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R&D Operations: Systems Engineering at the Z Pulsed Power Facility

Exploring nonlinear dynamics approaches for systems thinking

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INCOSE Enchantment Chapter June 2025 monthly meeting

U.S. DEPARTMENT OF ENERGY NNSA

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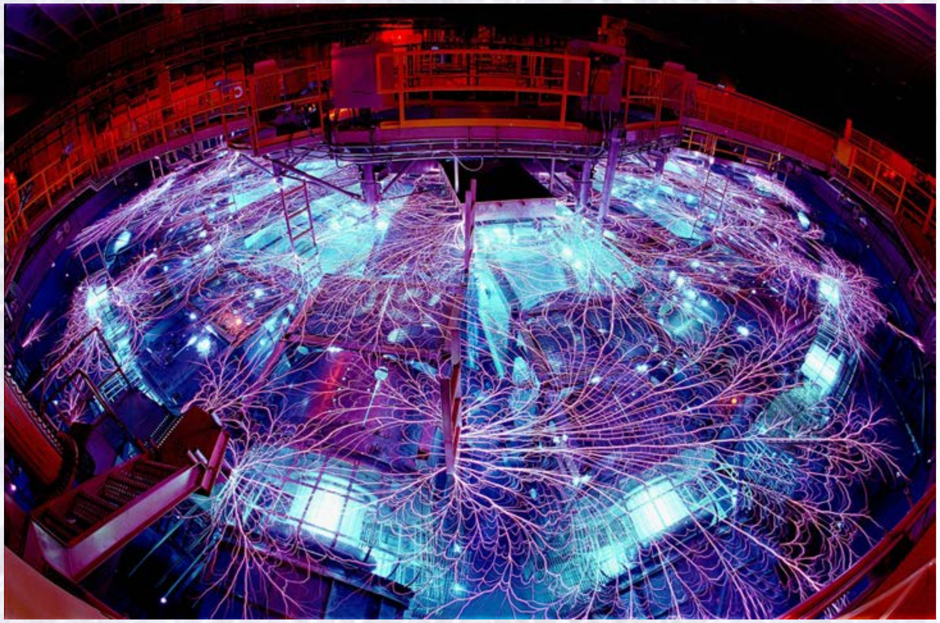
Outline

- Why traditional systems engineering is complicated at Z
- My background in nonlinear dynamics
  - How we sketch system dynamics to understand them
- The Z Facility!
- Archetyping the Z Facility: R&D operations
- Systems engineering in R&D operations

My job: systems engineer supporting Z pulsed power operations

- Z performs about 150 shots a year
- Each shot takes about a day* to configure, execute, and clean up
- Errors can result in damage to data, equipment, people, and the environment
- How do we succeed each day and each year?



* Shot complexity varies! Many shots take 2 days, some shots take up to 4 days!

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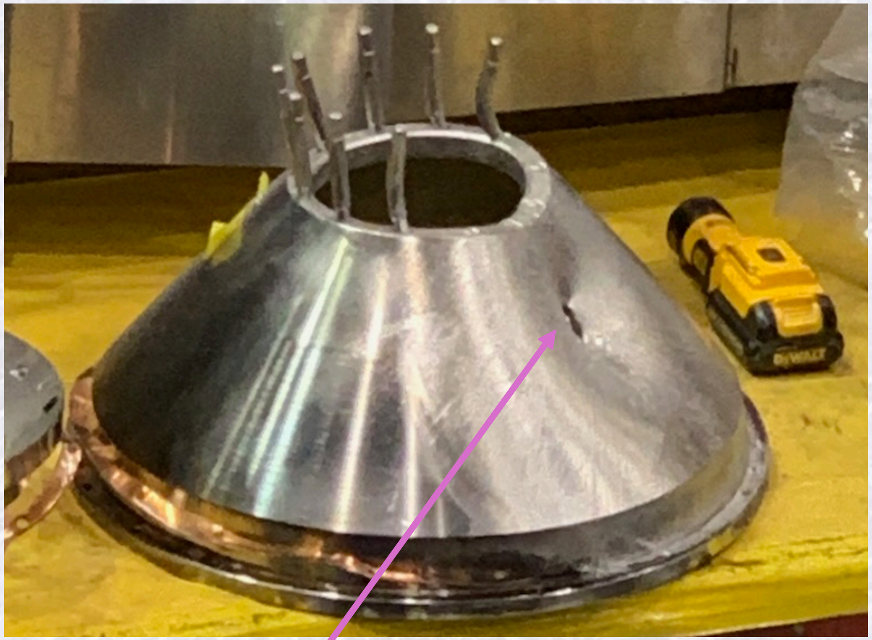
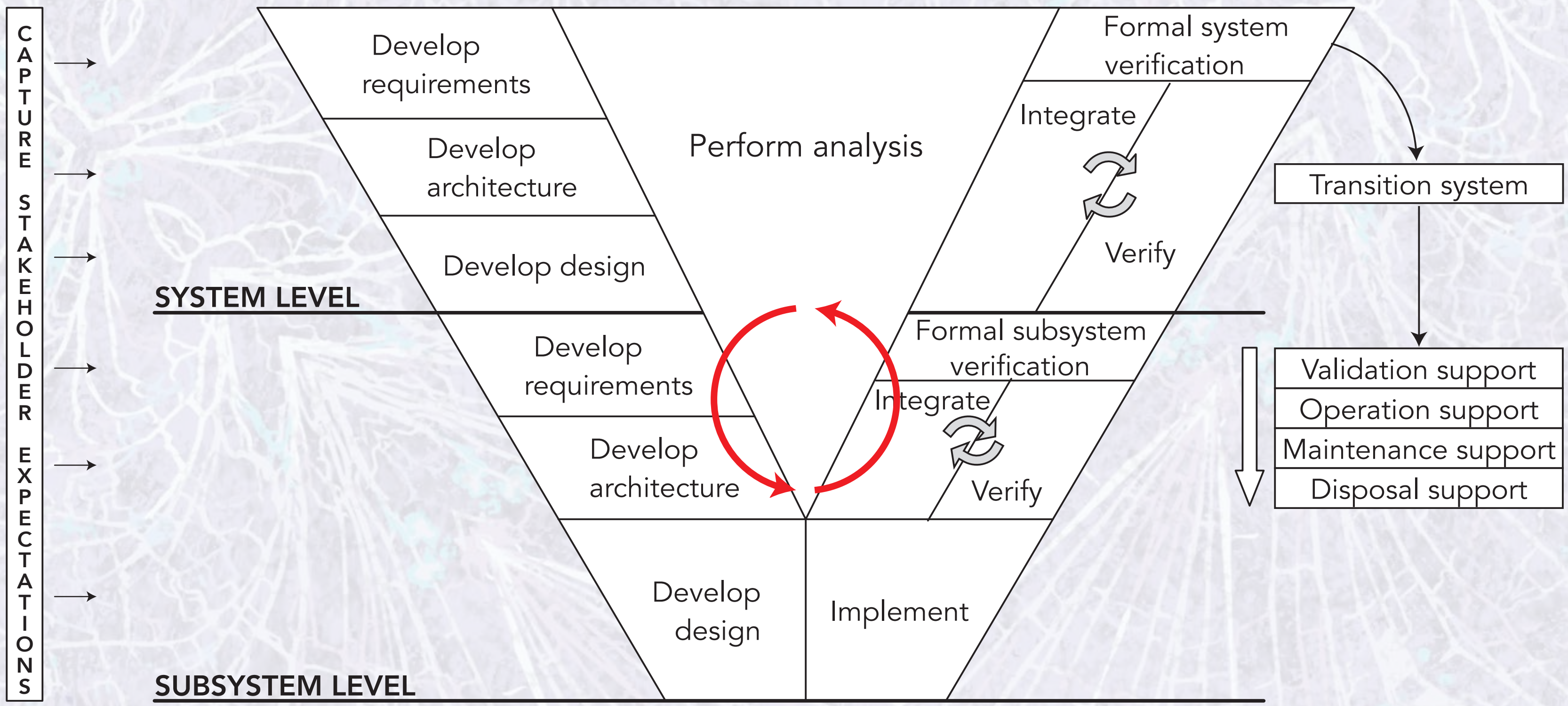


