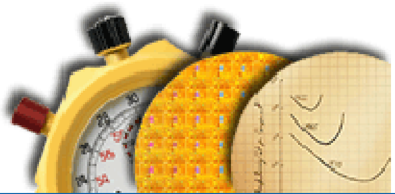

# Factory Physics®: A Fast Cycle Time Story

**Presenters**

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Intel Products, Vietnam

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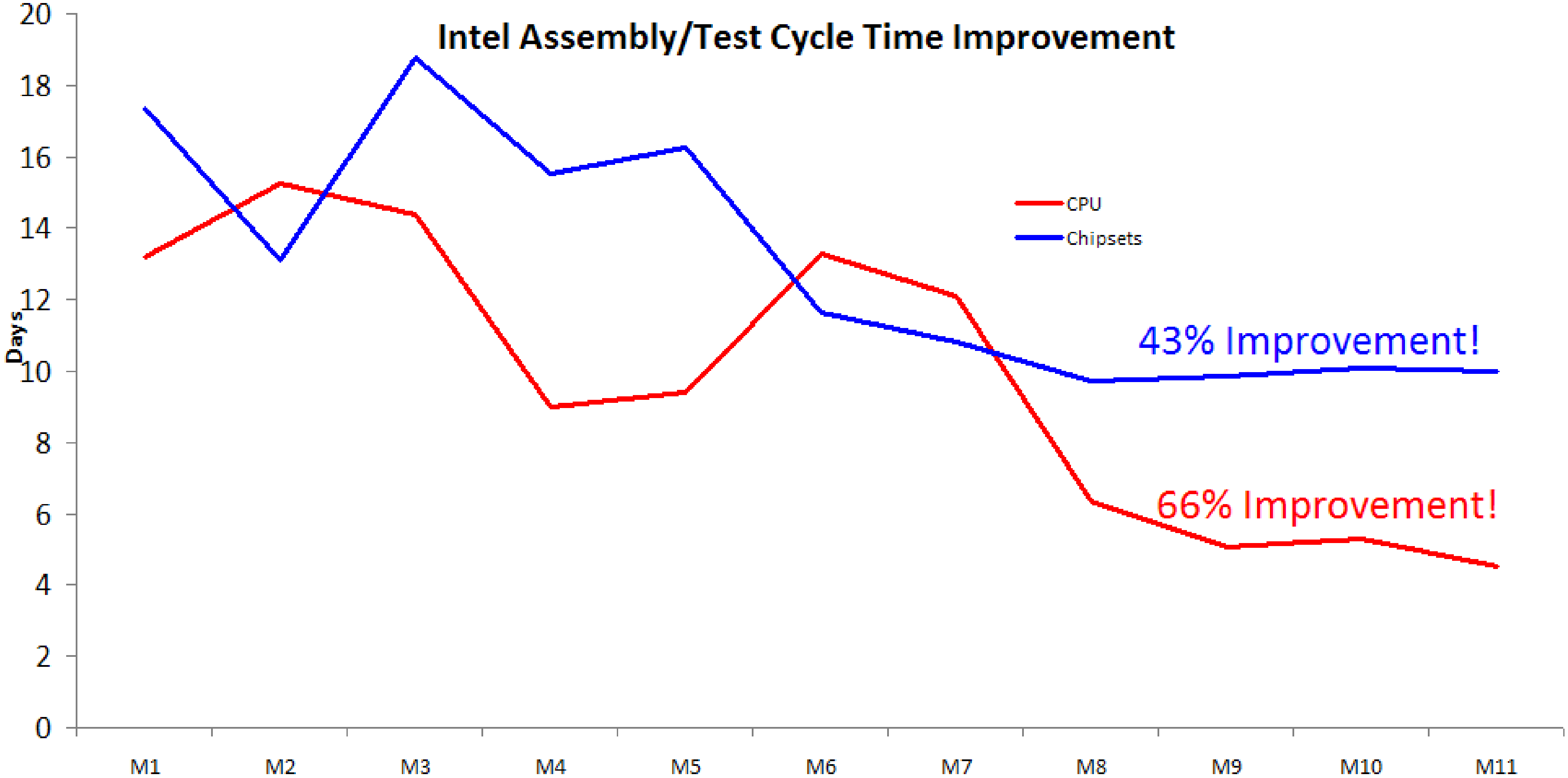
# Let's Start with the Results:



# How Did We Do This?

- Implementing a Lean Culture?
- Install a fancy pull / MRP system?
- Add Automation to our Factories?

***NO!.. None of These***

# Understand How Your Factory Works

## *Applying Math And The Scientific Method - Factory Physics ®*

Implementing rigorous engineering methods that we have all been taught.

» Improves Intuition

» Facilitates Data Based Decision Making

# What is Factory Physics ®

» Systematic process to identify areas for factory improvement

» Focuses heavily on variability (tool availability, outs, starts) as the primary source of inconsistent factory performance

**↓ variability = ↑ consistent output = ↓ cycle time**

» It is NOT a new catch phrase in the consulting arena.

