

Introduction to risk management in complex systems

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Massachusetts Institute of Technology

Agenda

- Introduction to system safety
 - Challenges for complex systems
 - Goals
- System-theoretic Process Analysis
- Application to a proton beam therapy machine

Three Mile Island

Events: A critical relief valve fails (stuck open) and begins venting coolant. Despite best efforts, operators are unable to mitigate this problem in time and the reactor experiences a meltdown. Radioactive materials are released. \$1B cleanup costs.



Component failure accidents

- These are accidents caused by physical component failures
 - E.g. valve stuck open
- What would you do about this?
- Beware of “tunnel vision”
 - Very easy to focus only on the physical failure
 - There are usually deeper systemic factors too

Three Mile Island

Events: A critical relief valve fails (stuck open) and begins venting coolant. Despite best efforts, **operators are unable to mitigate this problem in time** and the reactor experiences a meltdown. Radioactive materials are released. \$1B cleanup costs.

Systemic factors?



Three Mile Island

Causal Factors:

- Post-accident examination discovered the “open valve” indicator light was configured to show presence of power to the valve (regardless of valve position).



Design flaw!
Communication problems!
Inadequate procedures!
Etc.

System safety

- Modern systems involve complex interactions between many components
 - Software, hardware, human operators, environment, management, maintenance etc.
 - Interactions can be overlooked when components considered in isolation
 - Need to understand the whole system of interactions
 - Unanticipated and unexpected emergent system behavior
- Need to include systemic factors
 - Not just component failures

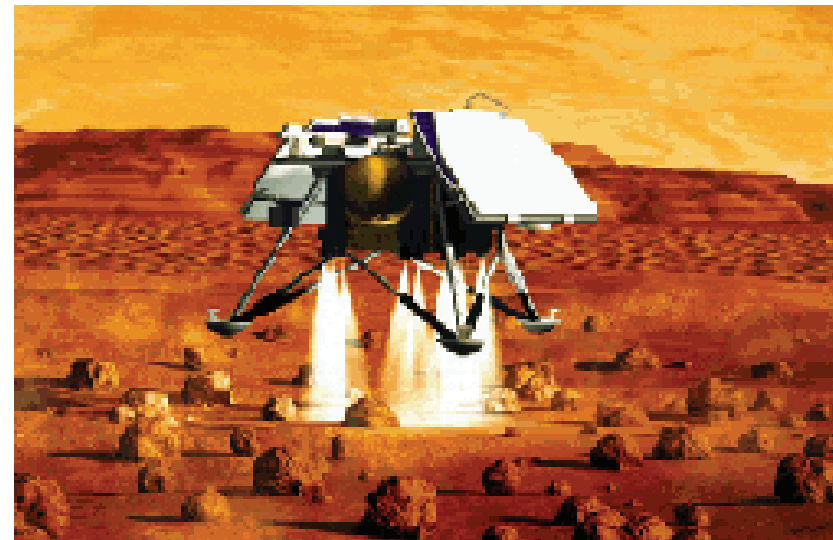
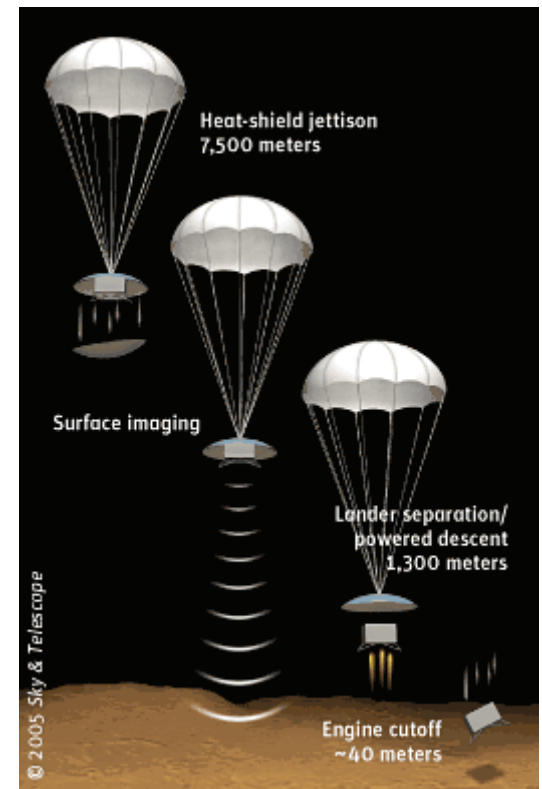
Goals for a systemic approach

- Need to address component failure accidents
 - Identify important failures, but also go beyond the failures
 - Why weren't the failures detected and mitigated?
 - Human-computer interaction issues?
 - Software-induced operator error?
 - Etc.
- What else is needed?

Mars Polar Lander

- During the descent to Mars, the legs were deployed at an altitude of 40 meters.
- Touchdown sensors (on the legs) sent a momentary signal
- The software responded as it was required to: by shutting down the descent engines.
- The vehicle free-fell and was destroyed upon hitting the surface at 50 mph.

No single component failed. All components performed as designed.



Component interaction accidents

- ... are accidents caused by interactions among several components
 - May not involve any component failures
 - All components may operate as designed
 - But the design may be wrong
 - Requirements may be flawed
 - Related to complexity
 - Becoming increasingly common in complex systems
 - Complexity of interactions leads to unexpected system behavior
 - Difficult to anticipate unsafe interactions
 - Especially problematic for software
 - Software always operates as designed

Goals for a systemic approach

- Need to address component failure accidents
- Need to address component interaction accidents
- What else?

2013 Ford Fusion / Escape



*Images from:

<http://www.newsomelaw.com/blog/2012/09/7/ford-announces-third-recall-of-escape-suvs-since-july>

<http://gearheads.org/stop-driving-your-ford-escape/>

2013 Ford Fusion / Escape

- Engine fires
 - 13 reports of engine fire
 - Short time frame
 - (~Sept - Dec)
- Ford asks all owners to “park their vehicles until further notice”
- 99,153 brand new vehicles affected



Images from:

<http://www.unionleader.com/article/20130119/NEWS03/130119090>

<http://www.thetruthaboutcars.com/2012/07/fire-escape-its-the-suppliers-fault/>

The Problem

- Ford press release:
 - “The original cooling system design was not able to address a loss of coolant system pressure under certain operating conditions, which could lead to a vehicle fire while the engine was running.”
- Ford VP:
 - “We had a sequence of events that caused the cooling system software to restrict coolant flow,” he says. Most of the time, that would not be a problem and is the intended behavior. But in rare cases the coolant pressure coupled with other conditions may cause the coolant to boil. When the coolant boils, the engine may go into extreme overheating causing more boiling and rapid pressure increase. This caused coolant leaks near the hot exhaust that led to an engine fire.
 - Ford has seen 12 fires in Escapes and one in a Fusion.

System requirements (and the engineers) never anticipated this worst-case possibility

Quotes from:

<http://corporate.ford.com/news-center/press-releases-detail/pr-ford-produces-fix-in-voluntary-37491>

<http://www.usatoday.com/story/money/cars/2012/12/10/ford-recall-escape-fusion-ecoboost/1769063/>

Quote

- “The hardest single part of building a software system is deciding precisely what to build.”
-- Fred Brooks, *The Mythical Man-Month*

Quote

- “The hardest single part of building a software system is deciding precisely what to build. No other part of the conceptual work is as difficult as establishing the detailed technical requirements ... No other part of the work so cripples the resulting system if done wrong. No other part is as difficult to rectify later.”

-- Fred Brooks, *The Mythical Man-Month*

Goals for a systemic approach

- Need to address component failure accidents
- Need to address component interaction accidents
- Need a worst-case analysis, not best case or most likely case
- Handle broad array of causes
 - Incorrect assumptions
 - Incorrect/incomplete requirements
 - Complex software behavior
 - In fact, most software-related accidents are caused by requirements flaws, not coding errors or failures
 - Design errors
 - Component failures
- What else?

Toyota

- **2004:** Push-button ignition
- **2004-2009**
 - 102 incidents of uncontrolled acceleration
 - Speeds exceed 100 mph despite stomping on the brake
 - 30 crashes
 - 20 injuries
- **2009, Aug:**
 - Car accelerates to 120 mph
 - Passenger calls 911, reports stuck accelerator
 - Car crashes killing 4 people
 - Driver was offensive driving instructor for police
- **Today**
 - Software fixes for pushbutton ignition, pedals



**Pushbutton was reliable, Software was reliable.
All requirements were met.
Didn't account for human behavior!**

Toyota

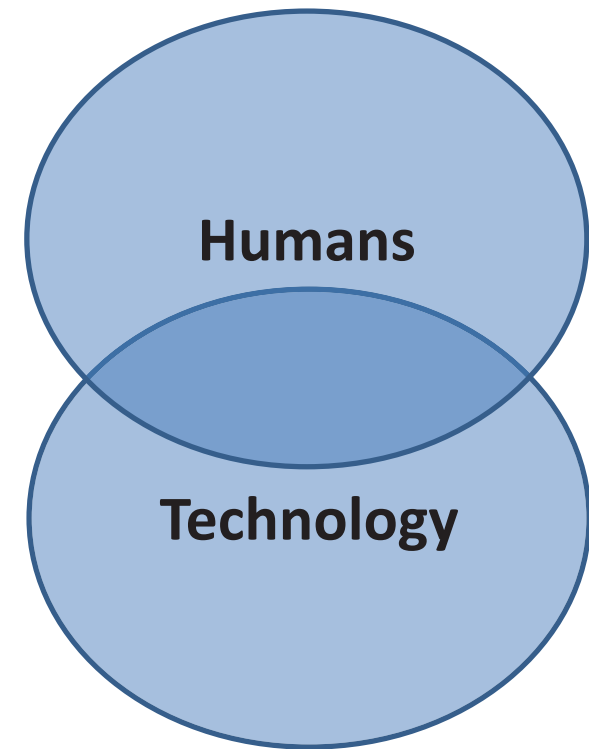
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In complex systems, human and technical considerations cannot be isolated

Goals for a systemic approach

- Need to address component failure accidents
 - Need to address component interaction accidents
 - Need a worst-case analysis, not best case or most likely case
 - Handle broad array of causes
 - Must account for human behavior / social factors
 - Easy to treat human error as a separate issue
 - Easy to look no deeper than human-machine interfaces
- But must also consider:
- “Clumsy automation”, mode confusion, etc.
 - How technology might induce human error
 - Human error often a symptom of deeper trouble (Dekker)
 - To fix, need to understand *why it would make sense* at the time



Human Factors: Old View

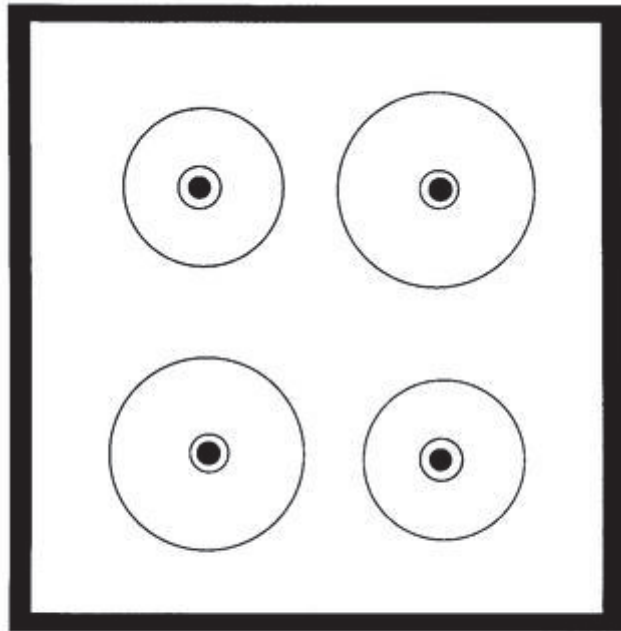
- Human error is cause of most incidents and accidents
- So do something about human involved
 - Fire them
 - Retrain them
 - Admonish them
 - Rigidify their work with more rules and procedures
- Or do something about humans in general
 - Marginalize them by putting in more automation

Human Factors: Systems View

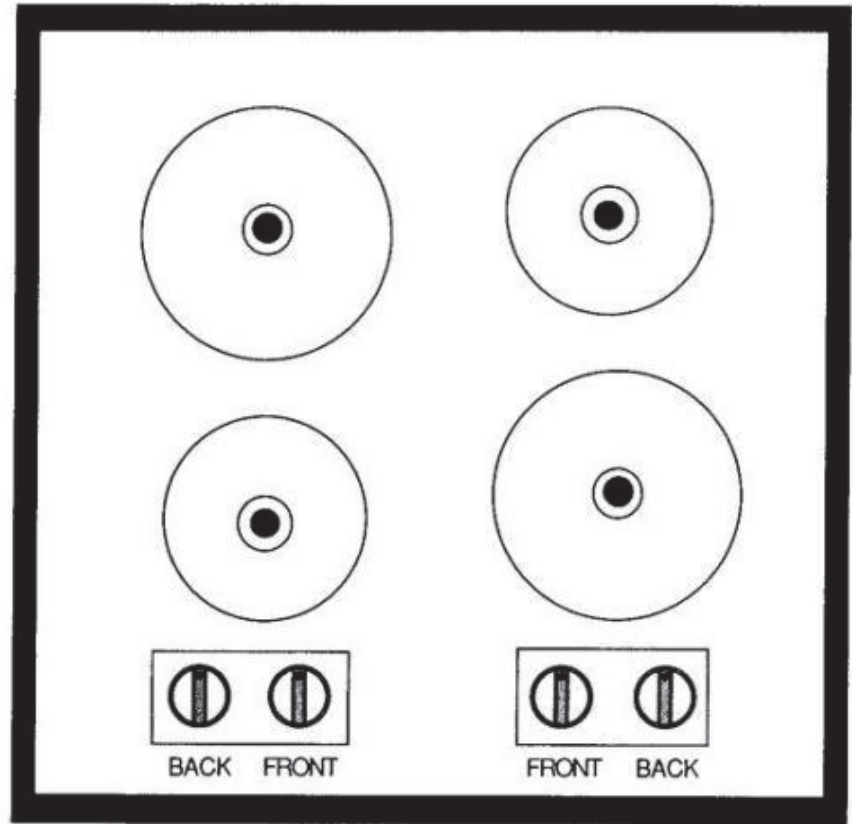
(Dekker, Rasmussen, Leveson, Woods, etc.)