Unknown failure point

* Shot complexity varies! Many shots take 2 days, some shots take up to 4 days!

We live in the trough of the systems V

We iterate on subsystems and components many times for every system-level redesign.

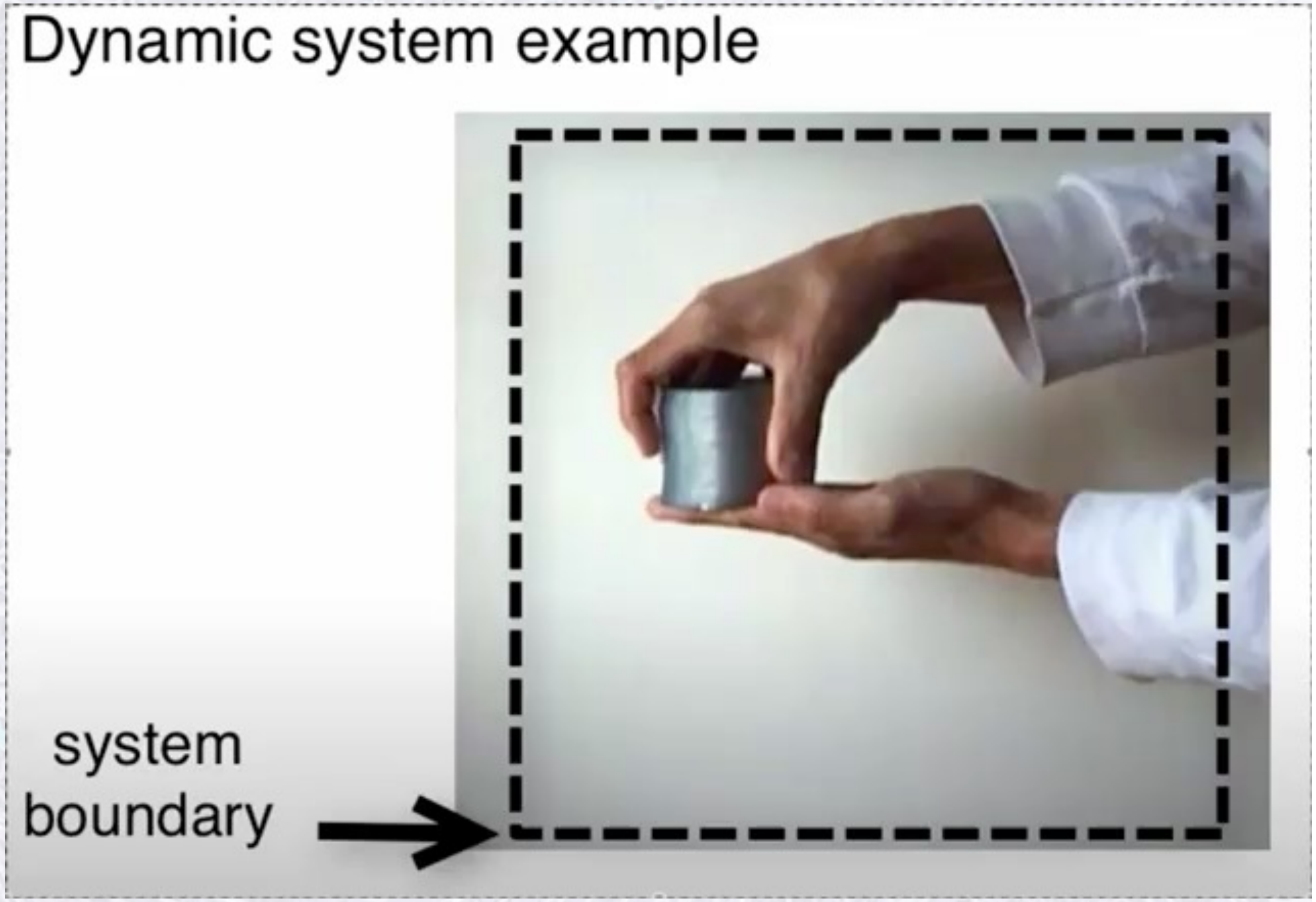


Tom Humpton, “Graphical View of SE”, Mar 6, 2025 talk to Sandia Systems Engineers.