» The core material is part of most Industrial Engineering curriculums and is practiced at many other companies

» Text book by Hopp and Spearmam

- Much more information than what we will touch of today…scheduling, forecasting, etc.

# A Manufacturing Law

Little's Law: ***The fundamental relation between WIP, CT, and TH over the long-term is:***

$$WIP = TH \times CT$$

- Example:

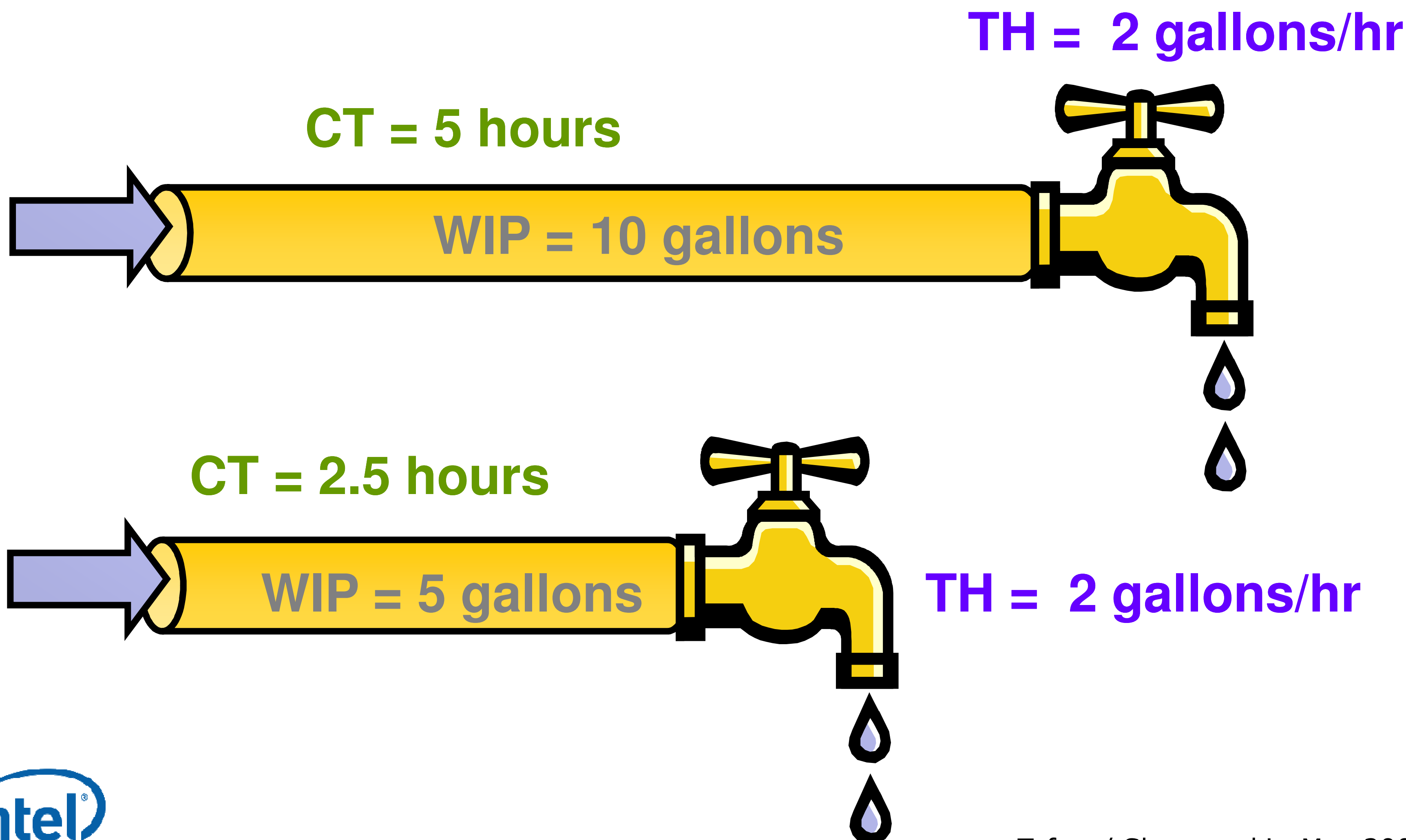
  Factory produces 100,000 parts/ week.

  To achieve a CT = 5 days and TH = 14,285 units / day

  WIP = 14.3k * 5 days = 71,500 units

# Illustrating Little's Law

## Cycle Time ↓ & WIP ↓: Throughput ?



# Definitions

**Throughput (TH):** Average quantity of *good* parts produced per unit time. EG: output or outs/ week

**Work in Process (WIP):** inventory between the start and endpoints of a product routing.

**Cycle Time (CT):** time between release of the job at the beginning of the routing until it reaches an inventory point at the end of the routing.