- Human error is a symptom, not a cause
- All behavior affected by context (system) in which it occurs
 - To understand human error, look at the system
 - Systems are stretching limits of comprehensibility
 - System designs can make human error inevitable
- To do something about operator error, look at:
 - Design of equipment
 - Usefulness of procedures
 - Existence of goal conflicts and production pressures
- Human error is a symptom of the system and its design

Most stove tops

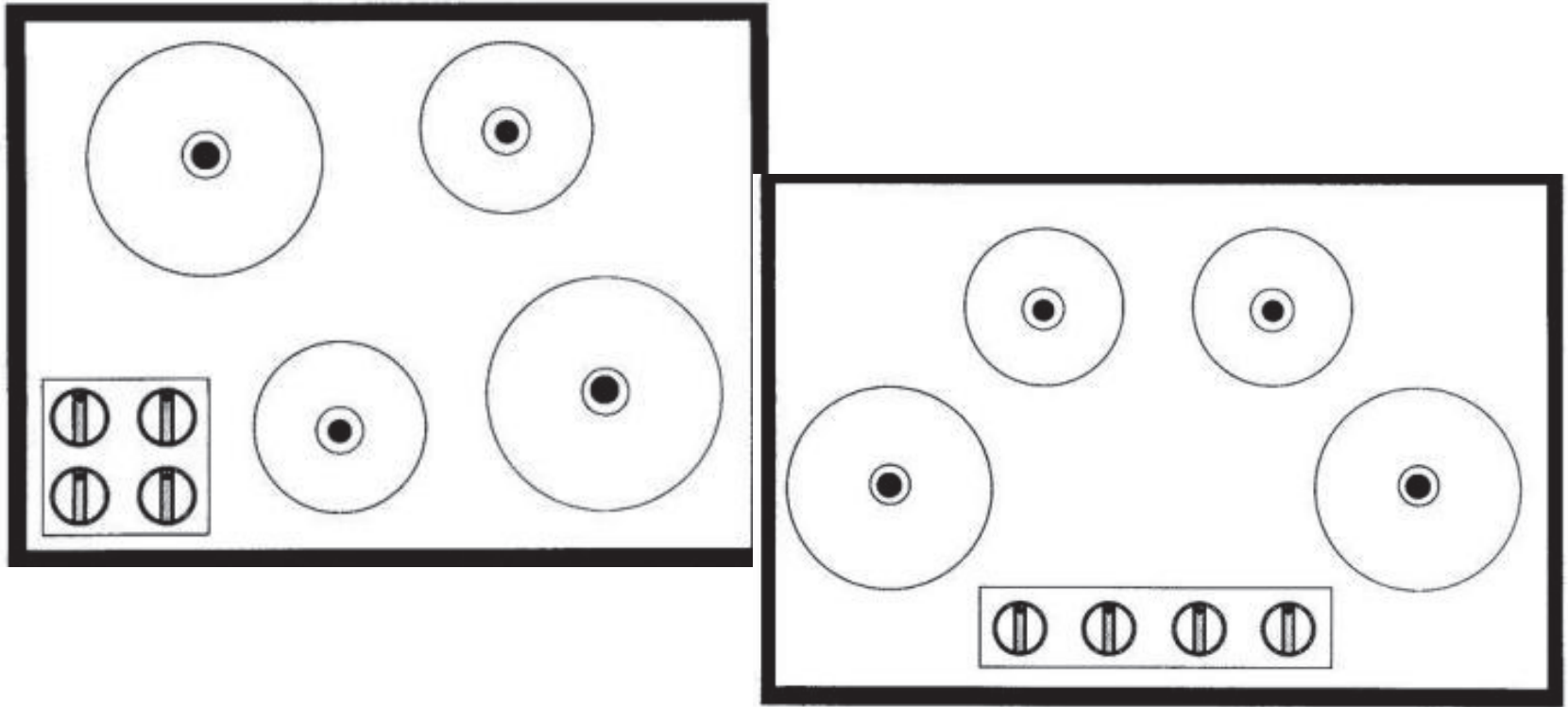


Back Right Front Left Back Left Front Right



Human error?

Natural Mapping



Human error? Or design problem?

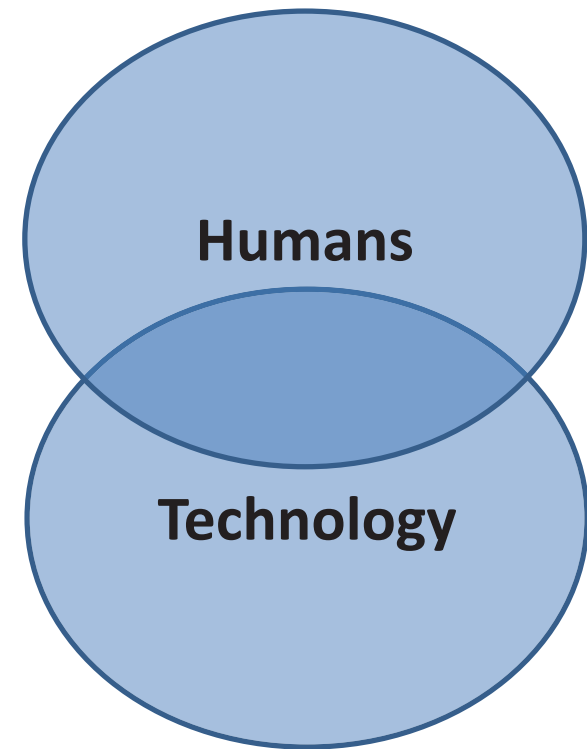
China Airlines 006

- Autopilot compensates for single engine malfunction
- Autopilot reaches max limits, aircraft turns slightly
- Pilots not notified Autopilot at its limits
- Pilots notice slight turn, disengage autopilot for manual control
 - Aircraft enters nosedive

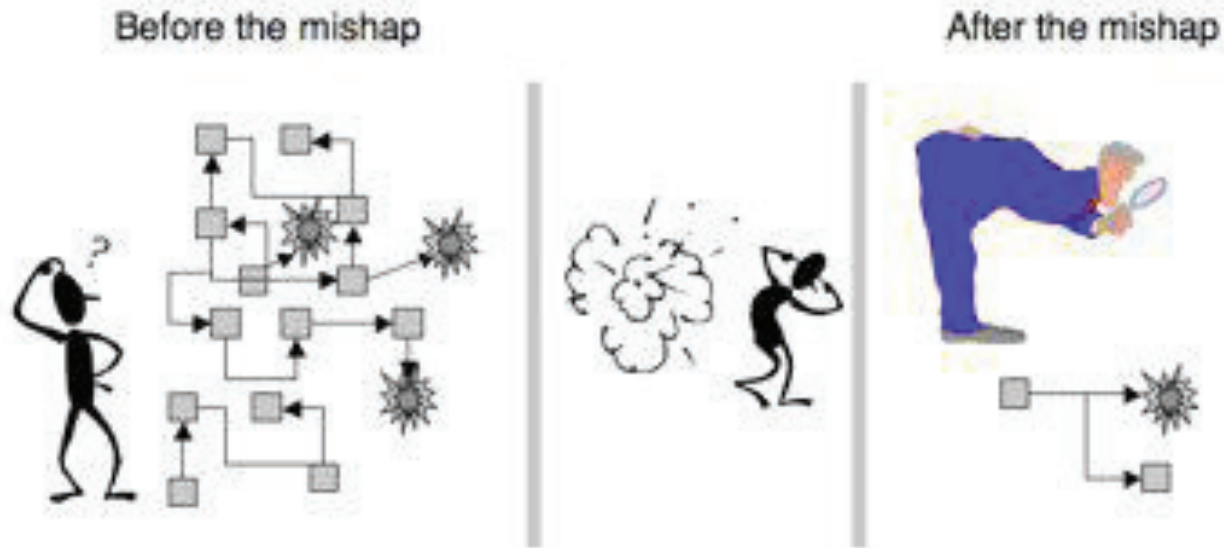


Goals for a systemic approach

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A note about hindsight bias



(Dekker, 2009)

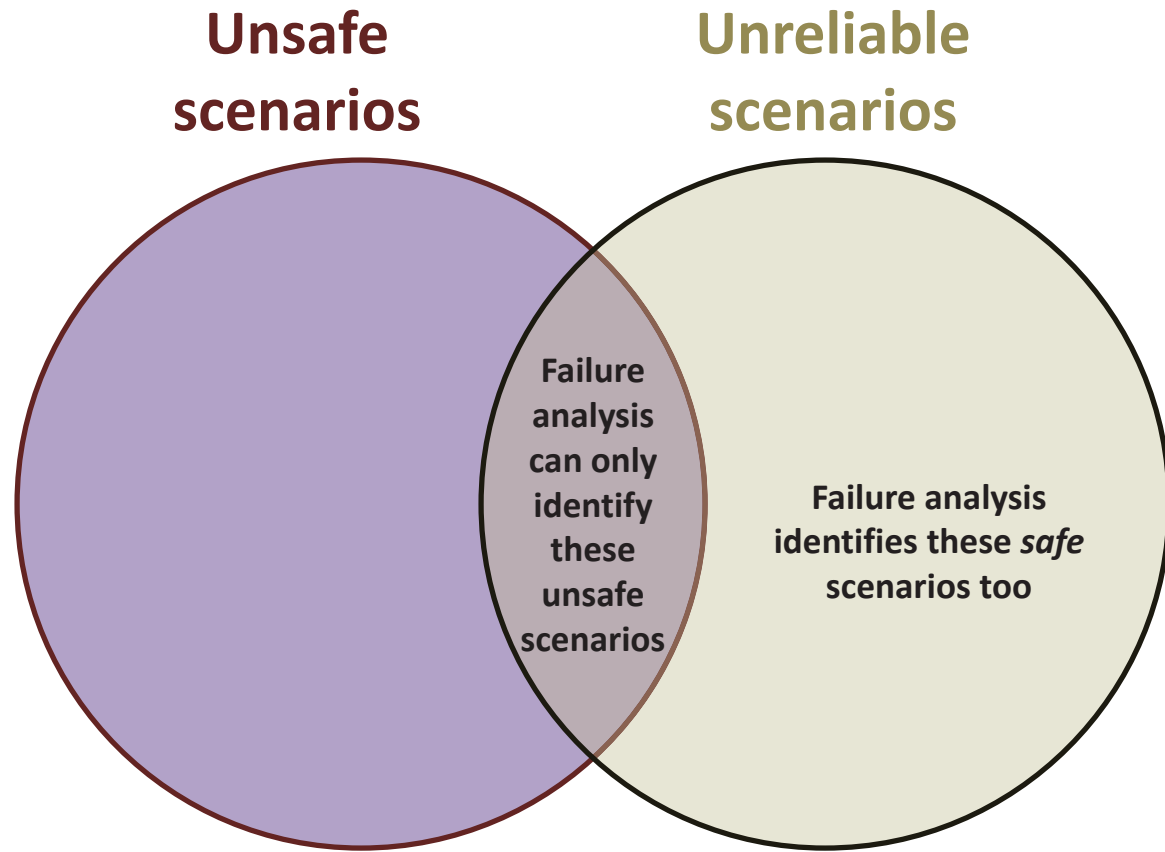
- After an accident, hindsight makes causes seem obvious
- In engineering, 1000s of variables and potential problems to consider
- Many of these problems only seem obvious after-the-fact

Safety vs. reliability

Reliability \leftrightarrow Failures

Safety \leftrightarrow Accidents

Safety vs. Reliability



- Failure analysis is a *reliability* technique
 - Inefficient for safety: analyzes non-safety-related failures
 - Insufficient for safety: may overlook non-failure accidents
- Failure analysis sometimes used as part of a safety analysis
 - Can (inefficiently) establish the end effects of failures

Safe \neq Reliable

- Safety often means making sure X never happens
- Reliability usually means making sure Y always happens

	Safe	Unsafe
Reliable	•Typical commercial flight	
Unreliable		•Aircraft engine fails in flight

Safe \neq Reliable

- Safety often means making sure X never happens
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	Safe	Unsafe
Reliable	•Typical commercial flight	<ul style="list-style-type: none">•Computer reliably executes unsafe commands•Increasing tank burst pressure•Retreating to safe state vs. achieving mission•A nail gun without safety lockout
Unreliable		•Aircraft engine fails in flight

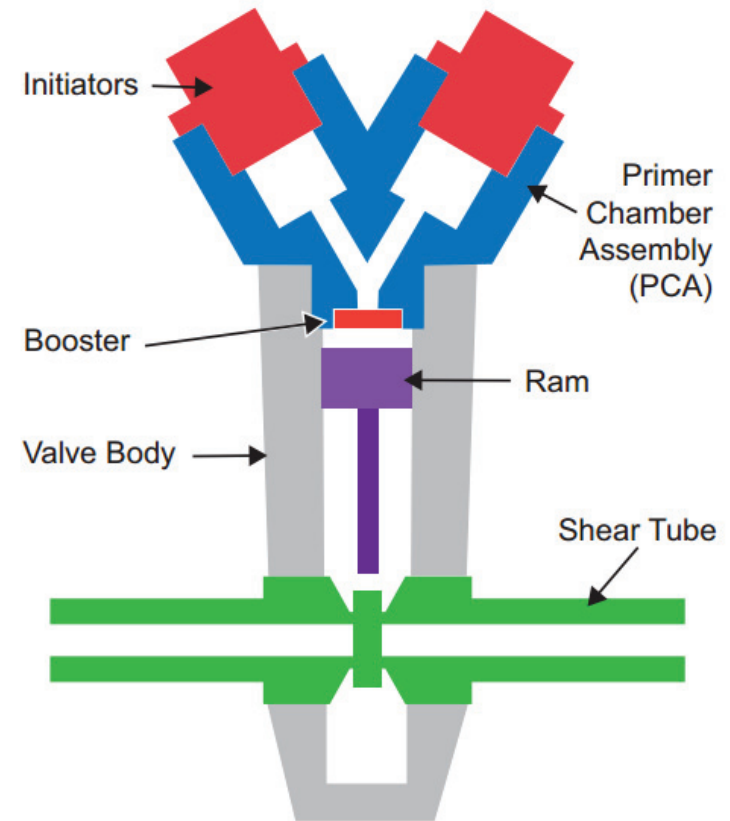
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	Safe	Unsafe
Reliable	<ul style="list-style-type: none">• Typical commercial flight	<ul style="list-style-type: none">• Computer reliably executes unsafe commands• Increasing tank burst pressure• Retreating to safe state vs. achieving mission• A nail gun without safety lockout
Unreliable	<ul style="list-style-type: none">• Aircraft engine won't start on ground?• Missile won't fire?	<ul style="list-style-type: none">• Aircraft engine fails in flight

Fault Modelling, Fault Injection

- Not enough to ensure safety
- Faults must be known in advance
 - Works well for some components, well-understood & established history
 - May be unknown for new components, or old components in new environment
 - E.g. **NASA injector vibrations**, Apollo switches, Ariane 5, etc.
 - Unk Unks
- Effect of fault must be known, accurate
 - Non-deterministic effects can be tricky (e.g. noise in nuclear detonation circuits, car stereo EMI)
- Multiple-point failures
 - Simulating all combinations of faults can be impractical
- May overlook accidents that occur with no failures