Modified systems engineering Vee model

System nature informs system behavior

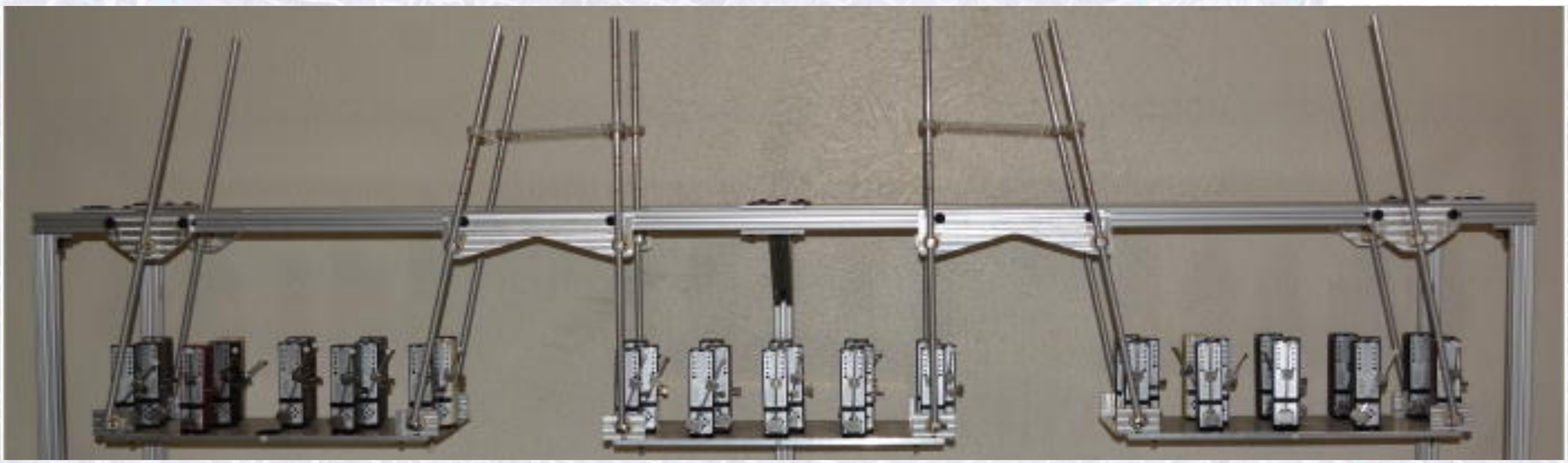
- Toy example: slinky
- Why does the system oscillate after removing the hand?
- It oscillates due to the nature of the slinky



Example from "Thinking in Systems" by Donella Meadows

My research background

- BS and PhD in chemical engineering from Mizzou and UVA
- Research in nonlinear dynamics, self organization, and complexity



Blaha, et al. "Symmetry effects on naturally arising chimera states in mechanical oscillator networks." *Chaos: An Interdisciplinary Journal of Nonlinear Science* 26.11 (2016).

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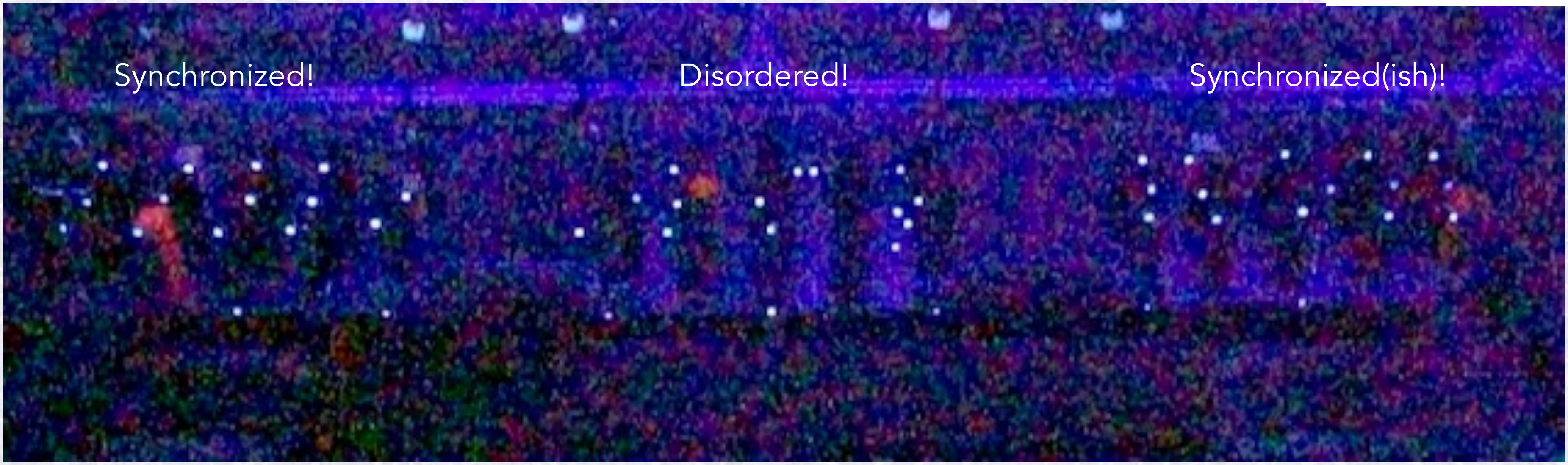

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A crash course in nonlinear dynamics in 5 slides!

How a qualitative understanding gives more behavioral insights than a quantitative solution

How do we understand a differential equation?

parameter

$$\frac{dx}{dt} = x' = \boxed{r}x - x^3$$

Pitchfork bifurcation "normal form"

ODE class: analytically solve for x(t), giving us a numerical value for x for all time

$$x(t) = \pm \frac{\sqrt{r}e^{r(c_1+t)}}{\sqrt{e^{2r(c_1+t)-1}}}$$

(according to Wolfram Alpha…)

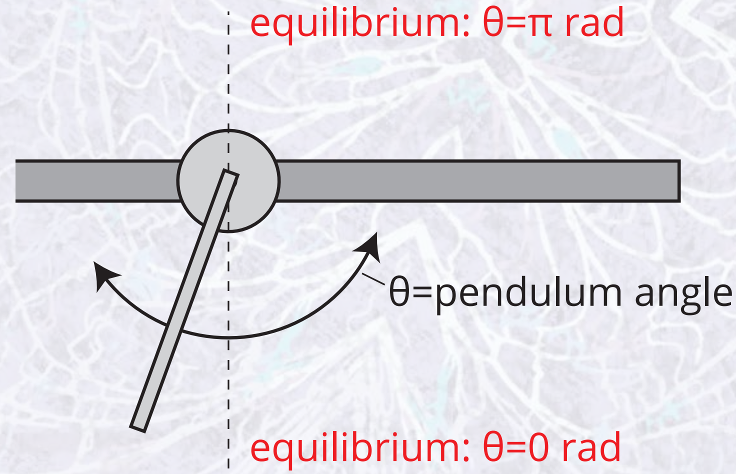
What does this tell us?