# Definitions

**Bottleneck Rate (BNR):** Rate (parts/unit time) of the process center having the highest *long-term* utilization.

**Raw Process Time (RPT):** Sum of the *long-term average* process times of each station in the line. This term isn't theortical and does not include queue time.

# Relationship of Terms:

**Critical WIP (CW):** WIP level in which a line having no variability would achieve maximum throughput (i.e., BNR) with minimum cycle time (i.e., RPT).

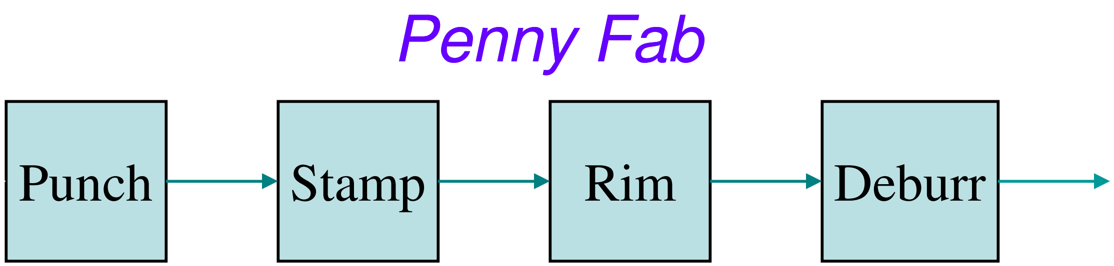
***The 'ideal' state***

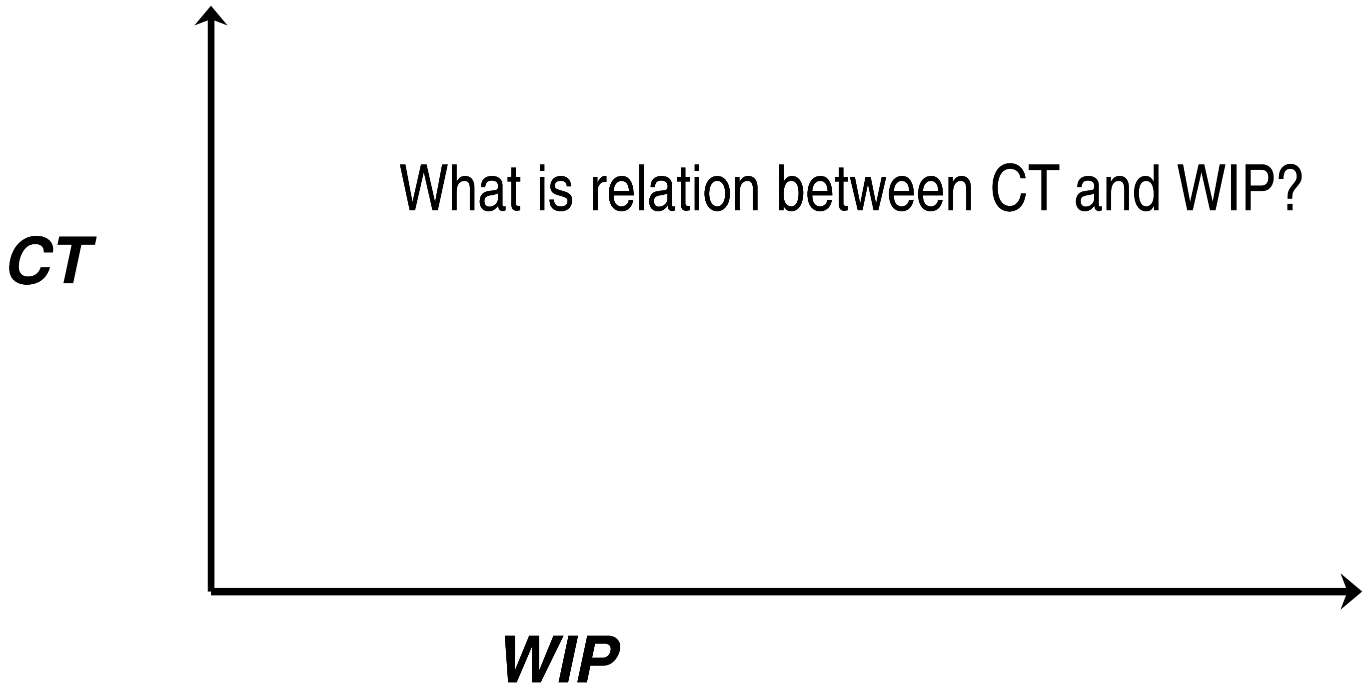
$$CW = RPT * BNR$$

So what does this look like?

