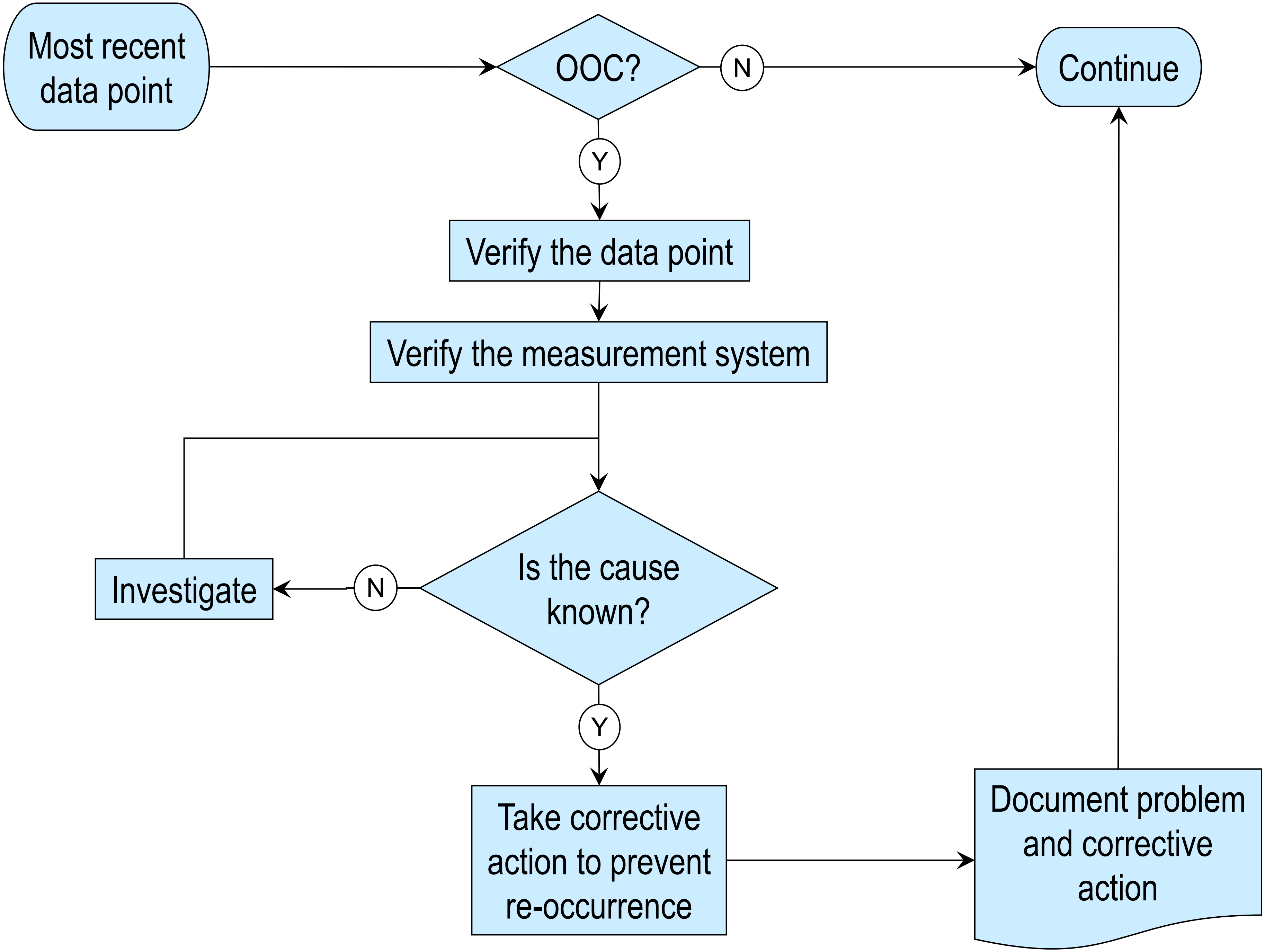
Out-of-control event (OOC)



1. Investigate to determine the cause
2. Take corrective action to eliminate the cause

Step 1 requires a *response plan*

Response plan “skeleton”



Most recent data point

OOC?

N

Continue

Y

Verify the data point

Verify the measurement system

Is the cause known?