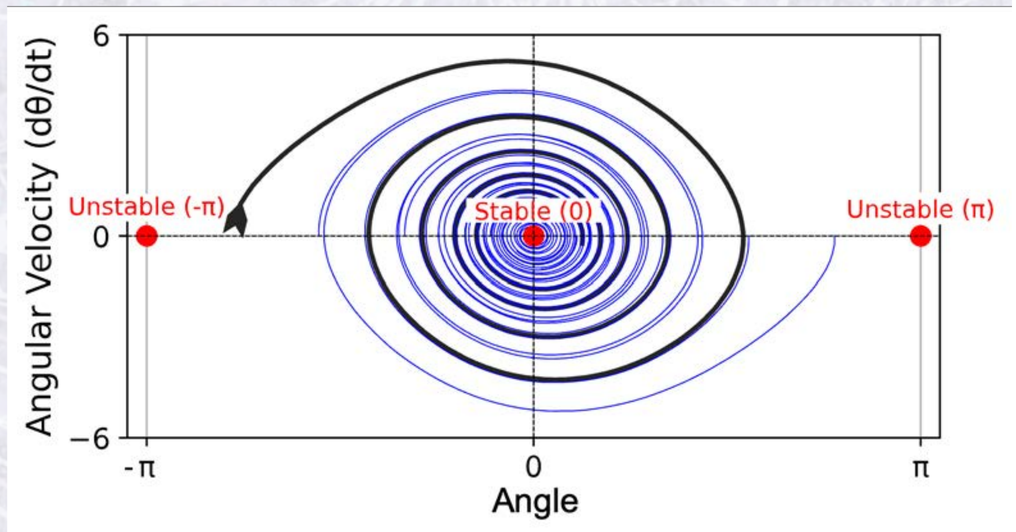
Nonlinear dynamics: Pictures guide intuition

1. Find equilibrium solutions
   - ie, where change in x, (x'), is 0

2. Test where trajectories go
   - Toward equilibrium: stable solution
   - Away from equilibrium: unstable solution

Simple pendulum



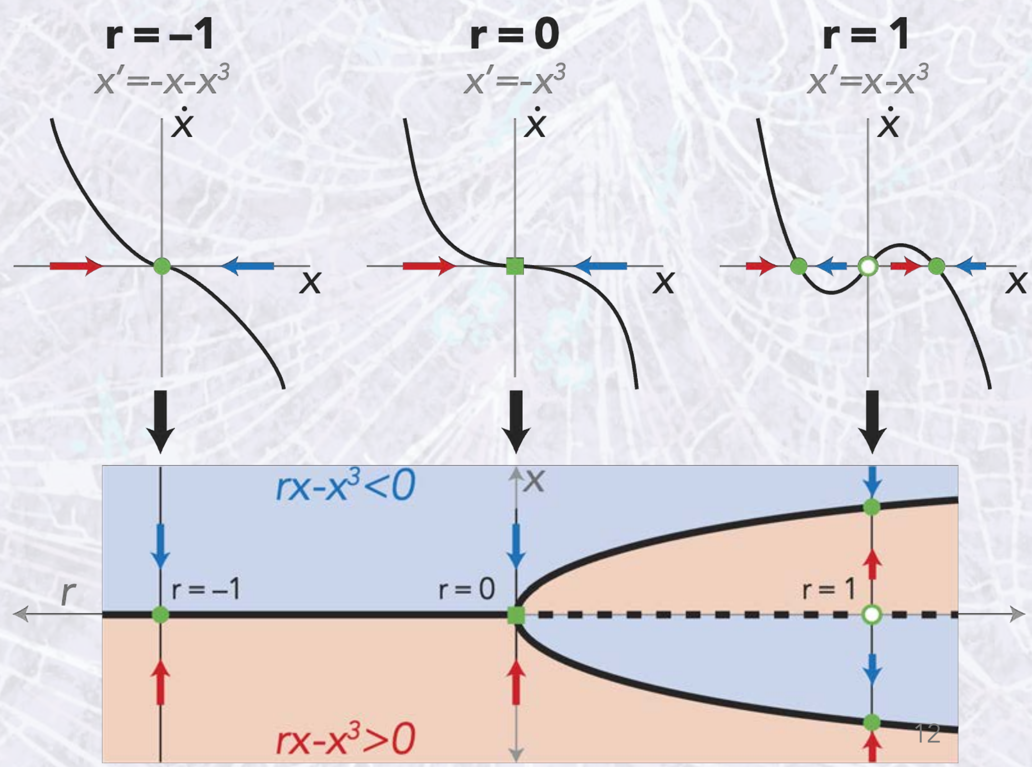


"Portraits" of a pitchfork bifurcation

Pictures gives a holistic understanding of system behavior!

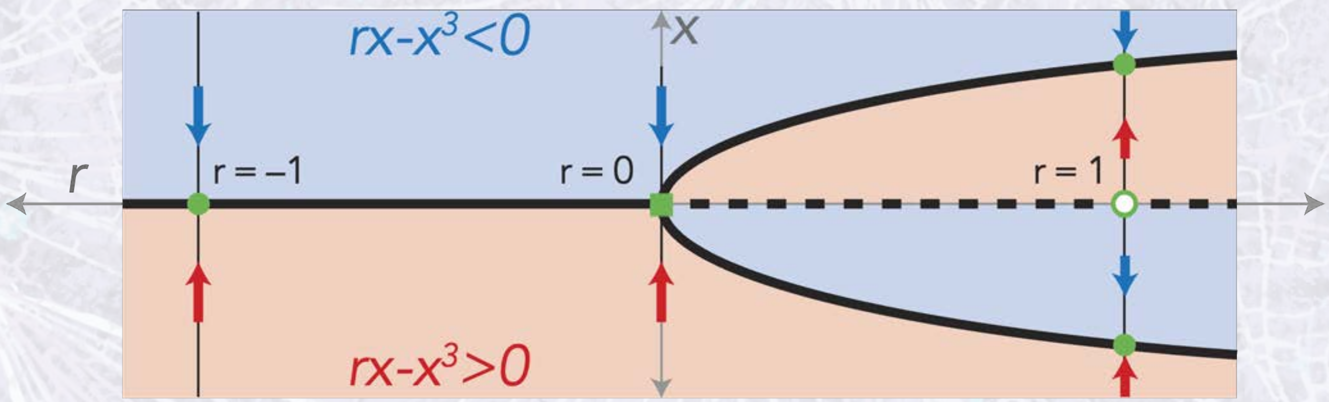
$$x' = \boxed{r}x - x^3$$

parameter



Systems with pitchfork bifurcations

- **Column under a load:** The column withstands the load until a critical value, then it can buckle to the left or to the right
- **Convection cell:** air heated from the bottom will eventually start to circulate. It can roll left or right

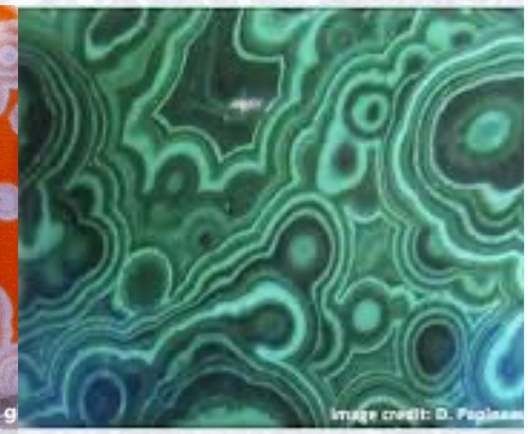


For more, see anything by Steven Strogatz, especially “Non-linear Dynamics and Chaos”