» ***CW is the WIP level where … any additional inventory would cause material to accumulate queue time.***

# Make It Simple



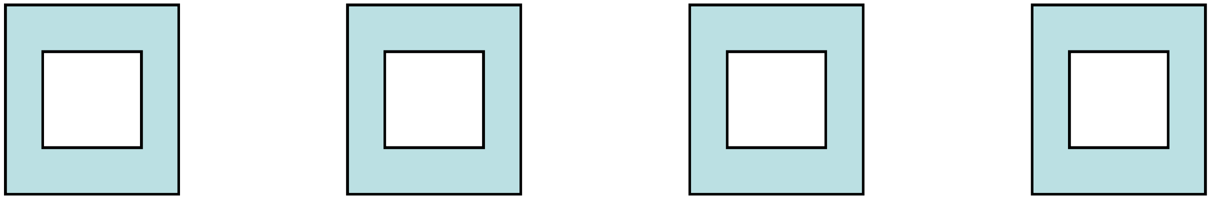




What is relation between CT and WIP?

# The Penny Fab

- Characteristics:
  - » Four identical tools in series.
  - » Each takes 2 hours per piece (penny).
  - » No variability.
  - » Jobs released to maintain target WIP levels (conwip)

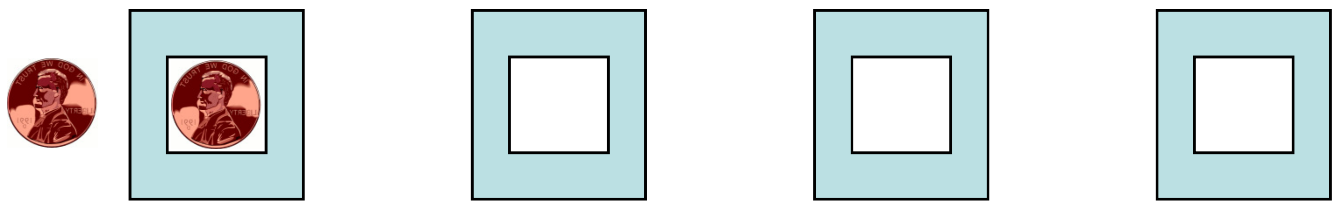
# The Penny Fab



# Penny Fab Performance

| WIP | TH | CT | TH* CT |
|---|---|---|---|
| 1 | 0.125 | 8 | 1 |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |

# The Penny Fab (WIP=2)

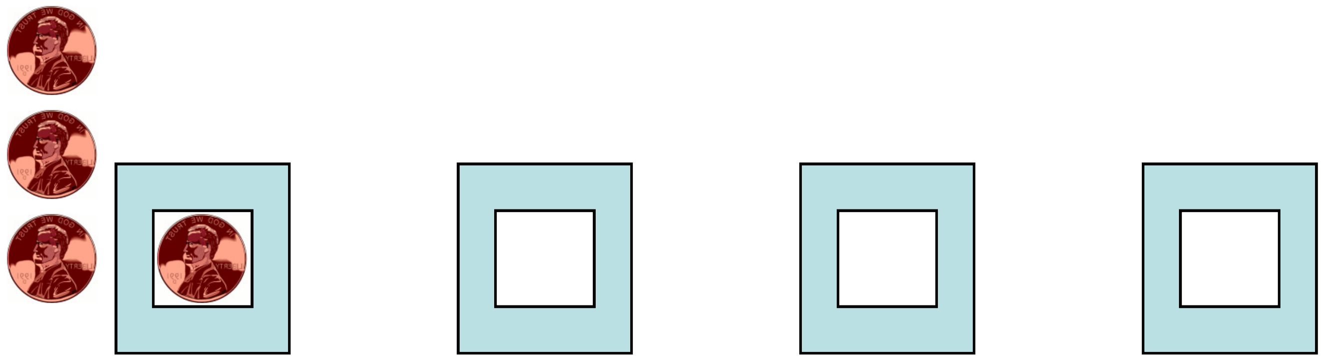


Time = 0 hours

# Penny Fab Performance

| WIP | TH | CT | TH*CT |
|---|---|---|---|
| 1 | 0.125 | 8 | 1 |
| 2 | 0.250 | 8 | 2 |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |