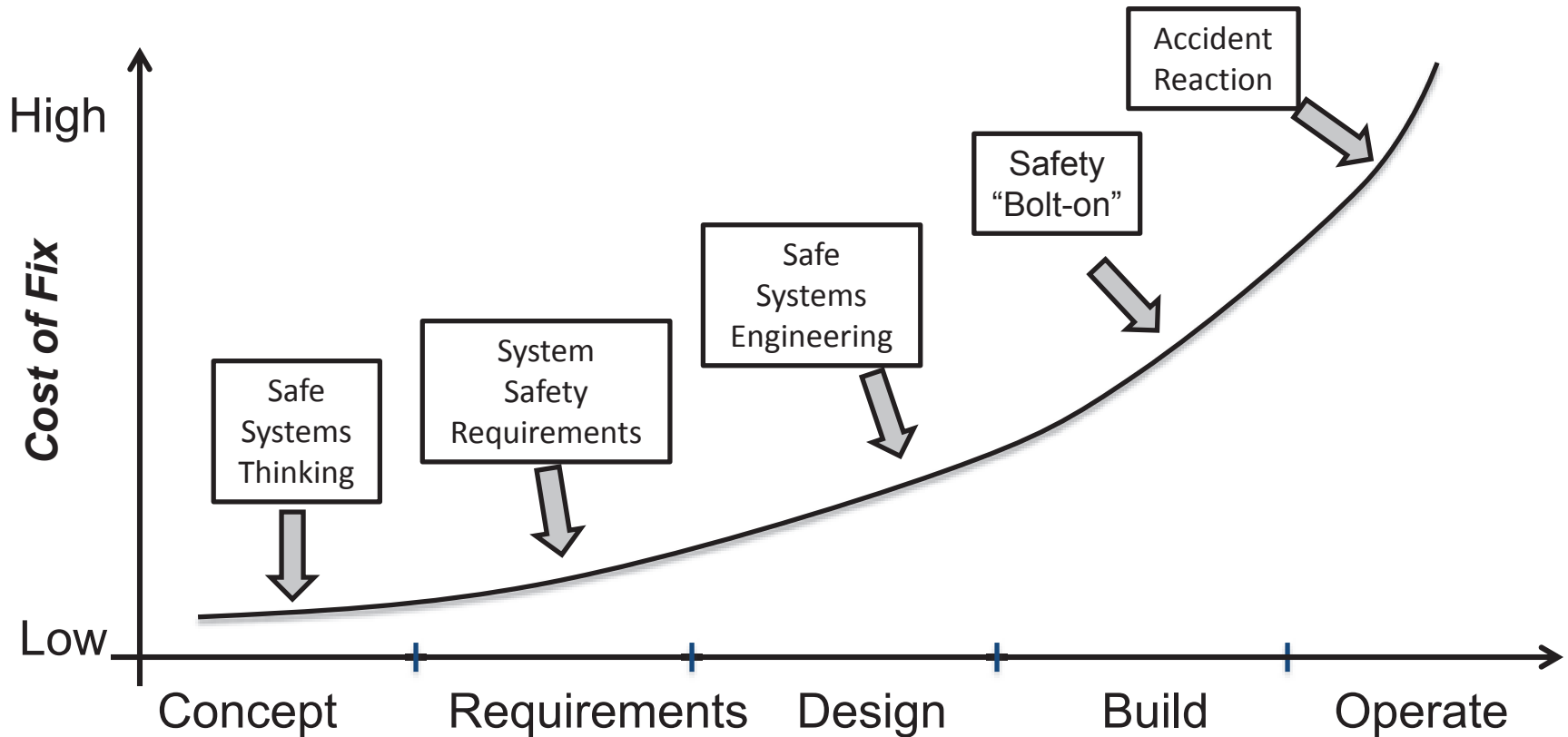


A normally closed pyrovalve

Goals for a systemic approach

- Need to address component failure accidents
- Need to address component interaction accidents
- Need a worst-case analysis, not best case or most likely case
- Handle broad array of causes
- Must account for human behavior / social factors
- Need to distinguish safety vs. reliability goals
- What else?

Building Safety into the System



Need to address safety early

**Early decisions tend to have
biggest impact on safety**

Goals for a systemic approach

- Need to address component failure accidents
- Need to address component interaction accidents
- Need a worst-case analysis, not best case or most likely case
- Handle broad array of causes
- Must account for human behavior / social factors
- Need to distinguish safety vs. reliability goals
- Must be applicable as early as possible
 - Drive the design and requirements
instead of causing rework

Boeing 787 Lithium Battery Fires

- 2013 – 2014
- Reliability analysis predicted 10 million flight hours between battery failures
 - Two fires caused by battery failures in 52,000 flight hours
 - Does not include 3 other less-reported incidents of smoke in battery compartment

Another simple component failure accident?



Why is this so hard?

- Coupling
 - Highly coupled systems have more interdependence
 - Number of dependencies can increase exponentially
- Indirect causality
 - Cause and effect may not be related in an obvious or direct way
- Interactive complexity
 - Number of possible interactions can challenge our ability to analyze and identify dangerous interactions
- Intellectual manageability
 - A simple system has a small number of unknowns in its interactions (within system and with environment)
 - Intellectually unmanageable when level of interactions reaches point can no longer be thoroughly
 - Planned
 - Understood
 - Anticipated
 - Guarded against

Safety vs. Reliability: another difference

Using standard engineering techniques of:

- Redundancy
- Increasing reliability
- Reusing designs in new environments

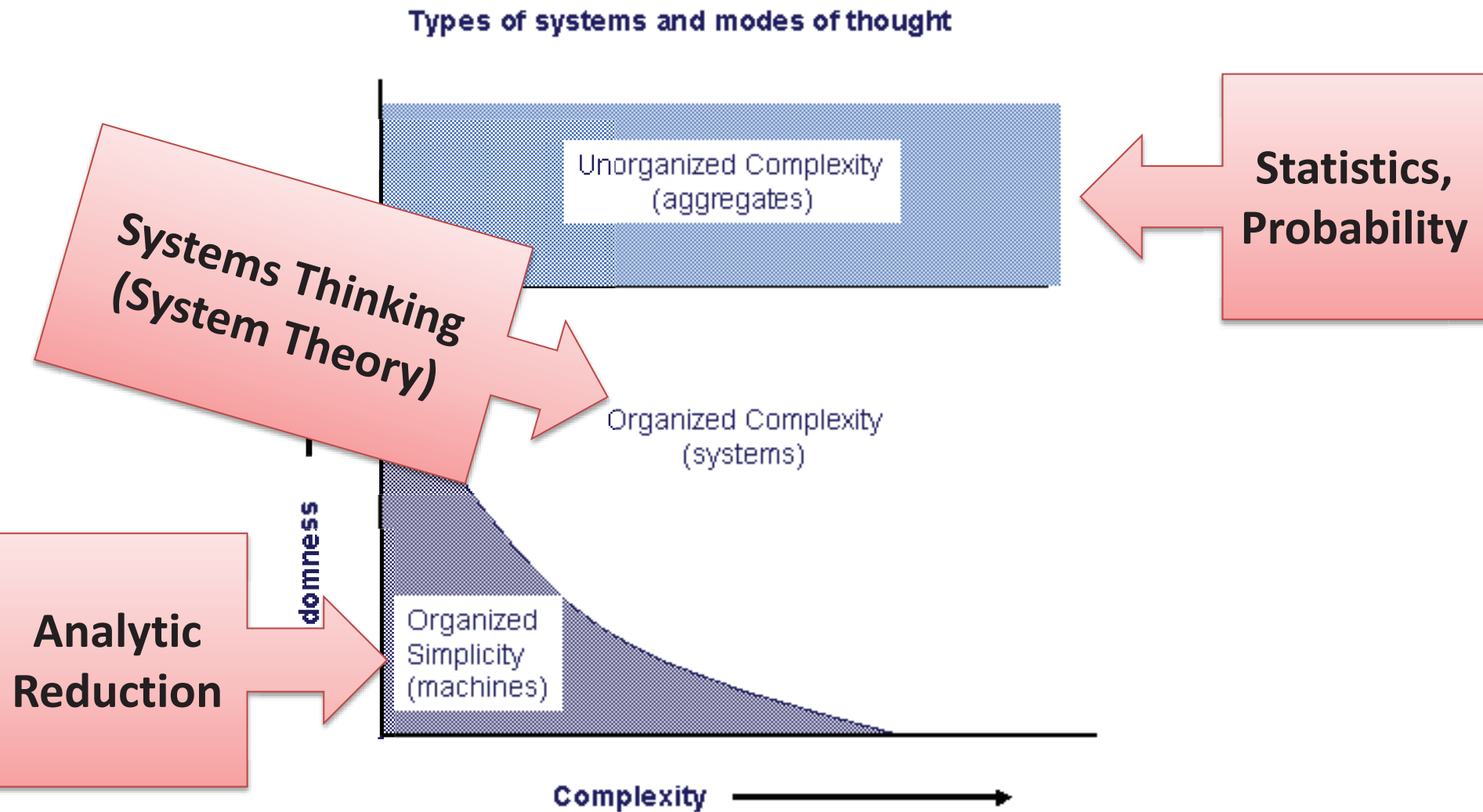
typically increases complexity:

- NASA pyrovalve example, Apollo computers

Solutions that add complexity will not solve problems that stem from intellectual unmanageability and interactive complexity

**Redundancy does not work for
component interaction accidents**

“Introduction to General Systems Thinking”



Source: Gerald Weinberg. *An Introduction to General Systems Thinking*. Wiley, 1975

How to manage complexity?

- A lesson from systems theory, cognitive science
- Human minds manage complexity through abstraction and hierarchy
- Use top-down processes
 - Start at a high abstract level
 - Iterate to drill down into more detail
 - Build hierarchical models of the system

Goals for a systemic approach

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- Need a worst-case analysis, not best case or most likely case
- Handle broad array of causes
- Must account for human behavior / social factors
- Need to distinguish safety vs. reliability goals
- Must be applicable as early as possible
- Provide ways to manage complexity
 - Top-down processes
 - Improve intellectual manageability

A systems approach to safety: STAMP and STPA

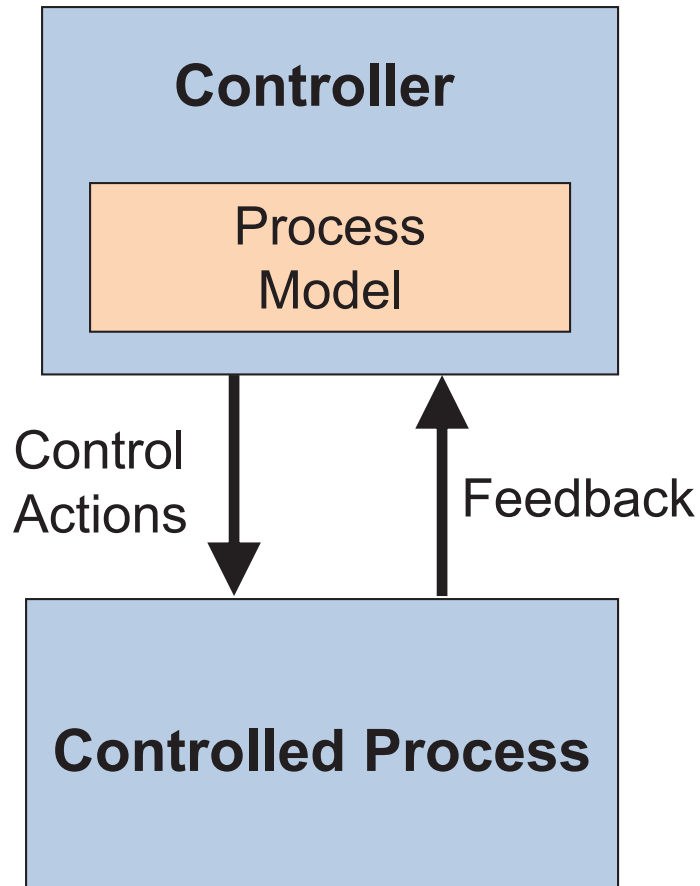
Systems approach to safety engineering (STAMP)



STAMP Model

- Accidents are more than a chain of events, they involve complex dynamic **processes**.
- Treat accidents as a **control problem**, not a failure problem
- Prevent accidents by enforcing constraints on component behavior and **interactions**
- Captures more causes of accidents:
 - Component failure accidents
 - Unsafe interactions among components
 - Complex human, software behavior
 - Design errors
 - Flawed requirements
 - esp. software-related accidents