N

Investigate

Y

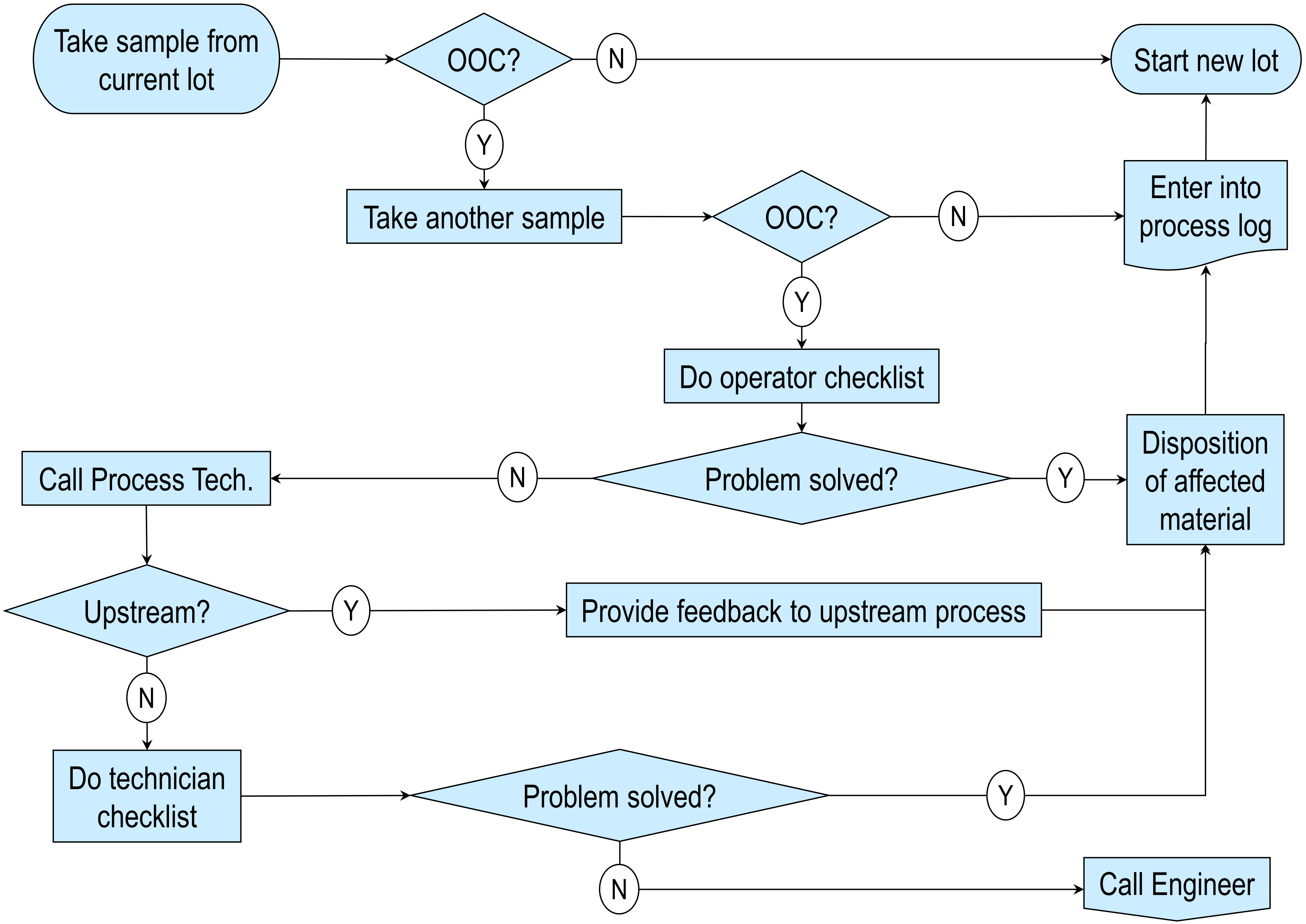
Take corrective action to prevent re-occurrence

Document problem and corrective action

Response plan (cont'd)

- OOC stands for *out of control*
- This means the control chart indicates an assignable cause according to one or more selected tests
- The success of statistical monitoring depends on having a documented plan for responding to OOCs
- The most effective form of documentation is a process map like the one shown above
- It should posted in a place clearly visible to process participants

Response plan example



Take sample from current lot

OOC?