# The Penny Fab (WIP=4)

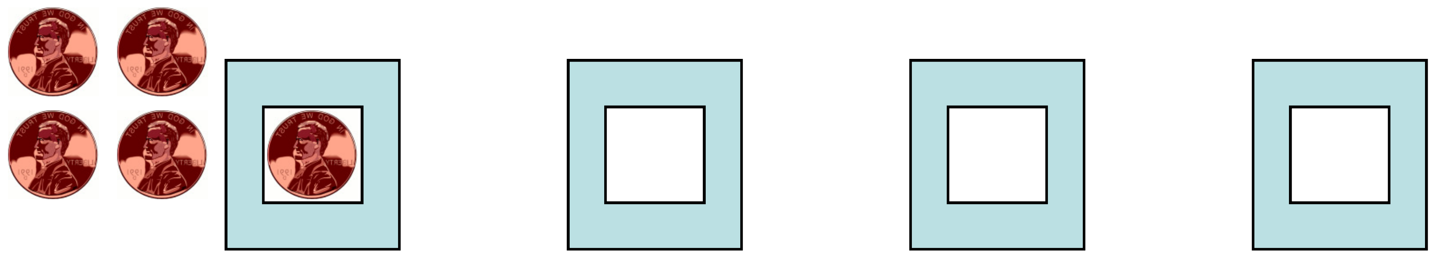


Time = 0 hours

# Penny Fab Performance

| WIP | TH | CT | TH*CT |
|---|---|---|---|
| 1 | 0.125 | 8 | 1 |
| 2 | 0.250 | 8 | 2 |
| 3 | 0.375 | 8 | 3 |
| 4 | 0.500 | 8 | 4 |
| 5 | | | |
| 6 | | | |

# The Penny Fab (WIP=5)



Time = 0 hours

# Penny Fab Performance

| WIP | TH | CT | TH*CT |
|---|---|---|---|
| 1 | 0.125 | 8 | 1 |
| 2 | 0.250 | 8 | 2 |
| 3 | 0.375 | 8 | 3 |
| 4 | 0.500 | 8 | 4 |
| 5 | 0.500 | 10 | 5 |
| 6 | 0.500 | 12 | 6 |

# Variability Buffering

- Buffering Law: *Systems with variability must be buffered by some combination of:*
  1. ***inventory***
  2. ***capacity***
  3. ***time.***

- Interpretation: **If you cannot pay to reduce variability, you will pay in terms of high WIP, under-utilized capacity, or reduced customer service (i.e., lost sales, long lead times, and/or late deliveries).**

# With Variability

| WIP | TH | CT | TH*CT |
|---|---|---|---|
| 1 | 0.125 | 8 | 1 |
| 2 | | | |
| 3 | | | |
| 4 | | | |
| 5 | | | |
| 6 | | | |

# With Variability is Much Worse

| WIP | TH | CT | TH*CT |
|---|---|---|---|
| 1 | 0.125 | 8 | 1 |
| 2 | 0.200 | 10 | 2 |
| 3 | 0.250 | 12 | 3 |
| 4 | 0.286 | 14 | 4 |
| 5 | 0.313 | 16 | 5 |
| 6 | 0.333 | 18 | 6 |

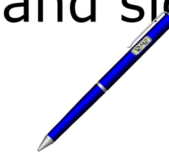
# Variability Buffering

- Buffering Law: *Systems with variability must be buffered by some combination of:*
    1. ***inventory***
    2. ***capacity***
    3. ***time.***

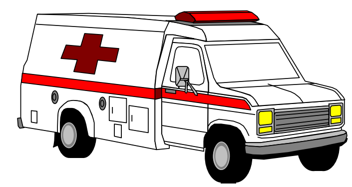
- Interpretation: **If you cannot pay to reduce variability, you will pay in terms of high WIP, under-utilized capacity, or reduced customer service (i.e., lost sales, long lead times, and/or late deliveries).**

# Variability Buffering Examples

- **Ballpoint Pens:**
  - » can't buffer with time (who will backorder a cheap pen?)
  - » can't buffer with capacity (too expensive, and slow)
  - » *must buffer with inventory*



- **Ambulance Service:**
  - » can't buffer with inventory (an inventory of trips to hospitals?)
  - » can't buffer with time (response time is *the key measure*)
  - » *must buffer with capacity*



- **Organ Transplants:**
  - » can't buffer with WIP (perishable - very short usable life)
  - » can't buffer with capacity (we cannot ethically increase capacity)
  - » *must buffer with time*