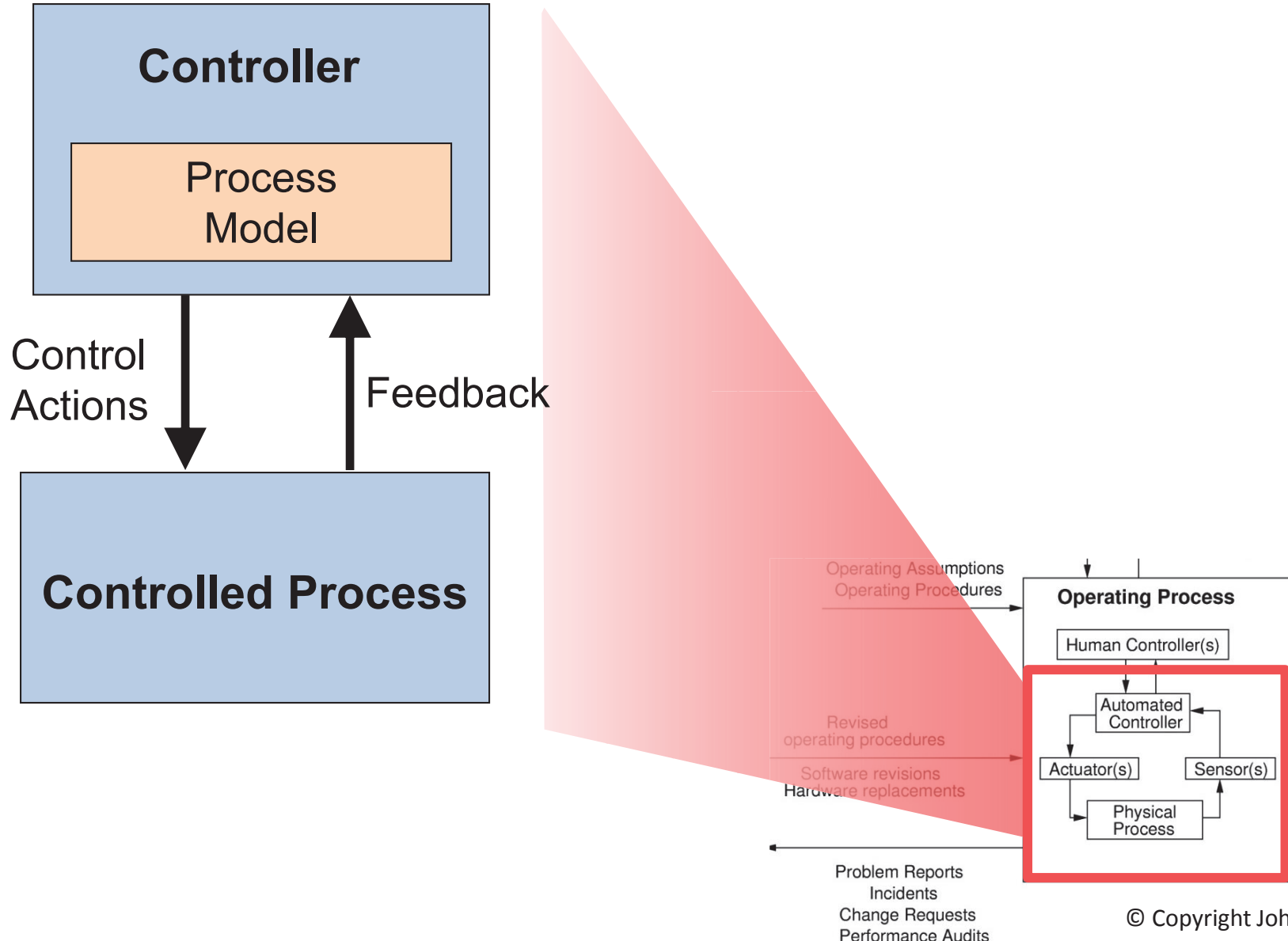
STAMP



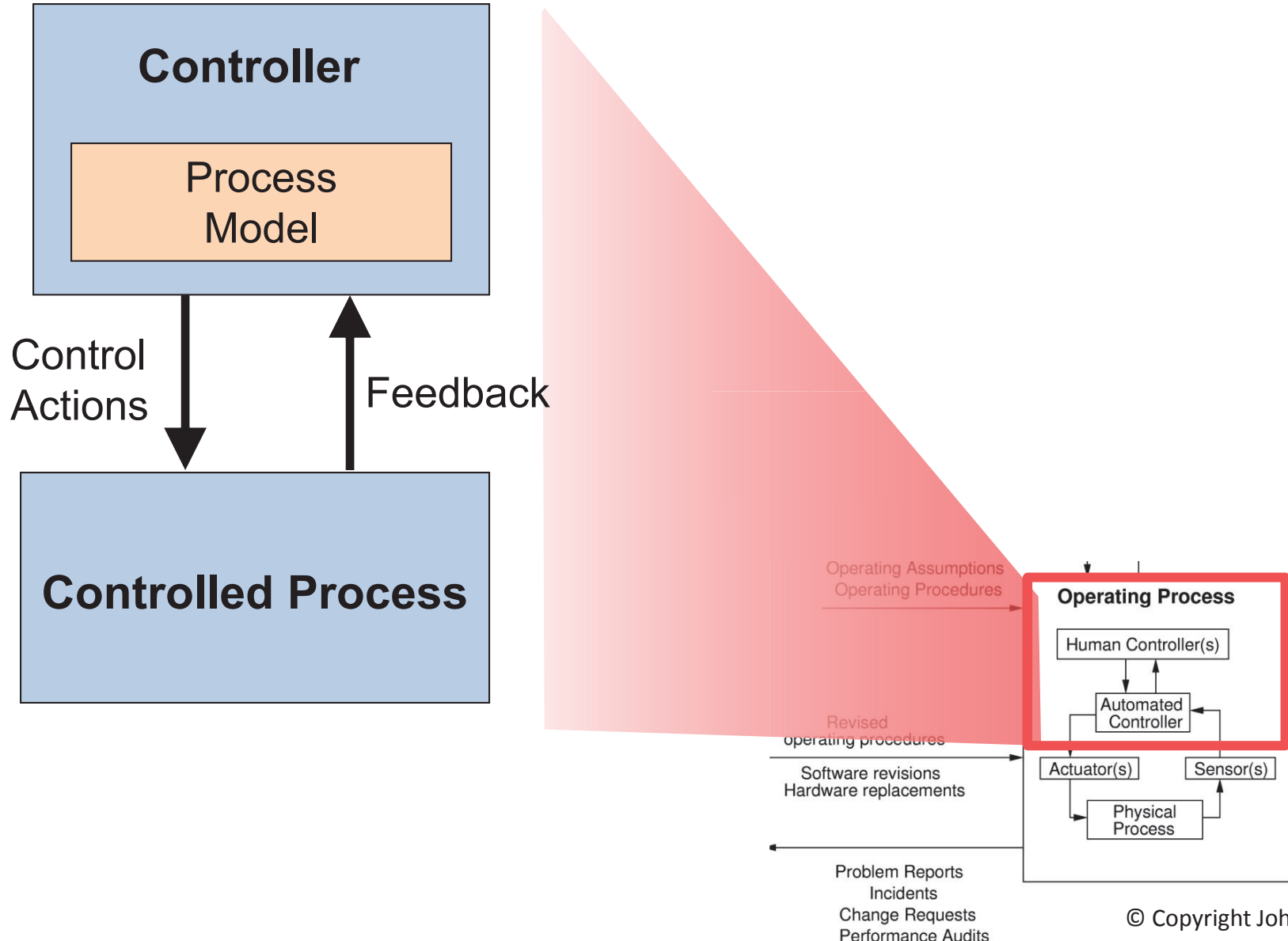
- Controllers use a **process model** to determine control actions
- Accidents often occur when the process model is incorrect
- Four types of **unsafe control actions**:
 - 1) Control commands required for safety are not given
 - 2) Unsafe ones are given
 - 3) Potentially safe commands but given too early, too late
 - 4) Control action stops too soon or applied too long

Tends to be a good model of both software and human behavior
Explains software errors, human errors, interaction accidents,⁵¹...

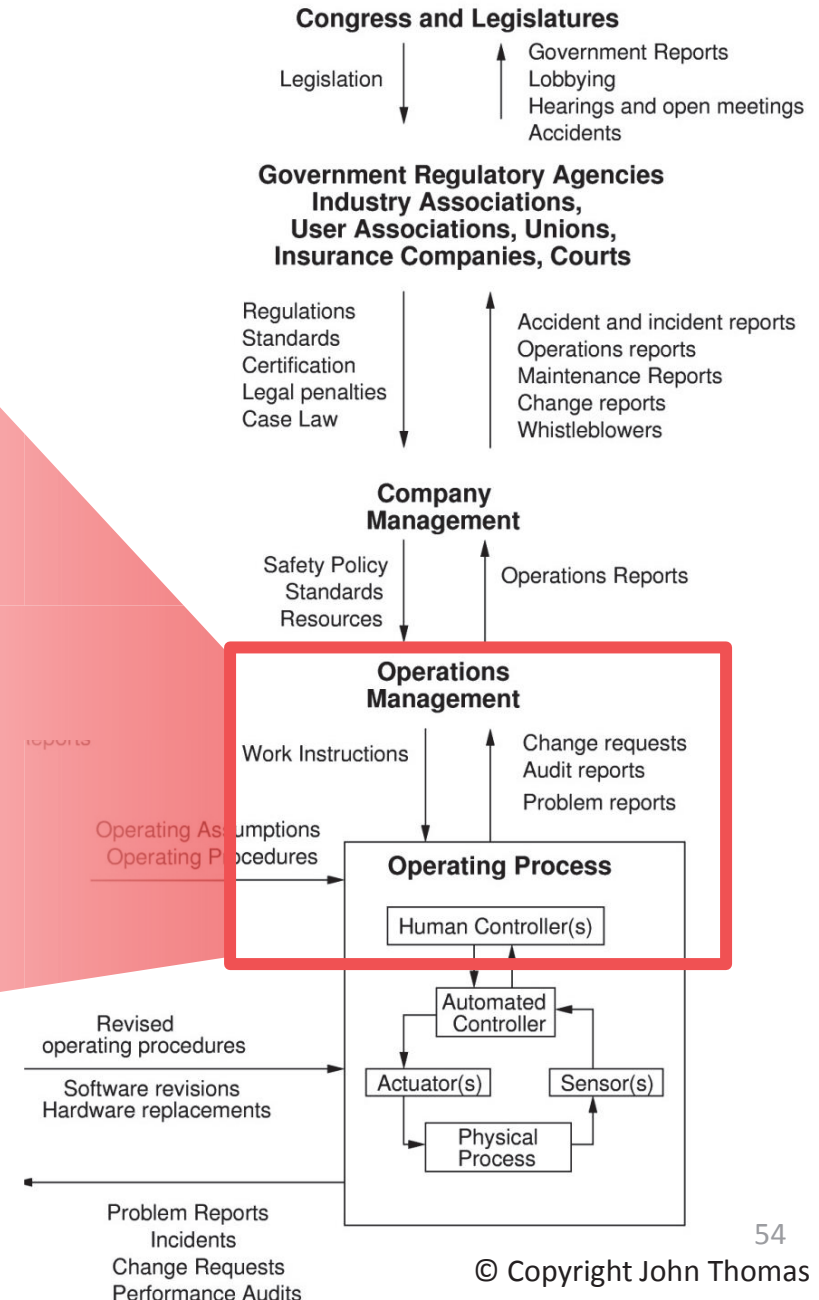
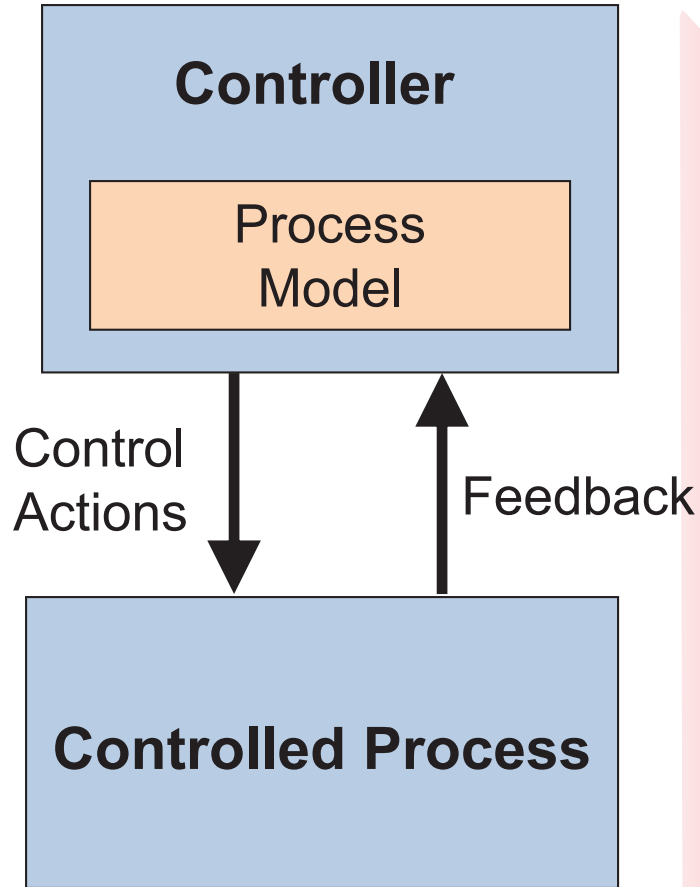
STAMP



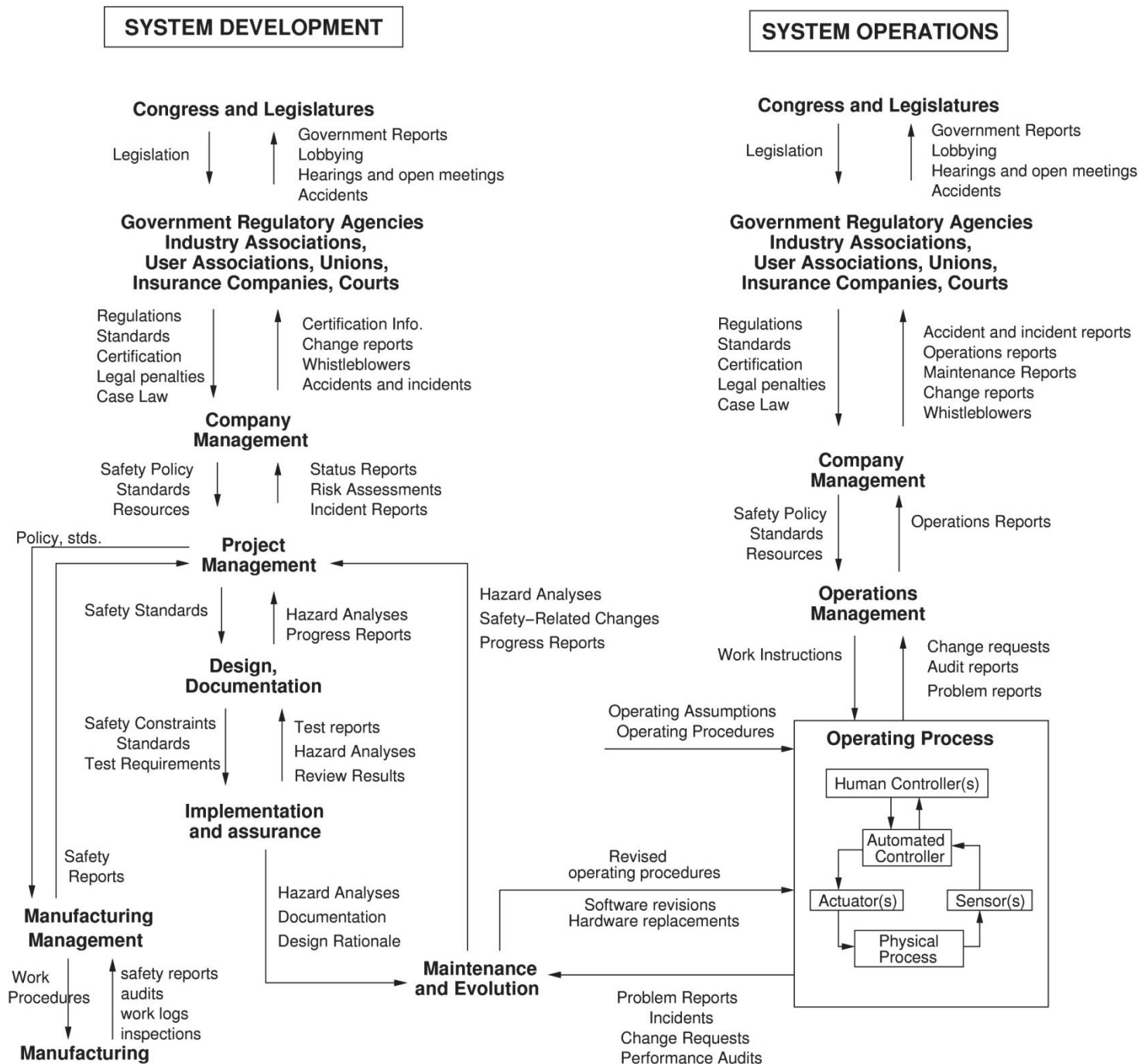
STAMP



STAMP



Example Safety Control Structure



STAMP and STPA



STAMP Model

Accidents are
caused by
inadequate control

STAMP and STPA



The diagram consists of two stacked rectangular boxes. The top box is orange and contains the text 'STPA Hazard Analysis'. The bottom box is purple and contains the text 'STAMP Model'. To the right of the orange box is an orange curly brace pointing to it, with the text 'How do we find inadequate control in a design?'. To the right of the purple box is a purple curly brace pointing to it, with the text 'Accidents are caused by inadequate control'.