N

Start new lot

Y

Take another sample

OOC?

N

Enter into process log

Y

Do operator checklist

Problem solved?

N

Call Process Tech.

Y

Disposition of affected material

Upstream?

Y

Provide feedback to upstream process

N

Do technician checklist

Problem solved?

Y

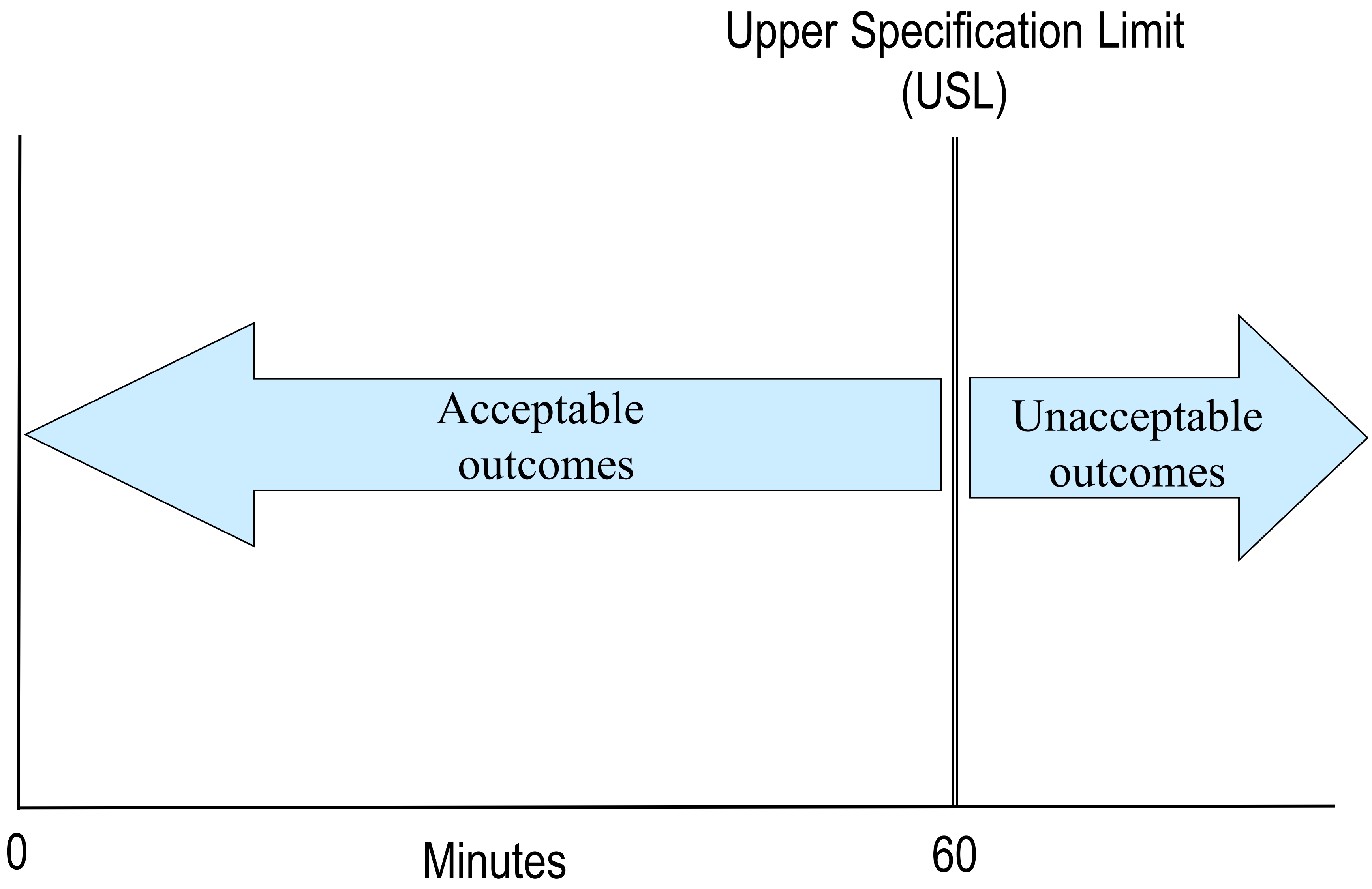
N

Call Engineer

Response plan (cont’d)