# A Manufacturing Law:

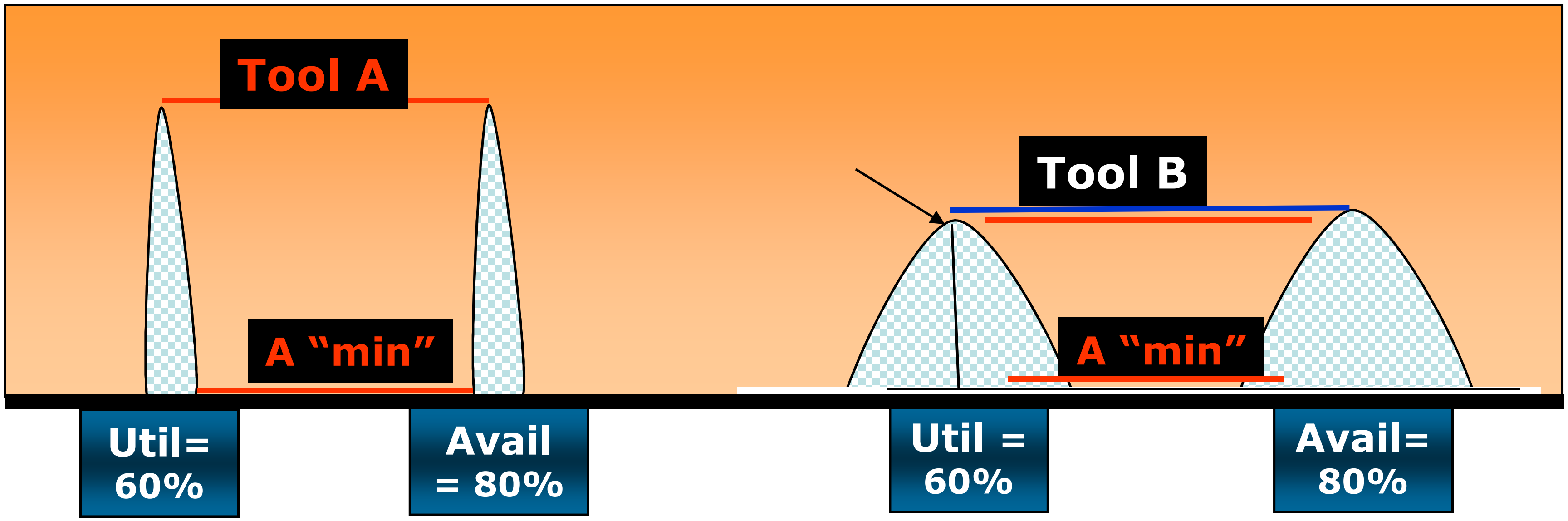
- **Little's Law:**
  - » *The fundamental relation between WIP, CT, and TH over the long-term is:*

**WIP =TH*CT**

- **Critical WIP (Lean: "Ideal State"):** WIP level in which a product flow having no variation would achieve maximum throughput (i.e., BNR) with minimum cycle time (i.e., RPT).