Behavior ↔Mathematics/System nature

- We see characteristic behaviors with a pitchfork bifurcation
- Sometimes common patterns allow us to deduce common mathematics—even when we don’t know how to write the math

Belousov-Zhabotinksy
Chemical reaction



Malachite stone

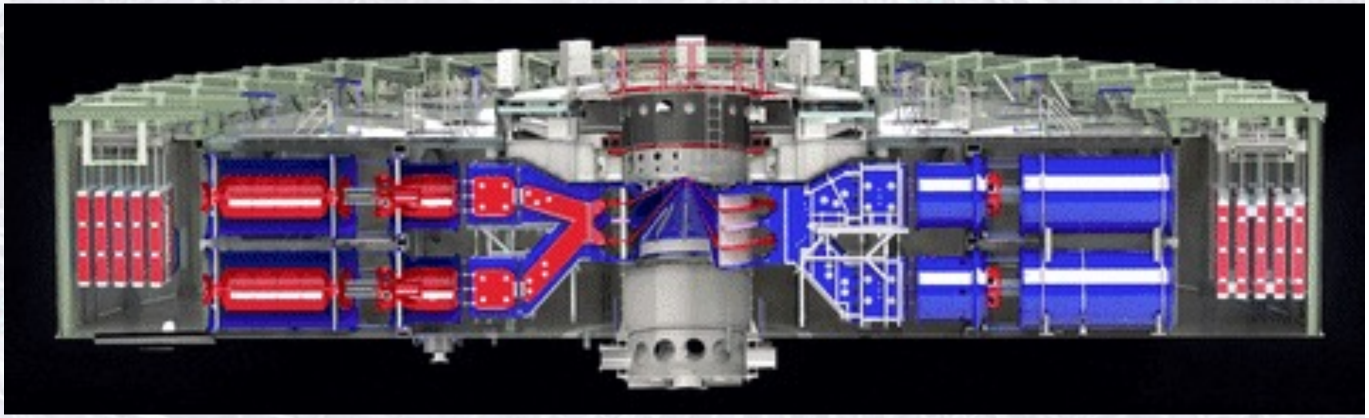
A chaotician* walks into the Z Machine…

*Yes, people use this term!

What does Z do

Something new today that it didn't do yesterday

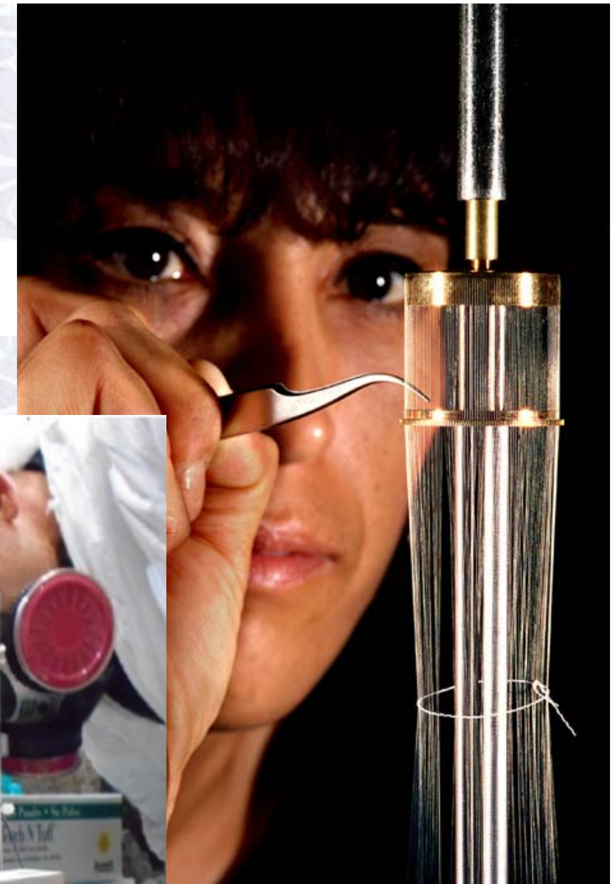
- Z is an R&D operational facility to probe physics questions at high temperatures and pressures
  - Fusion
  - Materials science
  - Radiation effects
- For many applications
  - Stockpile stewardship
  - Fundamental research (~10%)



How does Z do it?

A different way every day, every year

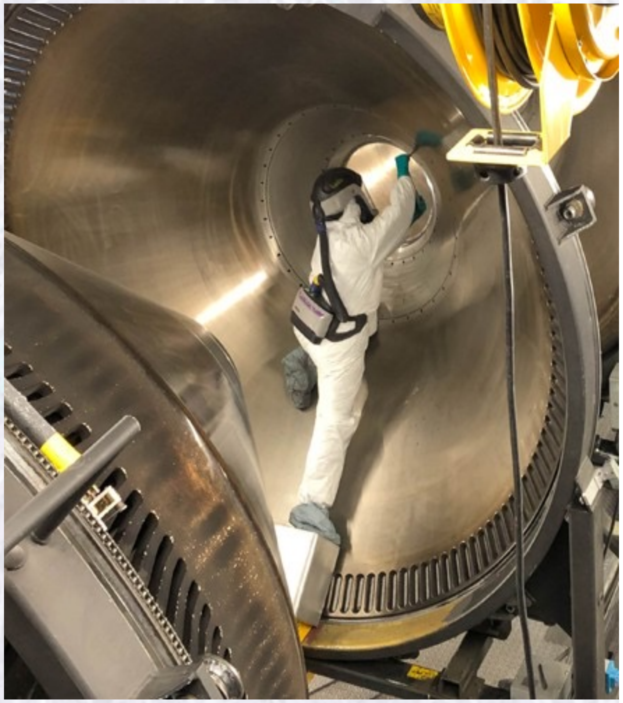
- Right: load hardware from ~1997
  - 100% of shots then
  - <10% of shots now
- Left: load hardware from ~2020
  - One of several configurations



These pictures show just a small piece of the change. We've also had huge changes in diagnostic types & quantities, fabrication, assembly & installation.

What is our system?

- "A **system** is an **interconnected set of elements** that is coherently organized in a way that **achieves something**." –*Thinking in Systems*, Donella Meadows
- Z Machine and its community of operators, engineers, and scientists.
- We expand scientific knowledge with pulsed power technology.