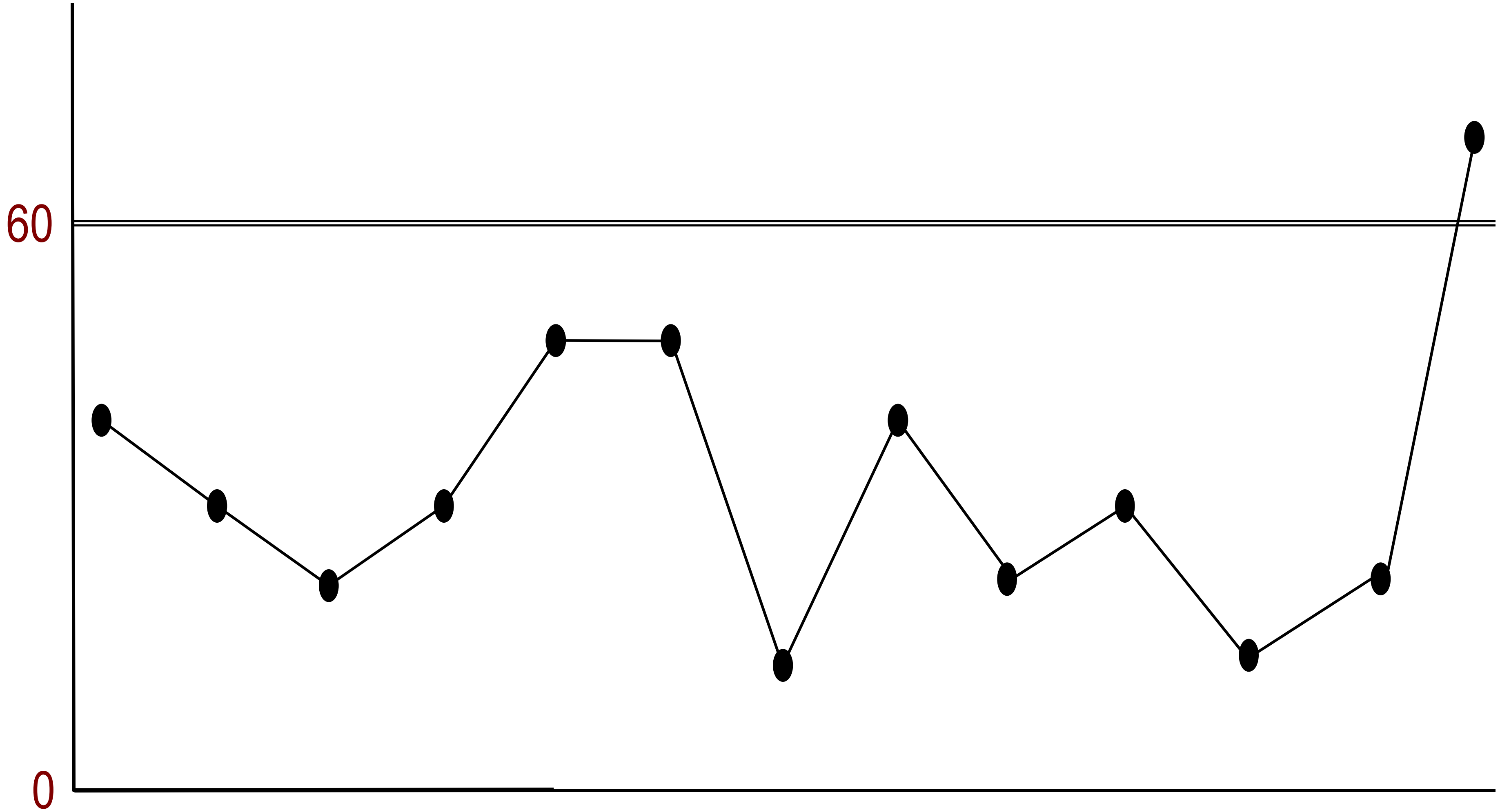
- Example from a high-volume automated assembly process (“sanitized”)
- Development team: operators, technicians, engineers, area manager
- Based on experience, they wanted to verify an OOC with a second sample from the same lot
- Note the escalation from Operator to Technician to Engineer.
- When an OOC was confirmed, production was halted
- Within a few months:
    - Chronic equipment and process problems were solved
    - Unplanned downtime and need for Engineering support plummeted
    - Engineers able to focus more on process improvement
    - Productivity increased dramatically

What about performance requirements?