**CW = RPT * BNR**

# Which Equipment Provides the Better Capacity and/or Velocity?

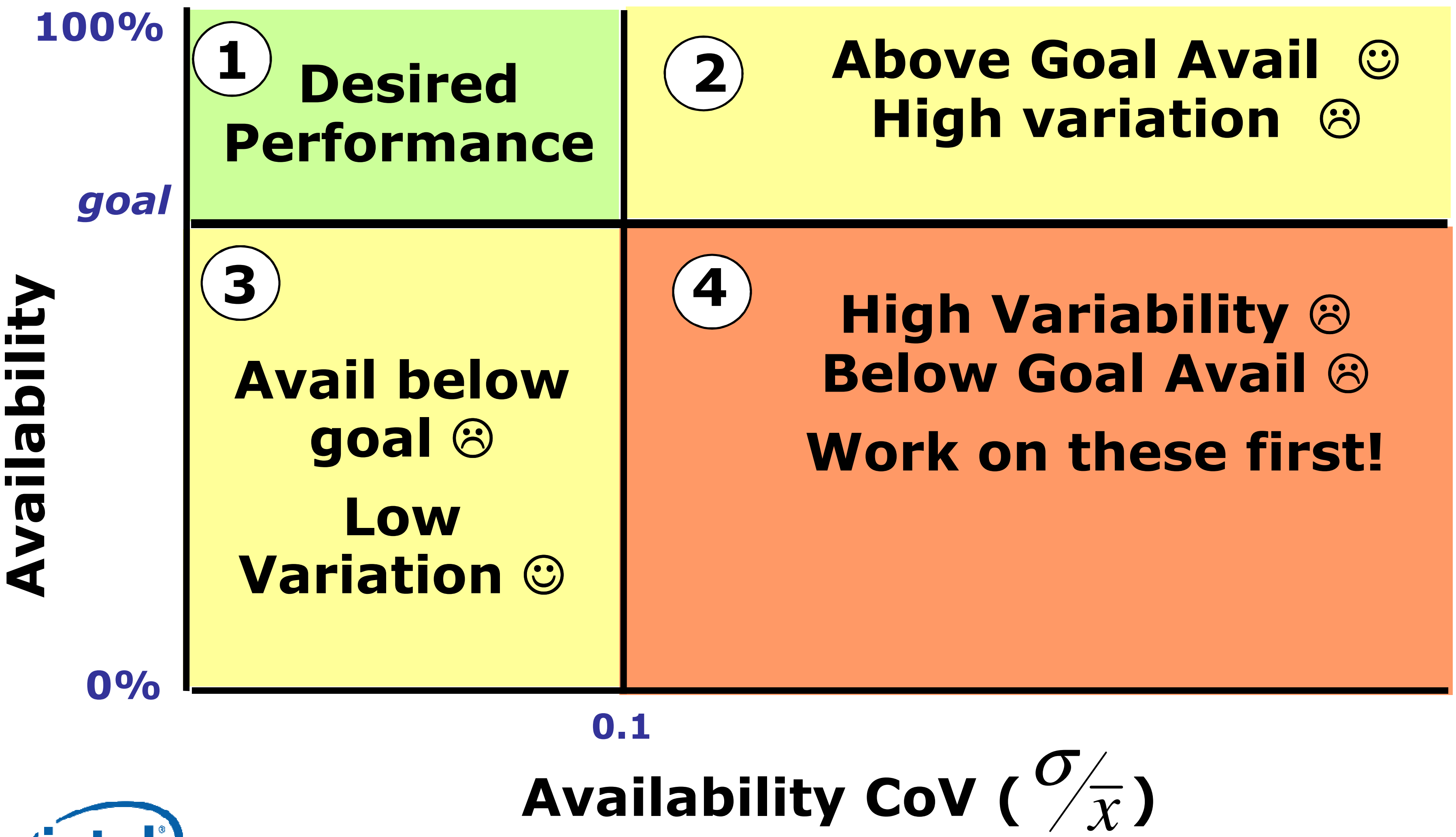



- Average capacities don't mean much w/o knowledge of *the distribution about the averages*
- Distributions imply knowing about the variation of your processes
- Coefficient of Variation (CoV) is a good measure distribution and variation. CoV= $\sigma / \bar{x}$

# Reducing Variation to Improve Factory Performance

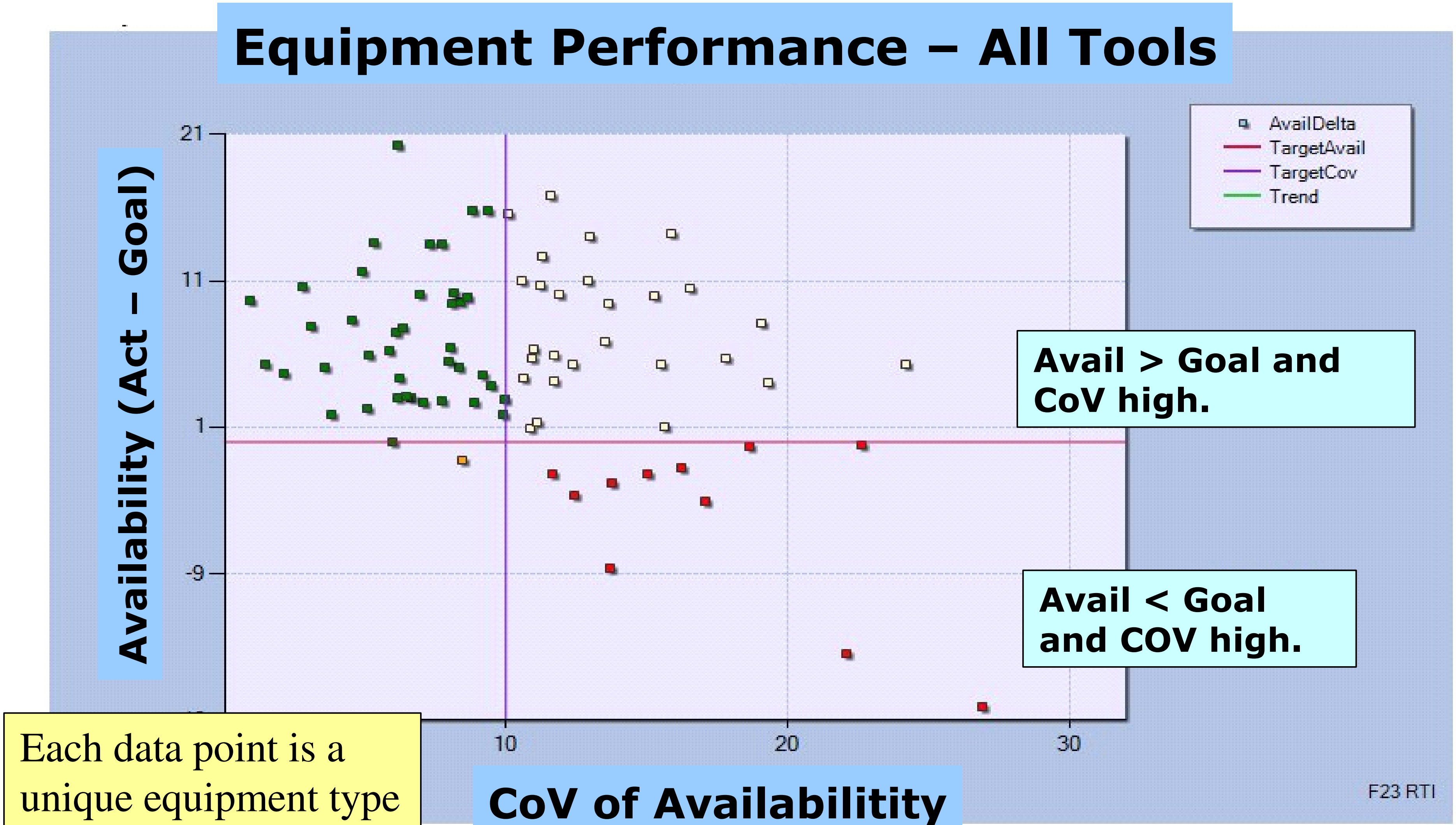
- **Equipment Performance**
  - » Frequency and duration of downtime events
  - » Stability of process (targets, rework, sampling)
- **Operational Rules**
  - » Lot Size, WIP processing strategy (FIFO, Customer commit date, etc)
  - » Response to material that is placed ‘on hold’ for being deviant from standard.
- **People**
  - » Coverage for breaks / lunches
  - » Skill level and competency on key tasks.