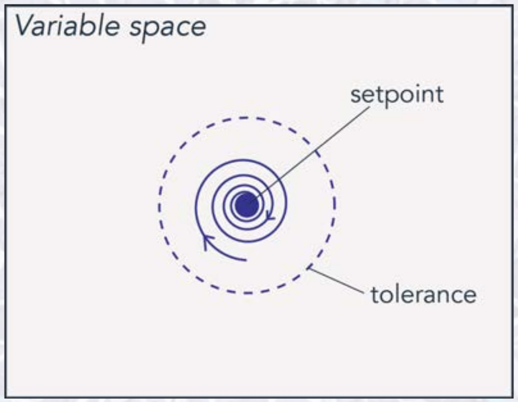
Z behavior: we expand scientific knowledge with pulsed power technology

- Every 1-4 days, Z does a different experiment.
- We combine hazards and controls in new ways!
- Rapid scientific evolution means we push our boundaries with each shot—the status quo is never enough.
- Mission needs require us to extend our accomplishments or look at something new.

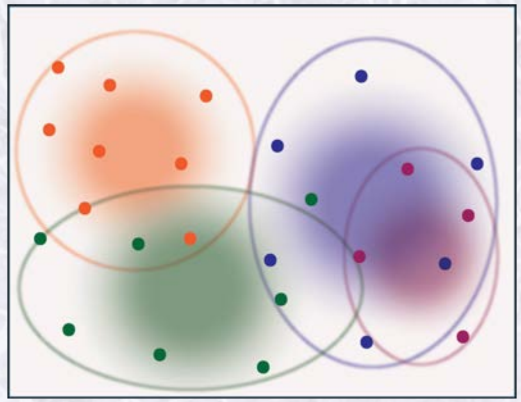
If this is the behavior of Z, what is its nature?

R&D Operations

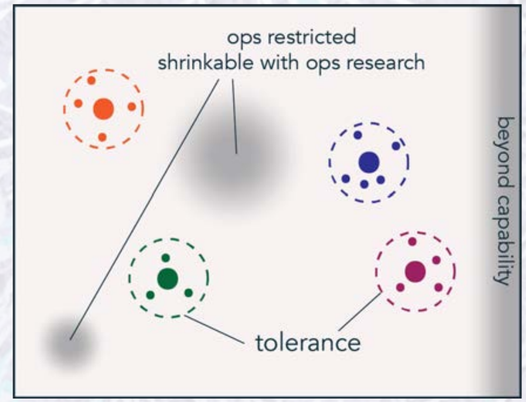
Production Operations



Research



R&D Ops



Minimized scope
Low agility
Prioritized definition & stability
Requires **capacity**

Maximized scope
High agility
Prioritizes exploration & modifiability
Requires **innovation**

Each scope small, **global scope large**
Low agility
Prioritizes encapsulation
Requires **capacity AND innovation**

How can we learn from this archetype?

We aren’t the only R&D operations facility

- Other facilities face similar R&D ops challenges
  - Understand how others face the associated challenges
- Some similar pain points, some dissimilar
  - Solar test facility vs Z vs Annular Core Research Reactor (ACRR)



Work in progress!

Systems engineering in R&D operations

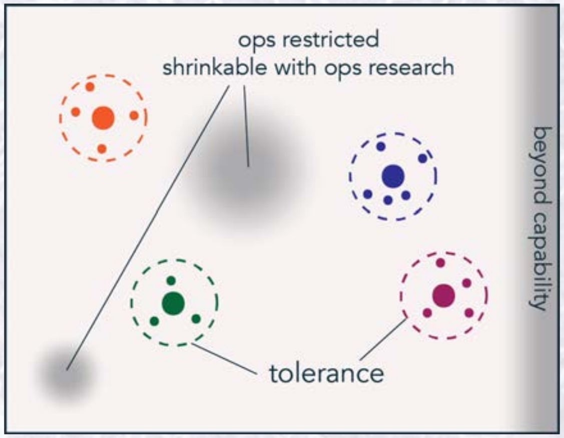
Two examples of how the label can support systems engineering

R&D ops: digesting research into ops

How do we translate research objectives into operational requirements and execution?

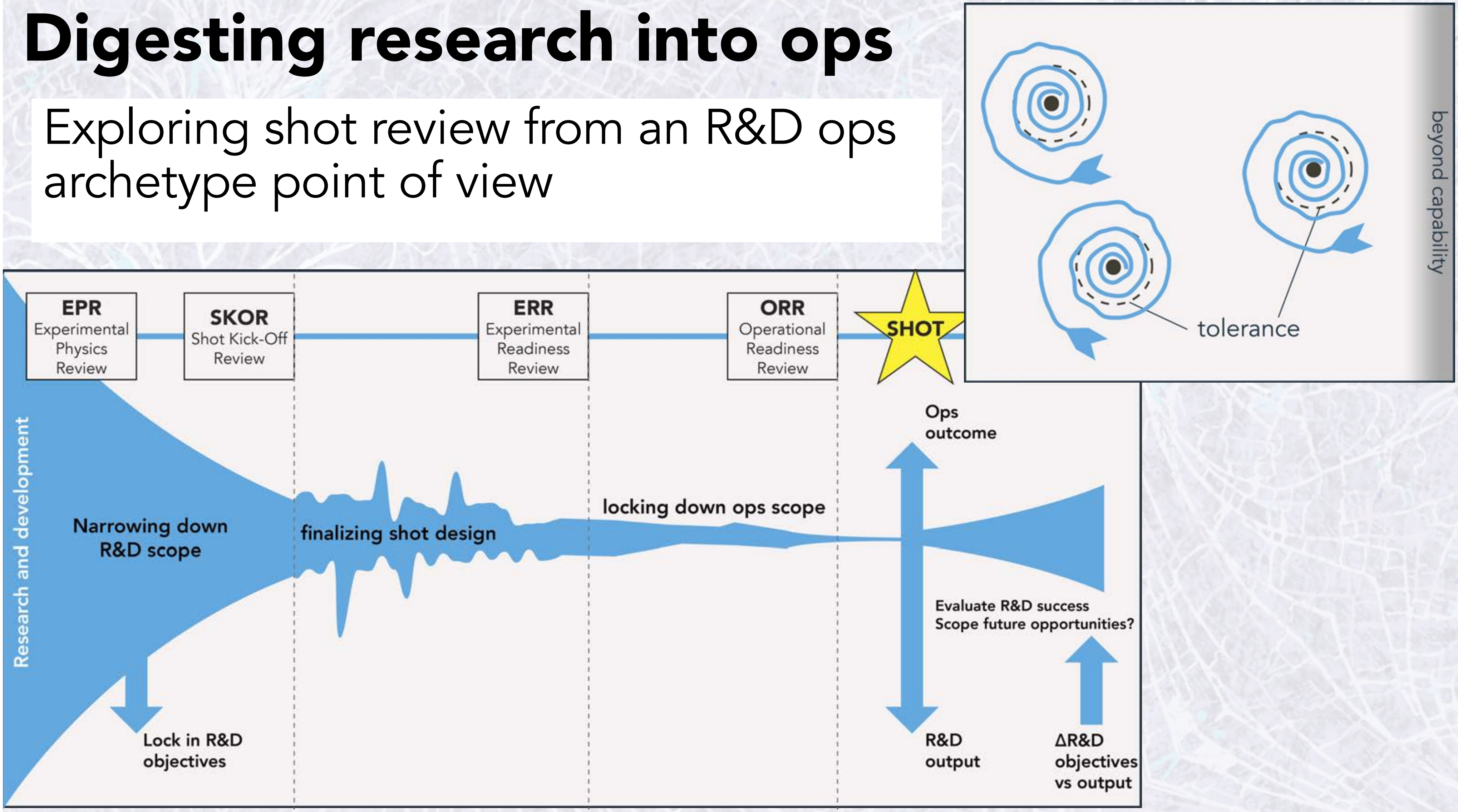
- Each shot can be different! How do we go from research to ops when the target is always moving?
- Need a repeatable but adjustable framework
- Each Z shot performs several readiness reviews—could the R&D ops idea help us better understand their goals?