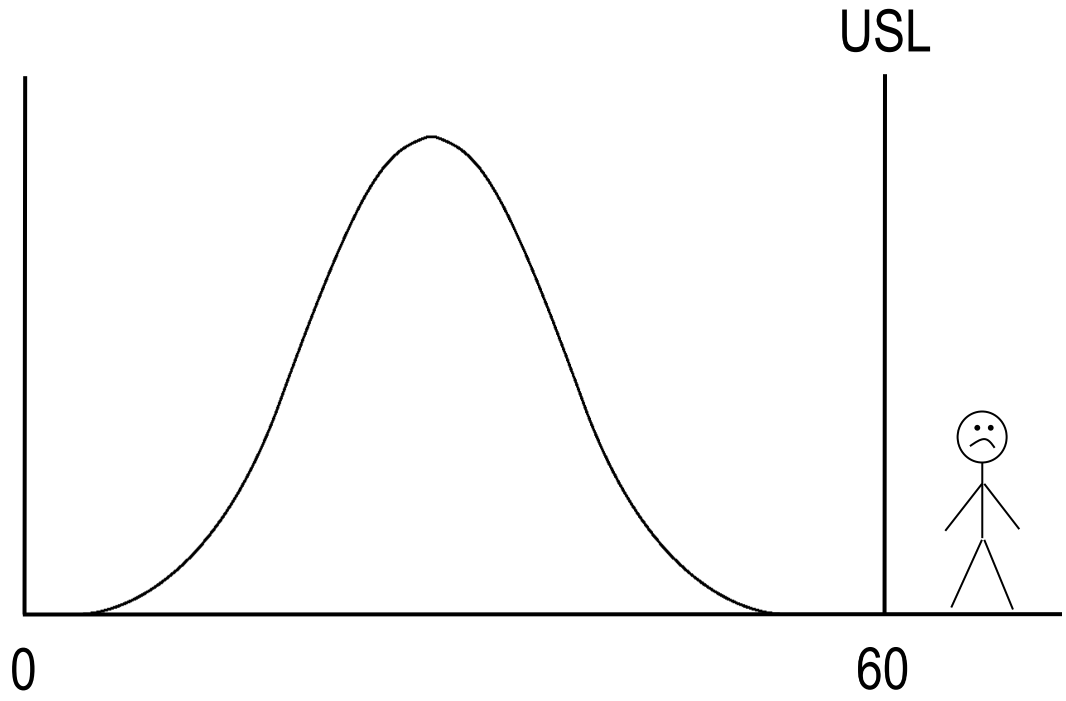


Out-of-specification event (OOS)

What do we do now?