**STPA
Hazard Analysis**

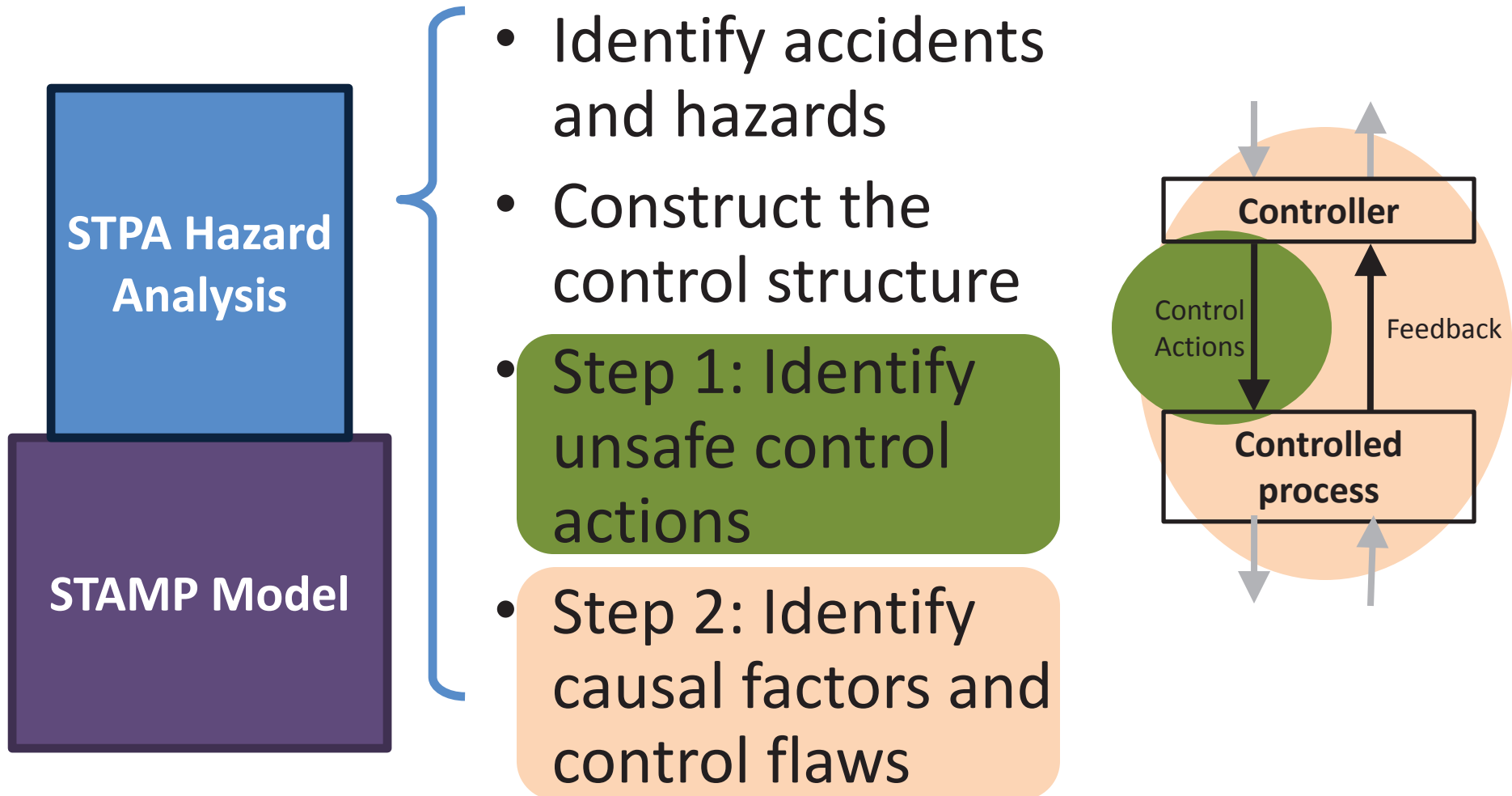
How do we find
inadequate control
in a design?

STAMP Model

Accidents are
caused by
inadequate control

STPA

(System-Theoretic Process Analysis)



Definitions

- Accident (Loss)
 - An undesired or unplanned event that results in a loss, including loss of human life or human injury, property damage, environmental pollution, mission loss, etc.
- Hazard
 - A system state or set of conditions that, together with a particular set of worst-case environment conditions, will lead to an accident (loss).

Definitions

- Accident (Loss)
 - An undesired or unplanned event that results in a loss, including loss of human life or human injury, property damage, environmental pollution, mission loss, etc.
 - May involve environmental factors **outside our control**
- Hazard
 - A system state or set of conditions that, together with a particular set of worst-case environment conditions, will lead to an accident (loss).
 - Something we can **control** in the design

Accident	System Hazard
People die from exposure to toxic chemicals	Toxic chemicals from the plant are in the atmosphere
People die from radiation sickness	Nuclear power plant radioactive materials are not contained
Vehicle collides with another vehicle	Vehicles do not maintain safe distance from each other
People die from food poisoning	Food products for sale contain pathogens

Definitions





- Accident (Loss)
 - An undesired or unplanned event that results in a loss, including loss of human life or human injury, property damage, environmental pollution, mission loss, etc.

Broad view of safety

“Accident” is anything that is unacceptable, that must be prevented. Not limited to loss of life or human injury!

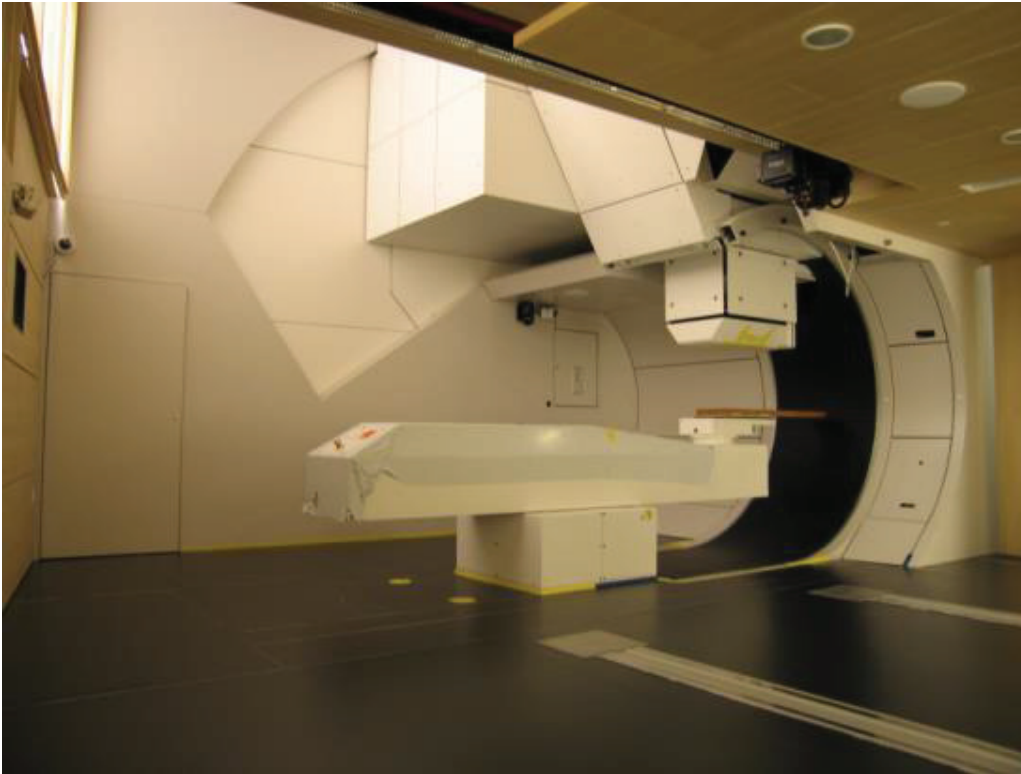
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System Safety Constraints

System Hazard		System Safety Constraint
Toxic chemicals from the plant are in the atmosphere		Toxic plant chemicals must not be released into the atmosphere
Nuclear power plant radioactive materials are not contained		Radioactive materials must not be released
Vehicles do not maintain safe distance from each other		Vehicles must always maintain safe distances from each other
Food products for sale contain pathogens		Food products with pathogens must not be sold

Proton Radiation Therapy System

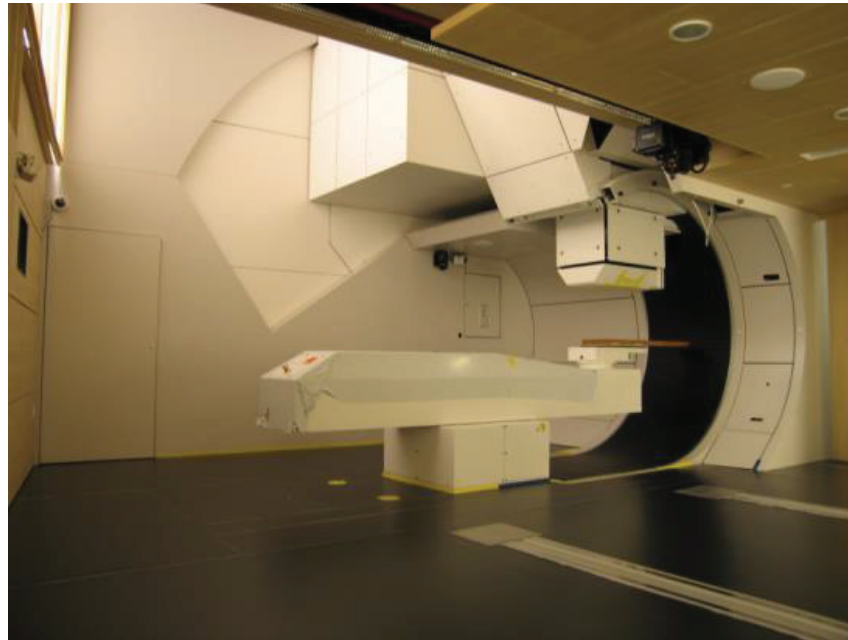
Paul Scherrer Institute, Switzerland



- Accidents?
- Hazards?

Proton Therapy Machine (Antoine)

- Accidents
 - ACC1. Patient injury or death
 - ACC2. Ineffective treatment
 - ACC3. Loss to non-patient quality of life (esp. personnel)
 - ACC4. Facility or equipment damage
- Hazards



Proton Therapy Machine (Antoine)

- Accidents
 - ACC1. Patient injury or death
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 - ACC3. Loss to non-patient quality of life (esp. personnel)
 - ACC4. Facility or equipment damage
- Hazards
 - H-R1. Patient tissues receive more dose than clinically desirable
 - H-R2. Patient tumor receives less dose than clinically desirable
 - H-R3. Non-patient (esp. personnel) is unnecessarily exposed to radiation
 - H-R4. Equipment is subject to unnecessary stress