R&D Ops



Digesting research into ops

Exploring shot review from an R&D ops archetype point of view

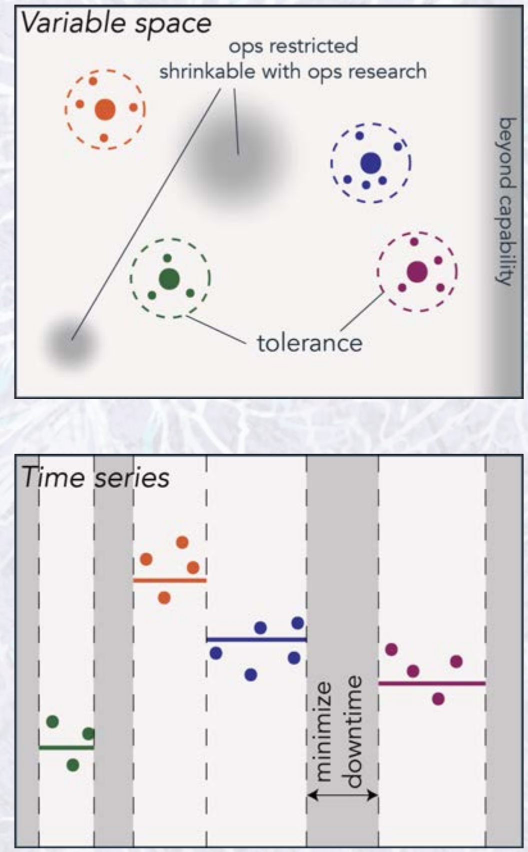


Subsystem upgrade: MUL

How can the R&D ops lens inform a subsystem upgrade?

- R&D ops:
  - **Large global scope, small individual scope:** how do different capabilities differ in execution for a subsystem?
  - **Support encapsulation:** how can a subsystem support (or hinder) encapsulation?
  - **Support capacity:** how can a subsystem support (or hinder) more shots?
  - **Support innovation:** how a subsystem support (or hinder) shot types which don't yet exist?

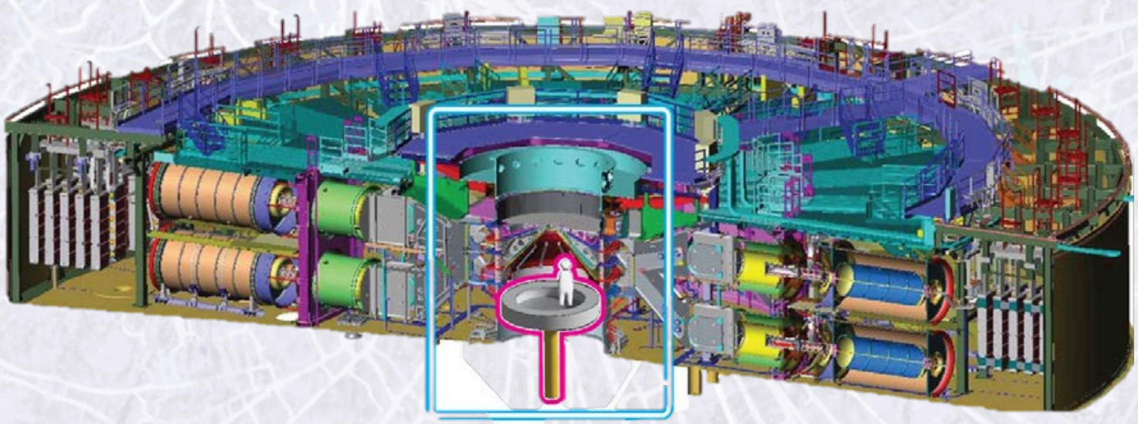
R&D Ops



Each scope small, **global scope large**
Low agility
Prioritizes encapsulation
Requires **capacity AND innovation**

Multistage Underground Lift (MUL)

- Replaces a subsystem designed and fielded in the 90s
- Supports almost all bottomside activities
  - Including many introduced after fielding

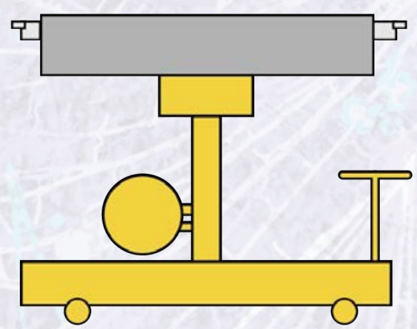


MUL

Multistage Underground Lift

Symptoms of R&D ops complexity

- Rapid changes in capability may lead to uneven documentation
- Different portions of operational scope may have different requirements and hazards
- Opportunities may not be as widely known as preferred