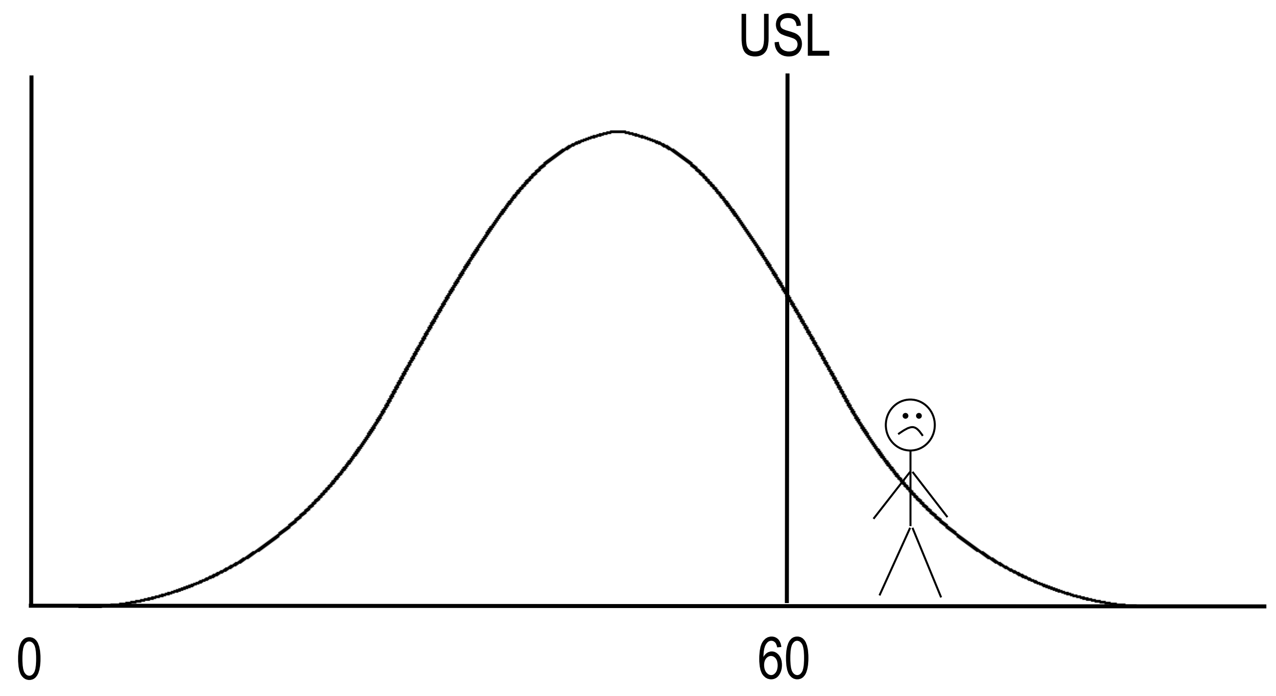


Scenario 1: process capability is good



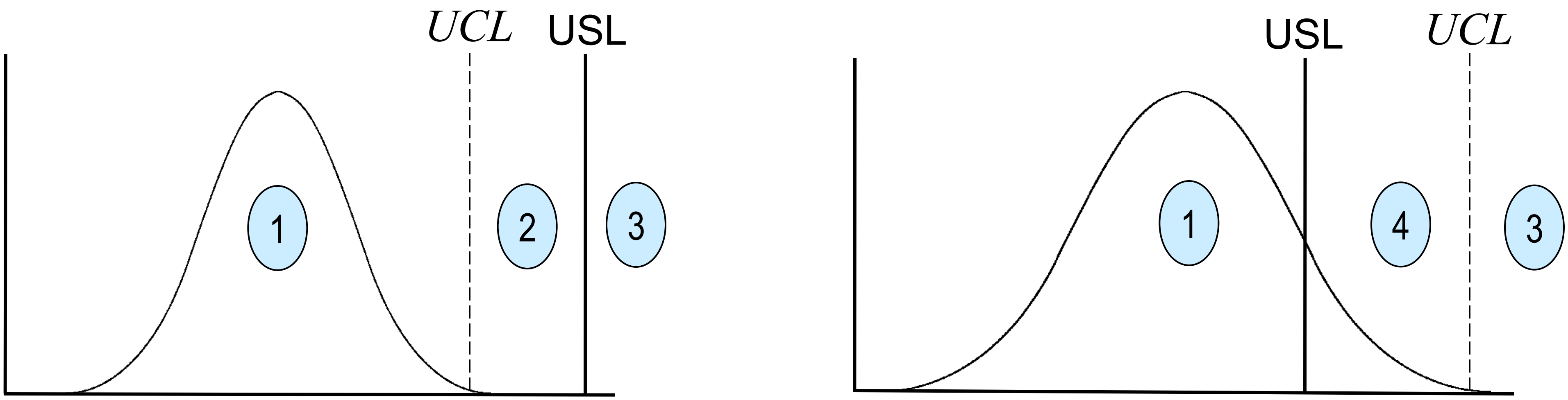
- If the process has good capability, it will virtually never produce a defective outcome, unless there is an assignable cause
- Any OOS point is also OOC
- Any OOS point should trigger the response plan

Scenario 2: process capability is poor



- If the process has poor capability, there will be OOS outcomes that are not OOC
- These outcomes do not indicate assignable causes
- They should *not* trigger the response plan

Exercise 22.1



Check the appropriate actions for outcomes in each of the 4 zones shown above.

Zone	Initiate OOC response plan	Scrap, rework, do over, etc.	Do nothing
1			
2			
3			
4			