Control Structures

Chemical Plant



Chemical Plant

Citicchem Safety Control Structure

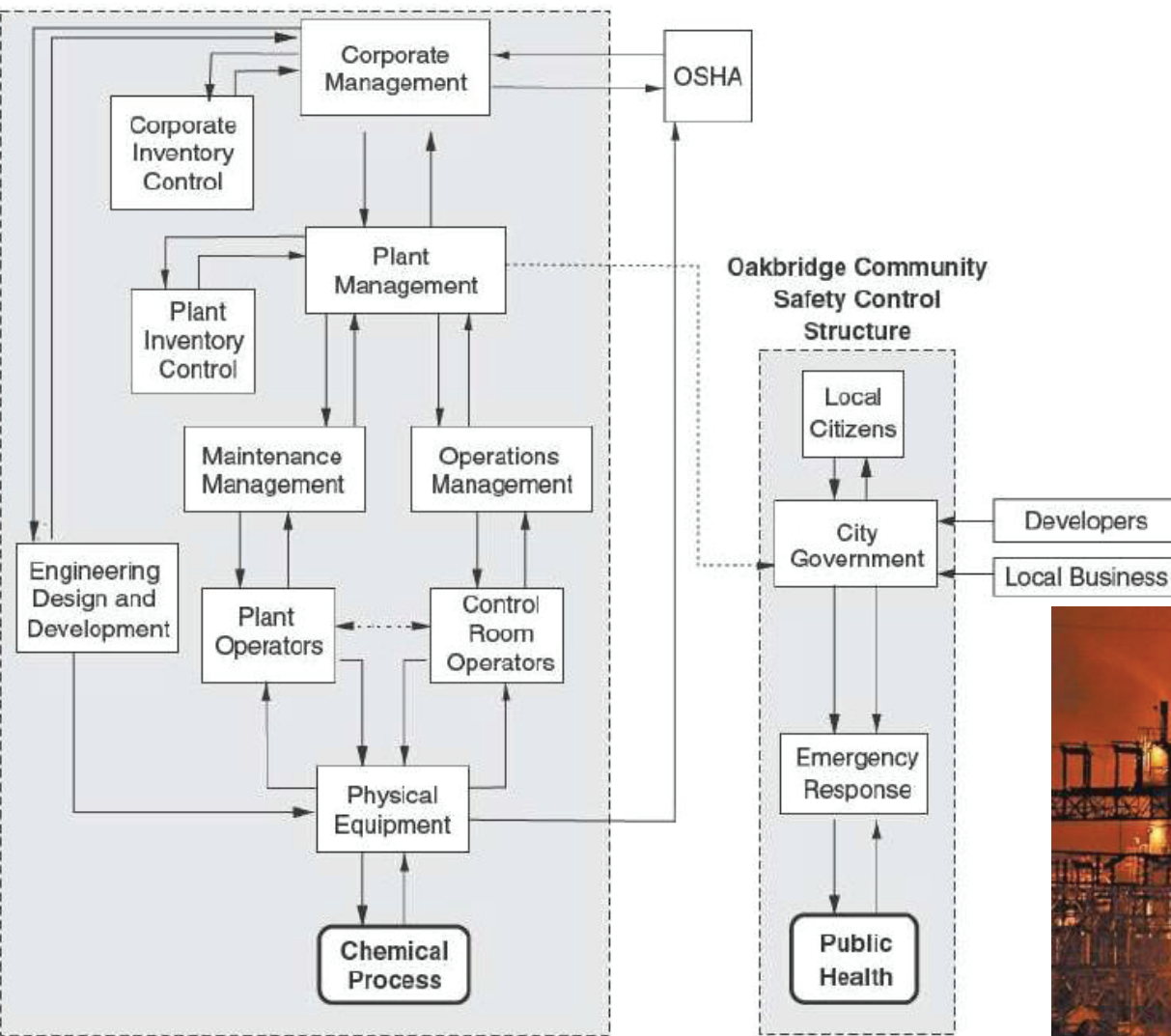
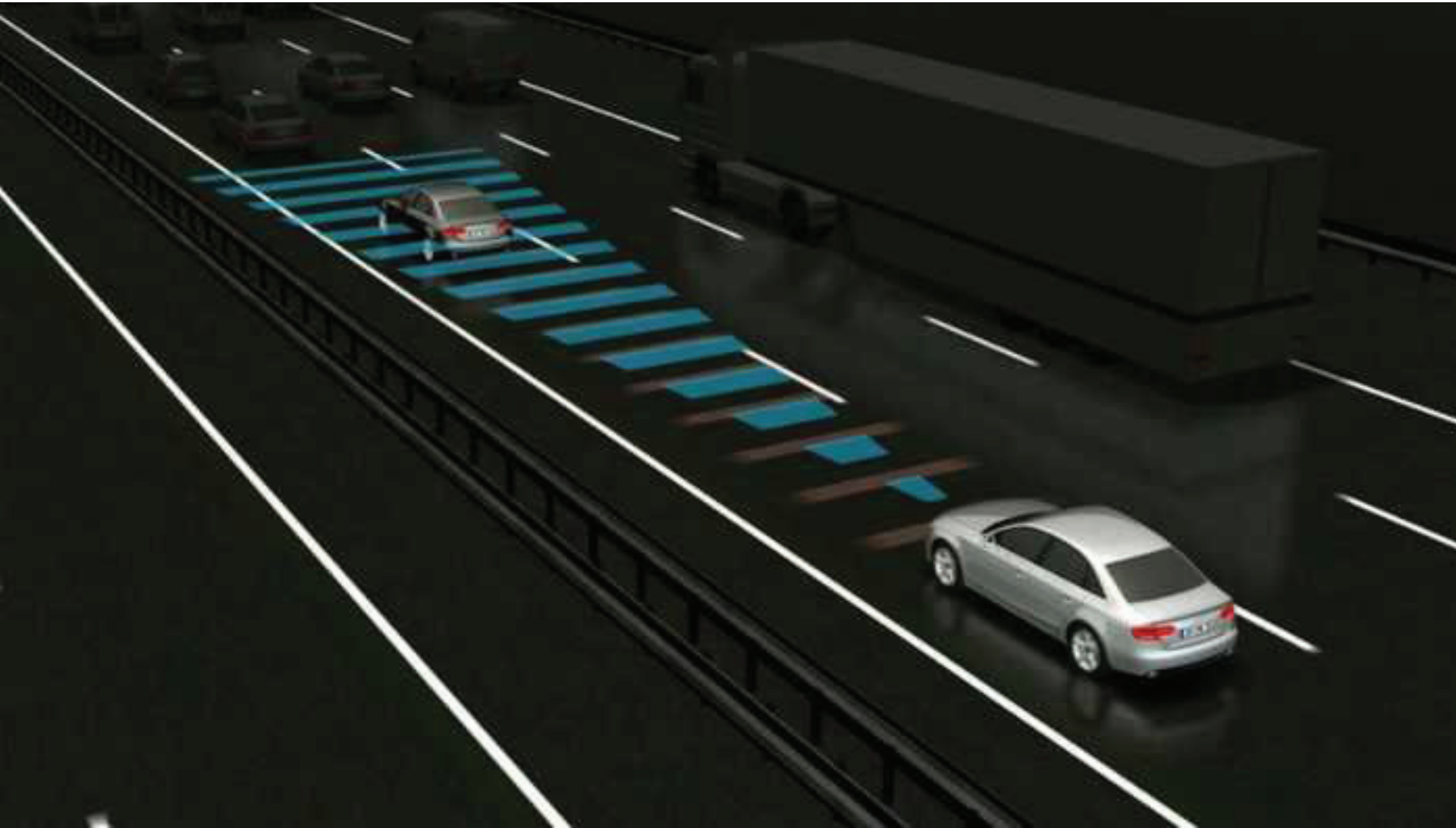


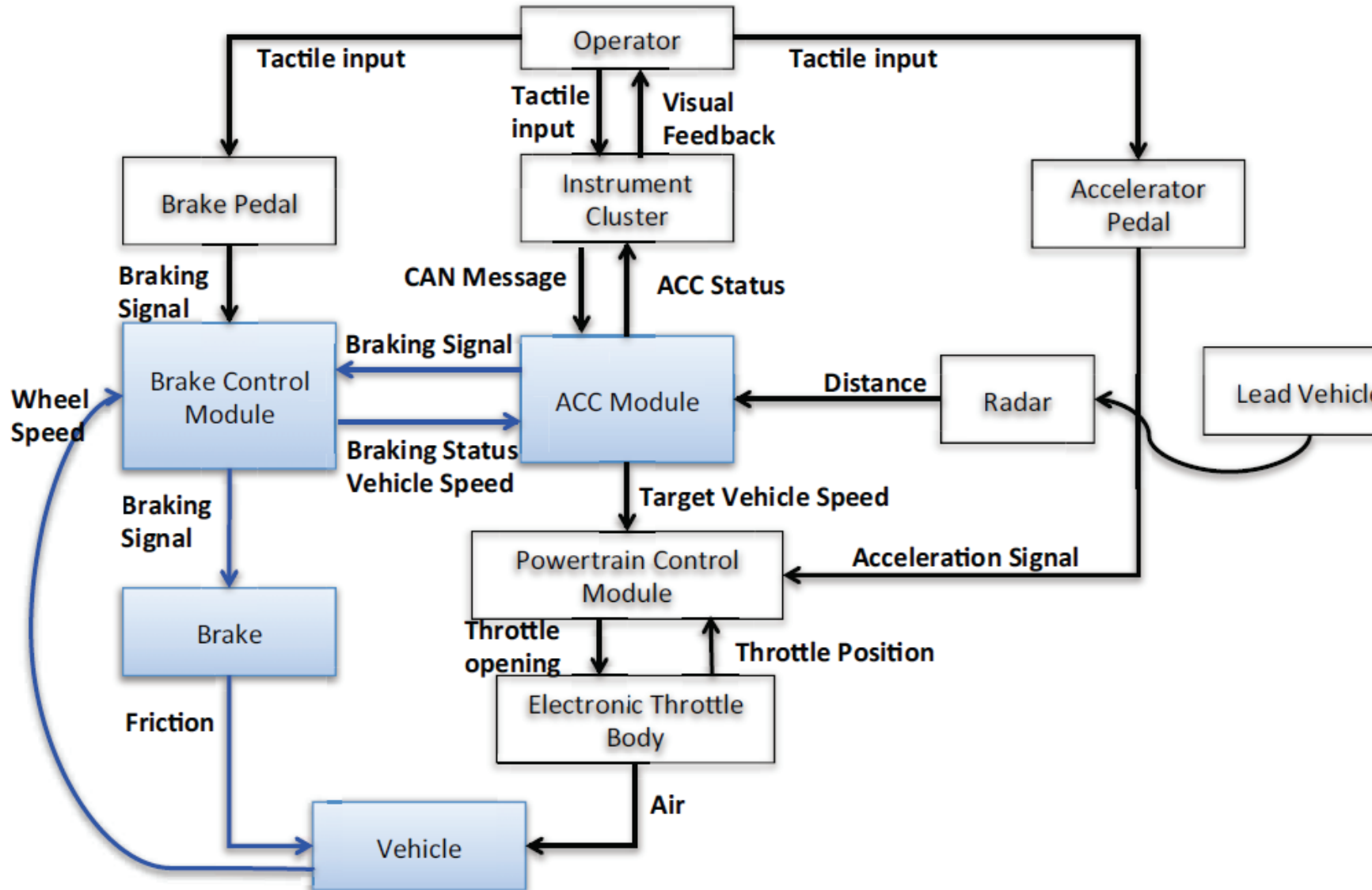
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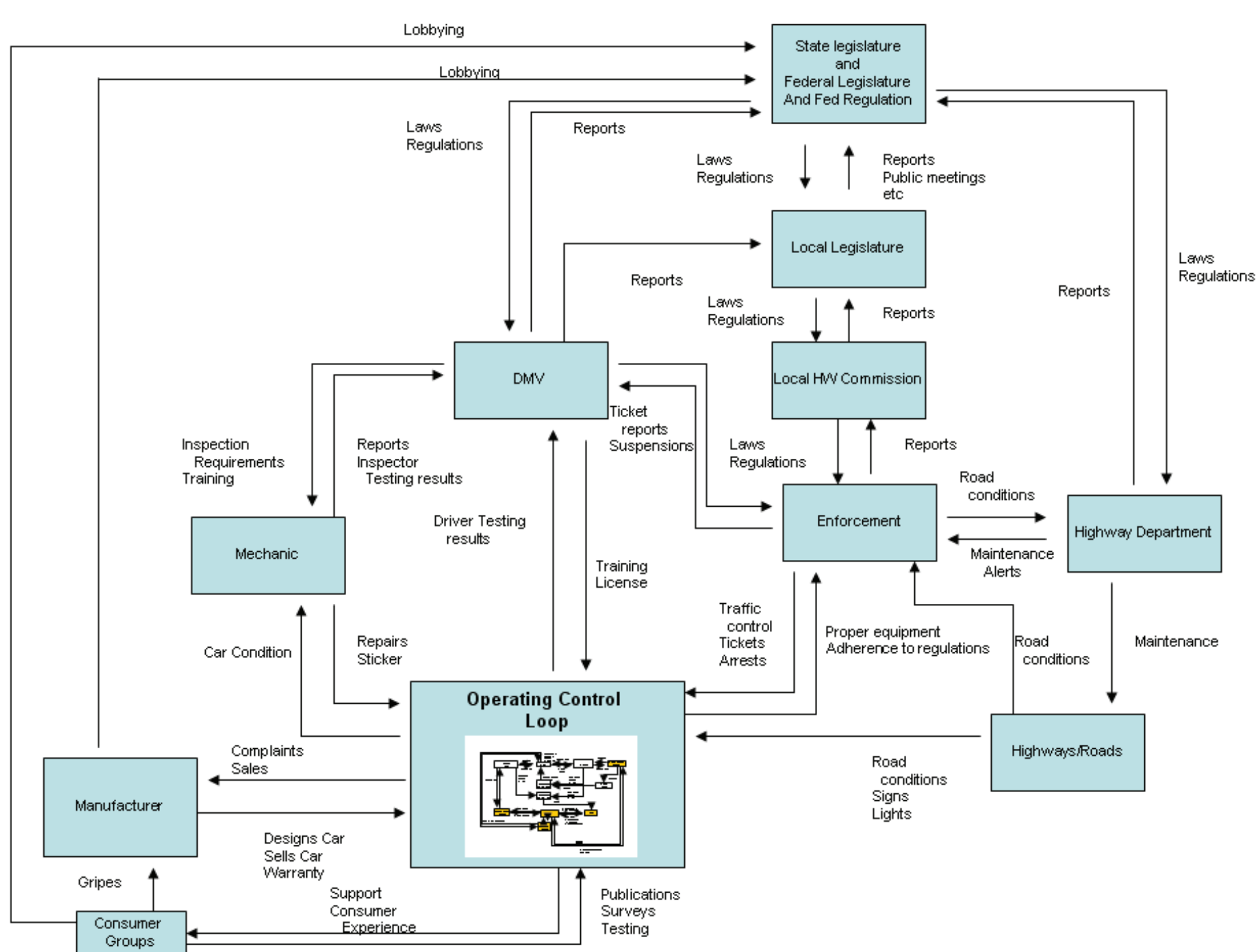


Adaptive Cruise Control



Example: ACC – BCM Control Loop





Ballistic Missile Defense System

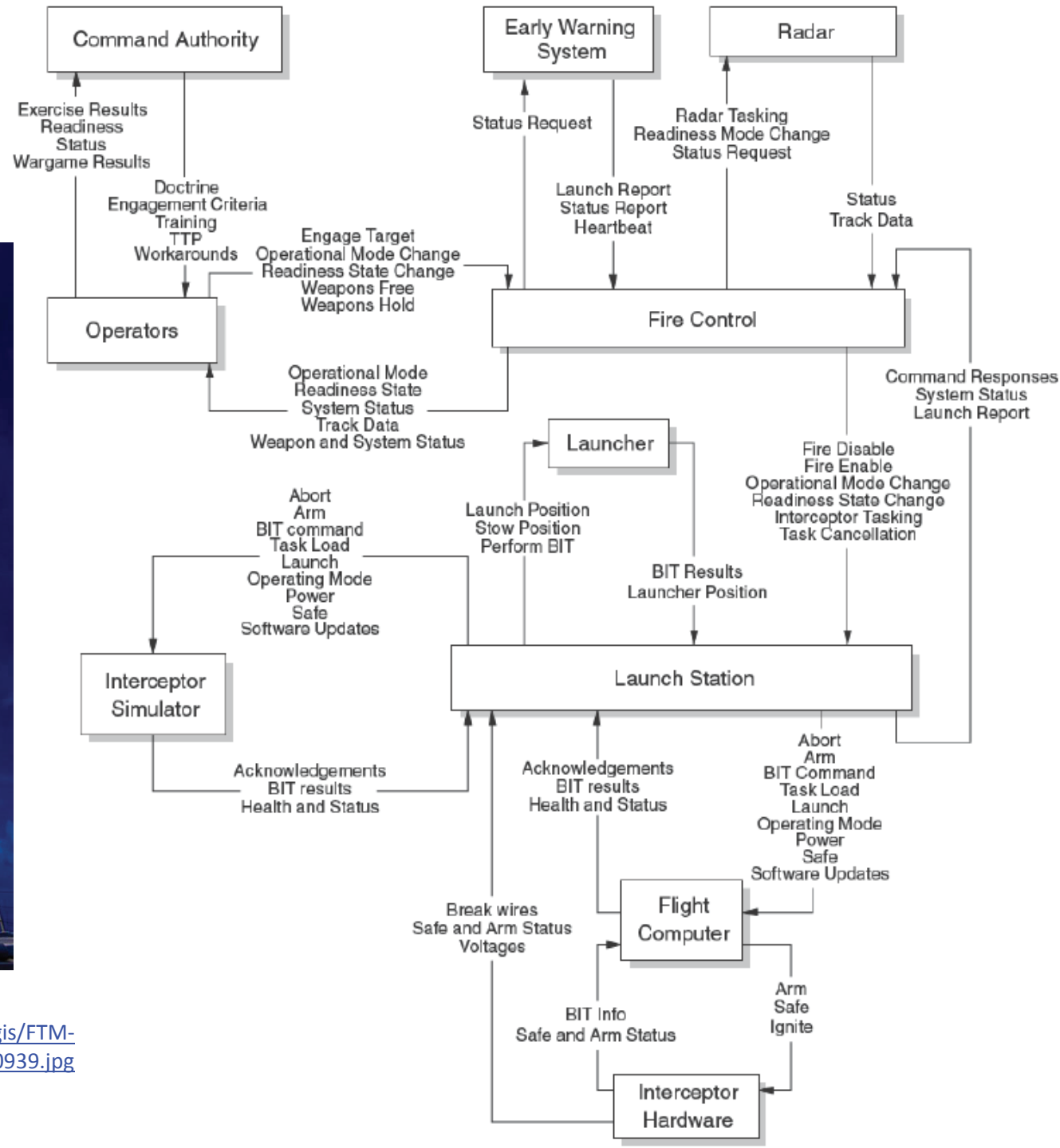


Image from:
http://www.mda.mil/global/images/system/aegis/FTM-21_Missile%20Bulkhead%20Center14_BN4H0939.jpg