# Equipment Availability Variability Analysis




Each data point equals unique tool. Smallest data increment possible

# Availability Variability



# Intel Application of Factory Physics® for Significant Reduction in Cycle Time

- **Build the Knowledge**
  - » Training for all in Factory Physics®
- **Apply the Learnings**
  - » Frequent metric review (CT, WIP, TH)
  - » Relentless efforts to reduce variation
  - » Active sharing of wins between factories
- **Embed the Knowledge**
  - » Reward variation reduction and low cycle time

# Intel Application: Build the Knowledge

Training for all in Factory Physics and Variation Reduction.

- 1 hr class for hourly line workers
- 2 hr class for introduction to terms/ concepts
- 1 day class for all salaried factory personnel
- 20 hr class (5 ½ days) for factory champions of cycle time and variation reduction

**Over 1000 people educated...**

# Intel Application: Apply the Learnings

- Little's Law based Cycle Time Goaling
  - » CONWIP implementation to control WIP and enable fast cycle time
  - » Functional Area level WIP and CT goals to identify factory bottlenecks
- Frequent Metric Review and Factory to Factory Comparison
  - » WIP levels: to ensure low CT
  - » Cycle Time in days: to benchmark across sites
  - » CoV of Availability: to drill-down on sources of variability
- Automated Reporting
  - » Enables real-time access to entire factory network performance

# Intel Application: Embed the Knowledge

- Reward low cycle time with bonus for employees
  - » Incentive inspired healthy competition between factories
- Further expand review of metrics
  - » Variability measures and Critical WIP ratios recognized by top management
- Educate business partners on Factory Physics ™ and the importance of variation reduction
  - » The revolution continues!

# Final Message

We are constantly learning and are never 'done'.

There is always more variation that can be reduced / eliminated.

# Three Formulas of Variability in Queuing Systems

1 **Polloczek-Khintchine** (P-K) *Equation*, also called 'VUT Equation' and its extensions

» To determine *cycle time and waiting time*

2 **Variability Propagation** (a.k.a.: "Linking") *Equation*

» To determine the *propagation of variability* throughout the factory

3 **Effective Process Time Variability** *Equation*

» To determine the impact of variability at a process step

1

# The P-K Equation: CTq (G/G/1 Queue Model)

$$\mathrm{CT}_q \approx V \times U \times T$$

$$\approx \left(\frac{c_{ar}^2 + c_{te}^2}{2}\right)\left(\frac{\rho}{1-\rho}\right)\cdot t_e$$

**Variability Of Flow:**

- » This is a measurement of the variability of inventory flows into the area (e.g., "we were dry for three weeks, and then we got dumped on and that's why our CT is red")
- » Batch/Cascading often "pulses" the factory

**Most flow issues in our factory have been caused by availability issues**

**Variability of process times:**

- » Variability of how long a lot takes to get through an operation once it gets there. (e.g., "all our tools went down, we built a ton of inventory and our CT went red until we ran it out.")

- **These issues are generally caused by:**
  - » Availability
  - » Variability in availability

2

# Variability Propagation: Estimating $c_{dr}^2$

## (Departure Rate Coefficient of Variation)

$$C_{dr}^2 \approx 1 + (1-\rho^2)(C_{ar}^2 - 1) + \frac{\rho^2 \cdot (C_{te}^2 - 1)}{\sqrt{m}}$$

**Where:**

ρ = occupancy rate

m = number of machines in workstation

$c_{ar}^2$ = squared CoV of the process step's arrival rate

$c_{dr}^2$ = *the squared CoV of the process step's departure rate*

$c_{te}^2$ = the squared CoV of the process step's effective processing time

# 3 Effective Process Time Variability: Estimating $c_{te}^2$

$$C_{te}^2 \approx C_t^2 + A \cdot (1-A) \cdot \frac{MTTR}{t} + A \cdot (1-A) \cdot \frac{MTTR}{t} \cdot C_r^2$$

**Where:**

- $c_t^2$ = *Inherent* process variability
- **A** = Machine Availability; A = MTTF/(MTTF + MTTR)
- **MTTR** = Mean Time To Repair (averaged across all repairs)
- **MTTF** = Mean Time To Failure (averaged across all uptimes)
- **t** = Process Time
- $c_r^2$ = CoV of Repair Times

**Since 2nd & 3rd terms increase with higher MTTR, *therefore***
**Longer repair times induce greater variability.**