Current

Upgrade

System upgrade: current and upgrade

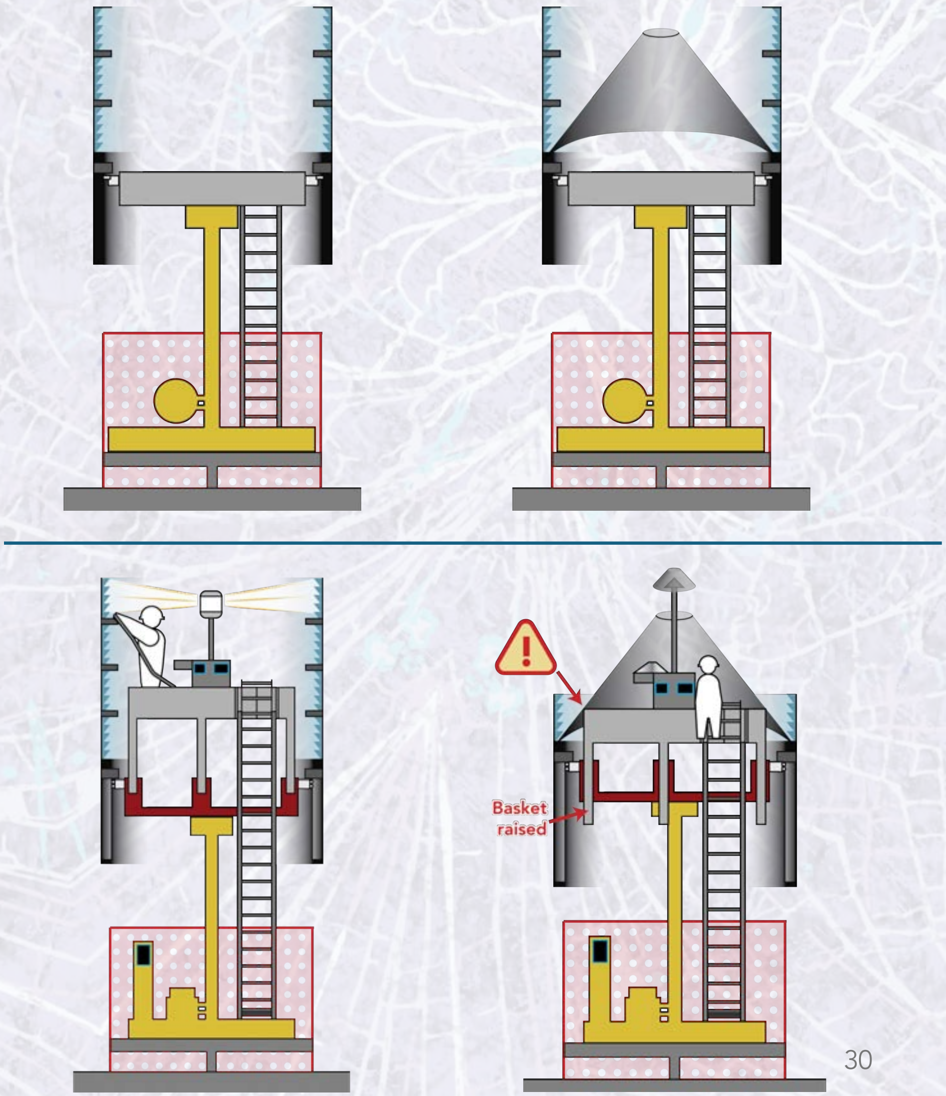
Current

Upgrade (still being commissioned)

Symptoms

Different portions of operational scope may have different requirements and hazards

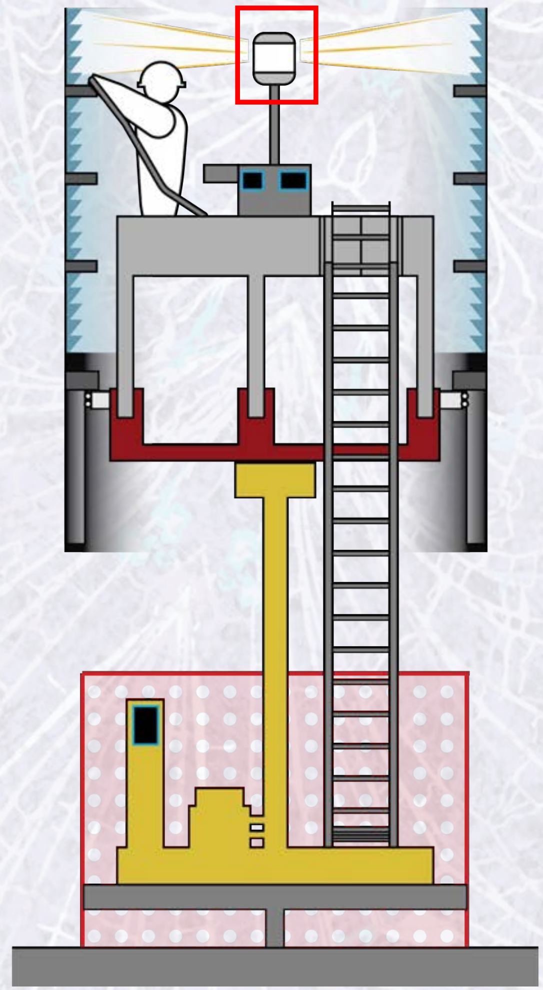
- MUL example: added feature to reach upper stack adds hazards



Symptoms

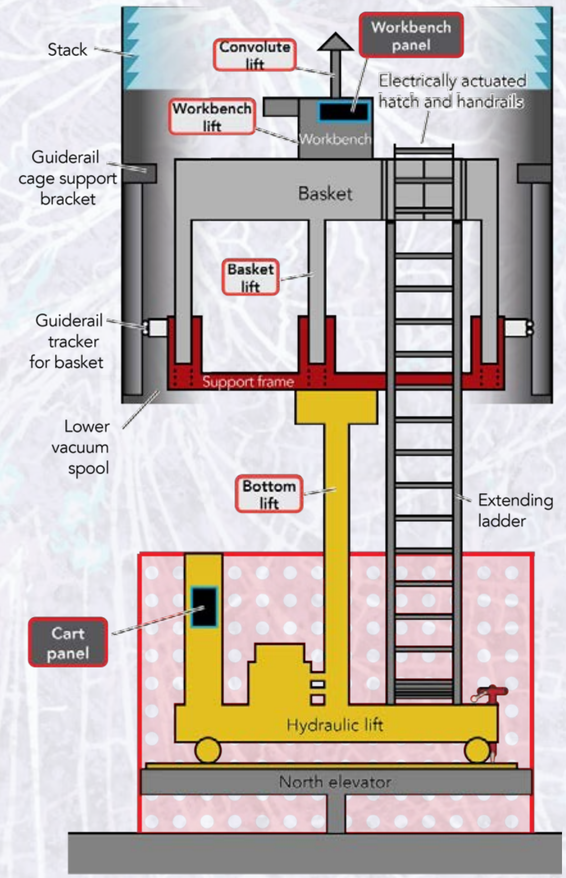
Opportunities may not be as widely known as preferred

- MUL example: Centered convolute lift allows tools like a refurb light—and other opportunities!



Strategies for addressing R&D ops complexity

- Aggressive characterization of current state—really really know how it supports current efforts
- Lots of stakeholder reviews to vet proposed subsystem and for futureproofing
  - >53 bite-sized design reviews with various stakeholders inspired by agile methodology
- Lots of cartoons and process models!



In conclusion

- Executing experiments at Z is dynamic and challenging
- Nonlinear dynamics methods can guide system thinking
- Z is an R&D operations facility
- We can use this R&D ops categorization to guide future efforts and communication