Congress
U.S. pharmaceutical
safety control
structure

FDA

Pharmaceutical
Companies

Doctors

Patients

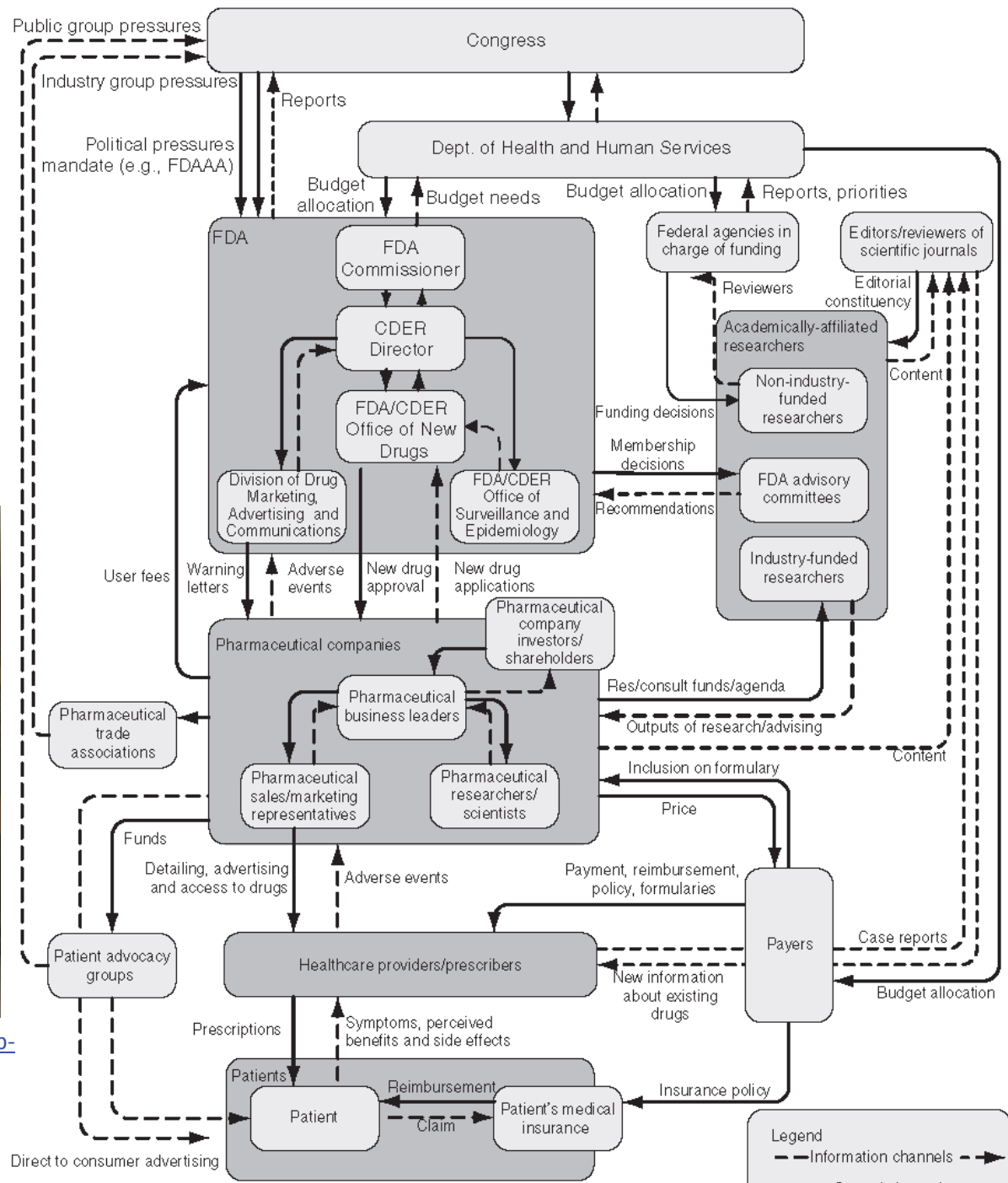
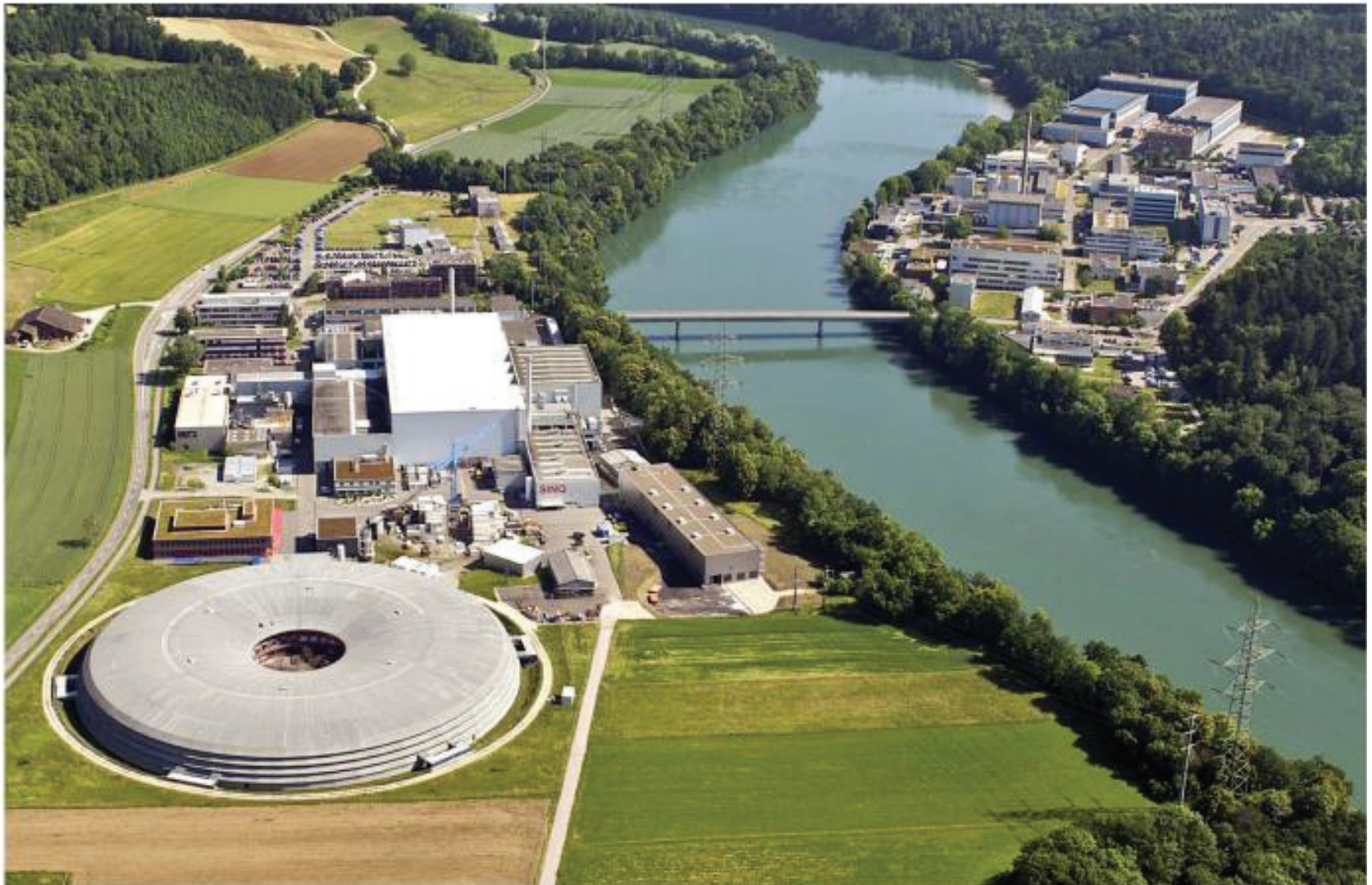


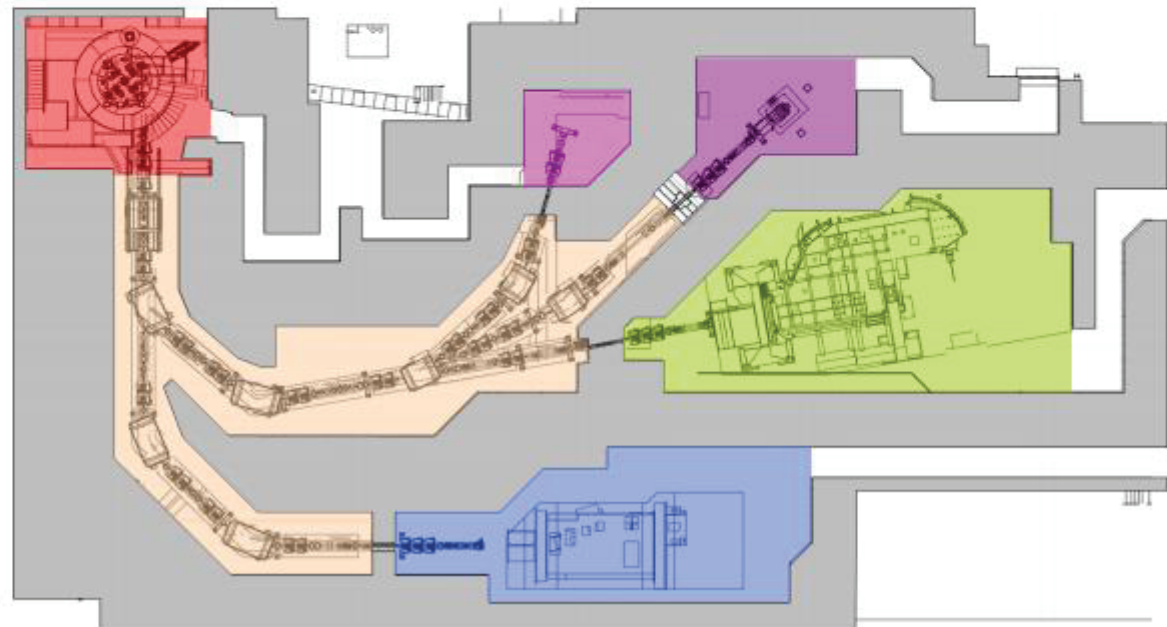
Image from: <http://www.kleantreatmentcenter.com/wp-content/uploads/2012/07/vioxx.jpg>

Proton Radiation Therapy System Paul Scherrer Institute, Switzerland



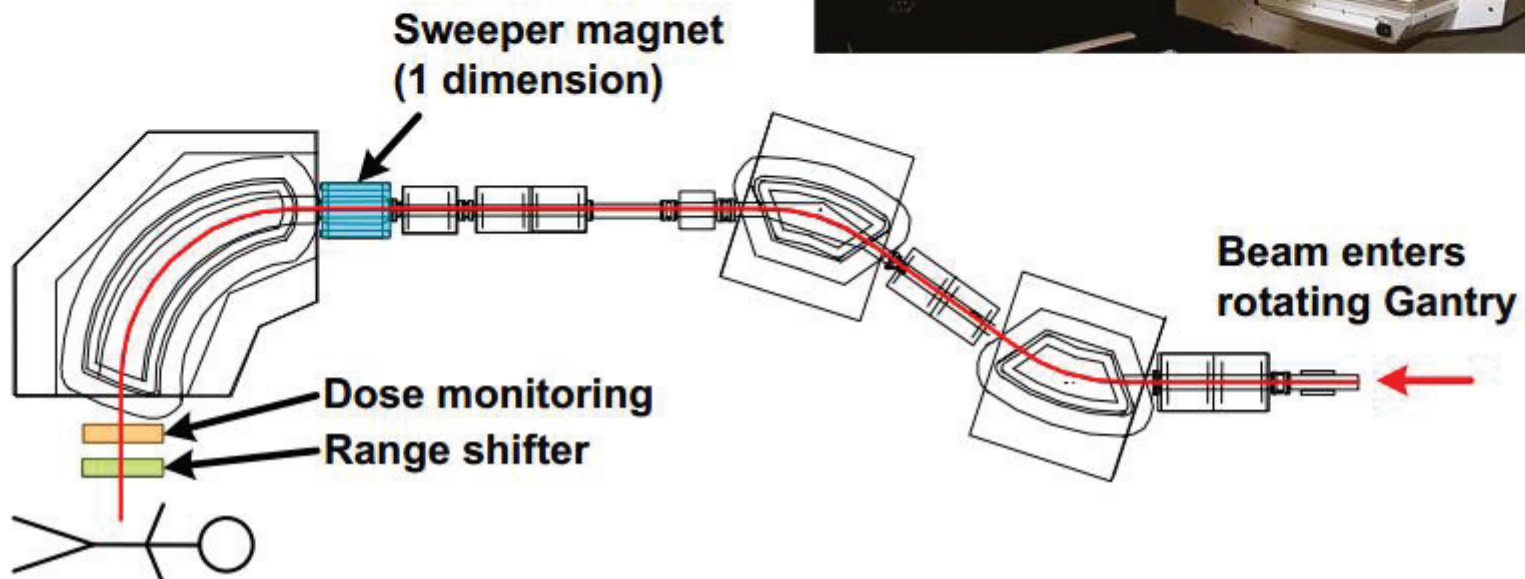
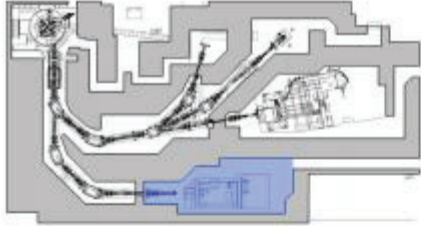
Proton Radiation Therapy System Paul Scherrer Institute, Switzerland

- 250 MeV Proton accelerator (superconducting cyclotron)
- Beamlines to 4 user areas
- OPTIS
- Gantry 1
- Gantry 2
- Experimental area



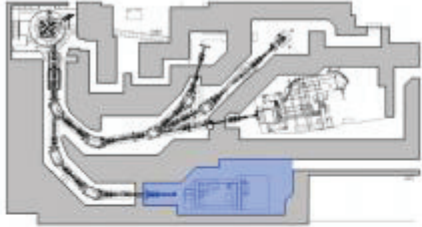
Proton Radiation Therapy System

Gantry 1



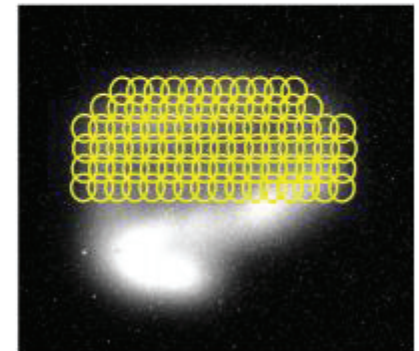
Proton Radiation Therapy System

Spot Scanning Technique

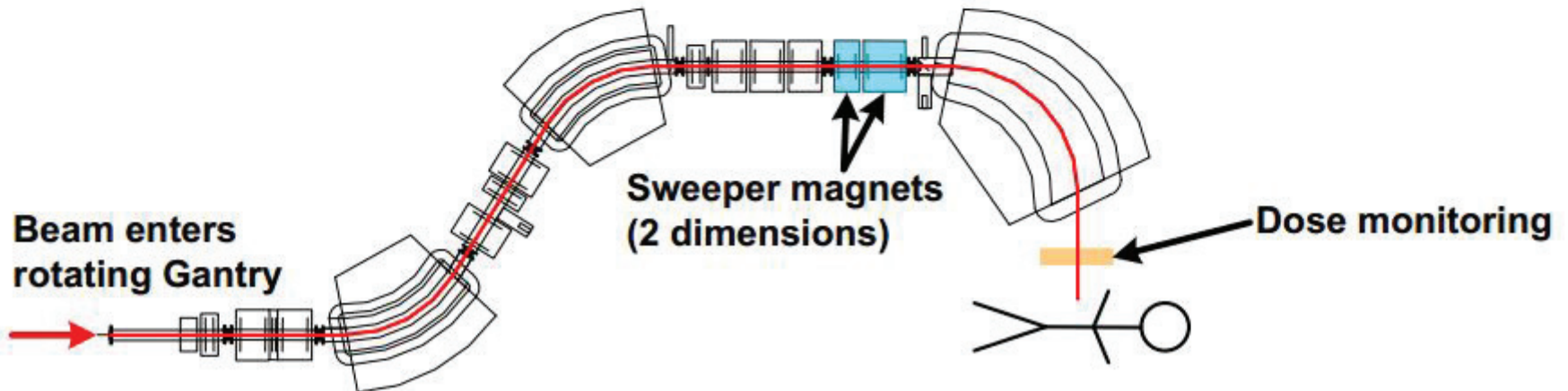


Elements of spot scanning:

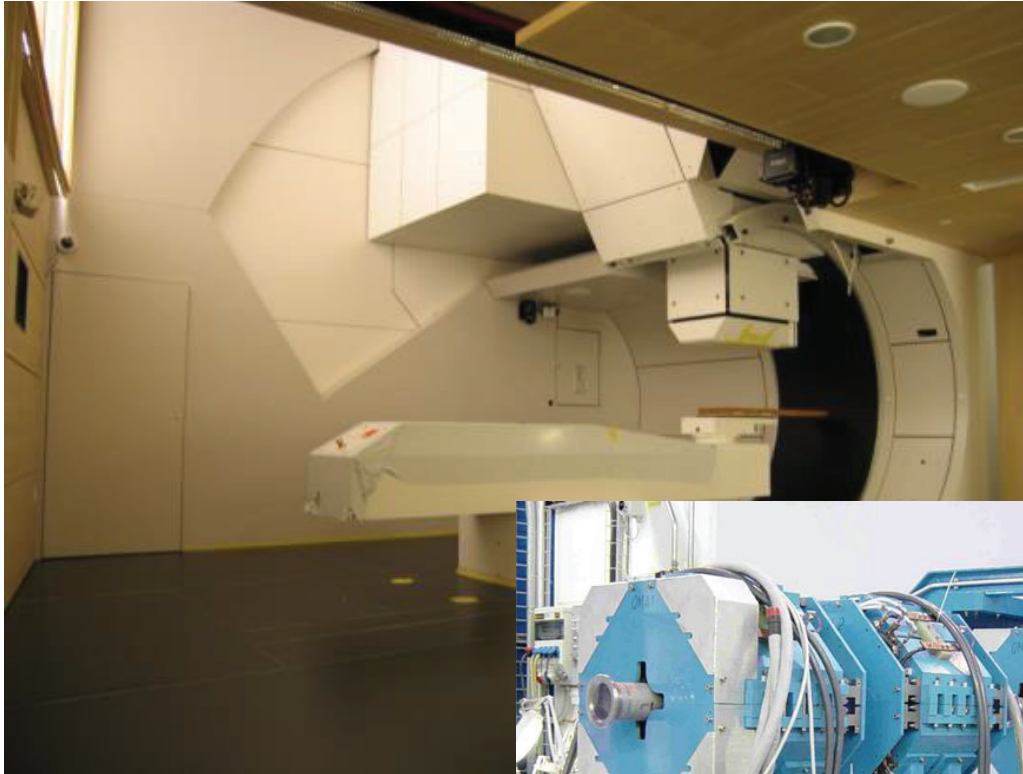
- Beam on/off $50 \mu\text{s}$
 - Sweeper magnet 5 ms/step
 - Range shifter 30 ms
 - Patient table 1 cm/s
- 10'000 spots to treat 1 liter volume



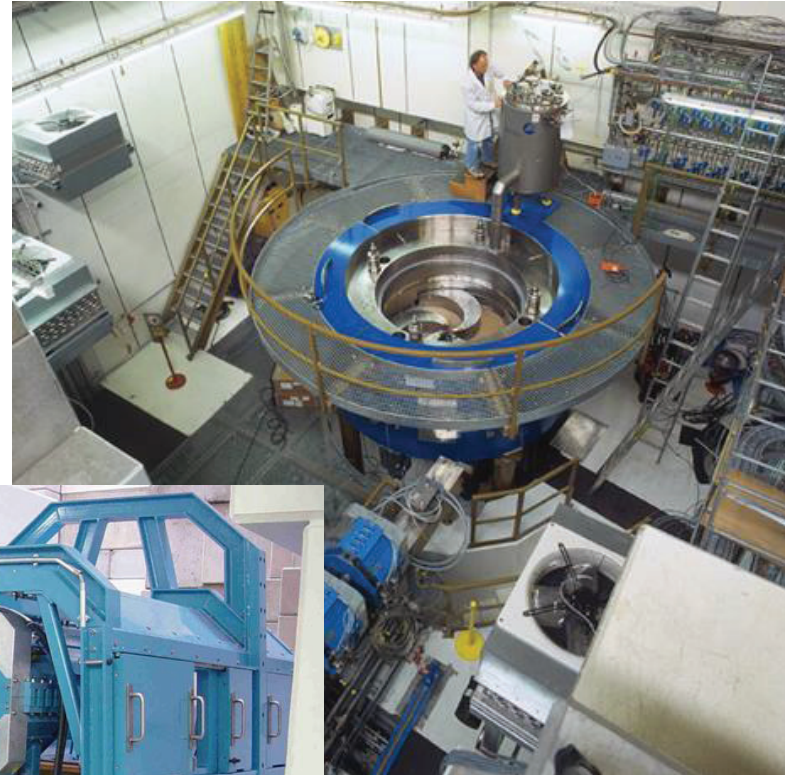
Proton Radiation Therapy System Gantry 2



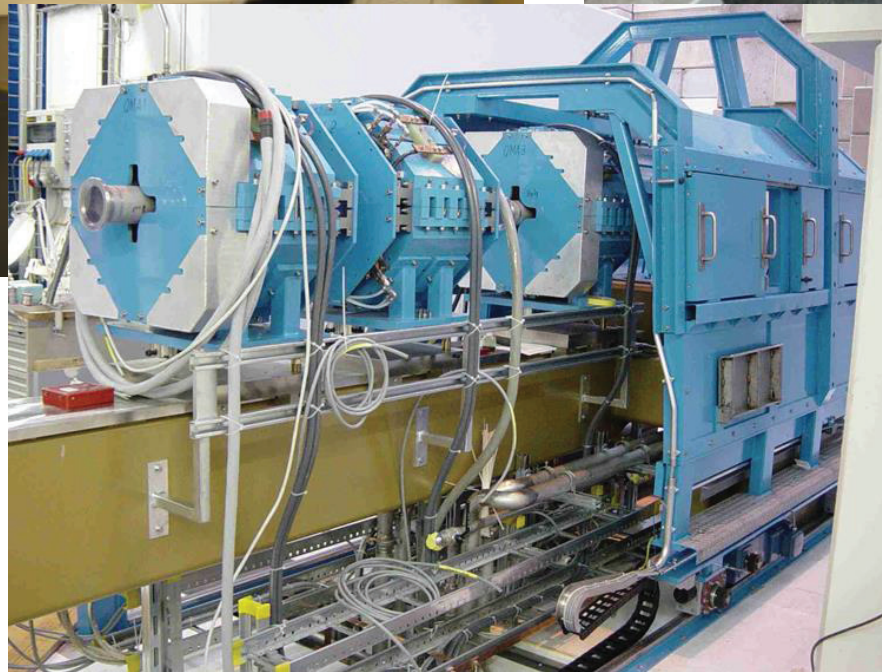
Proton Therapy Machine Overview



Gantry



Cyclotron



Beam path and
control elements

Proton Therapy Machine

High-level Control Structure



- How big do you think the high-level control structure is?

Proton Therapy Machine

High-level Control Structure

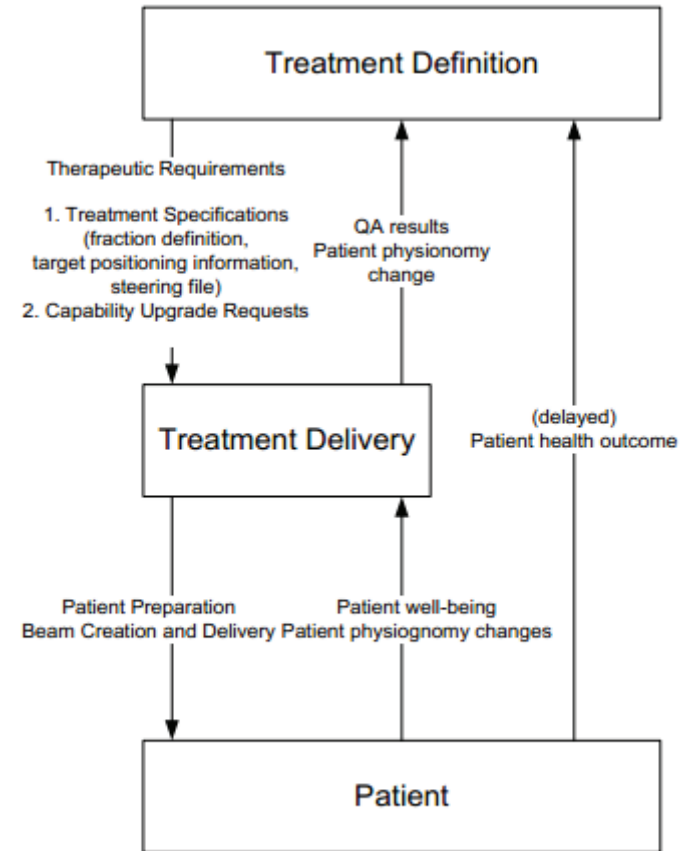
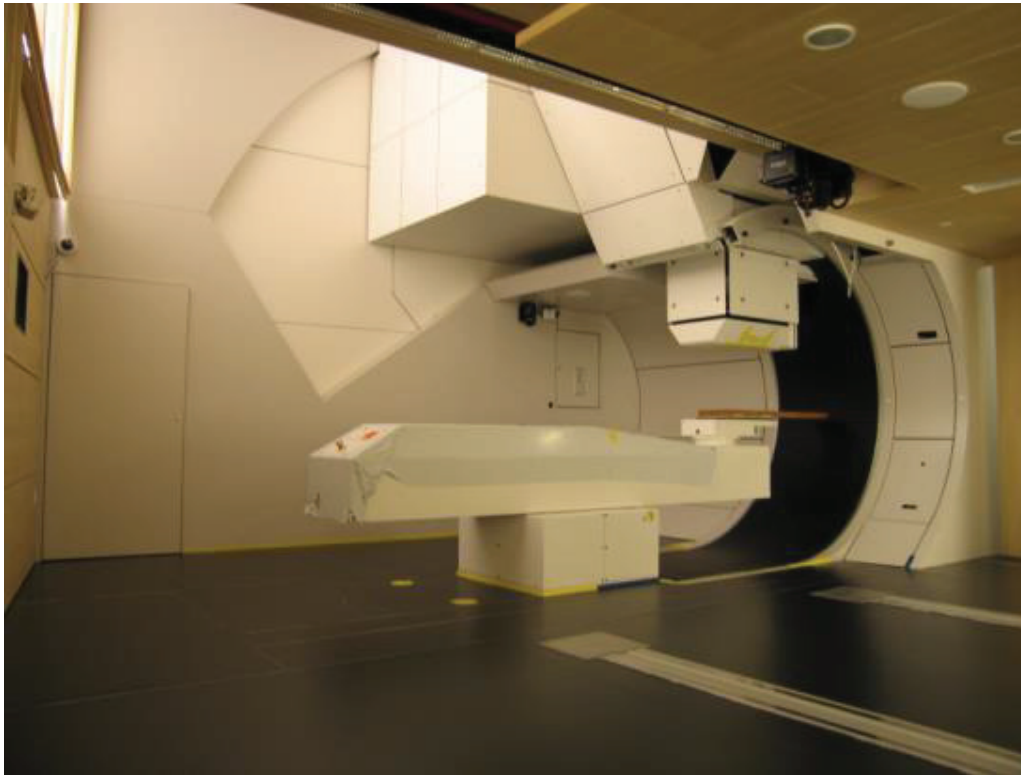


Figure 11 - High-level functional description of the PROSCAN facility (D0)

Proton Therapy Machine Control Structure

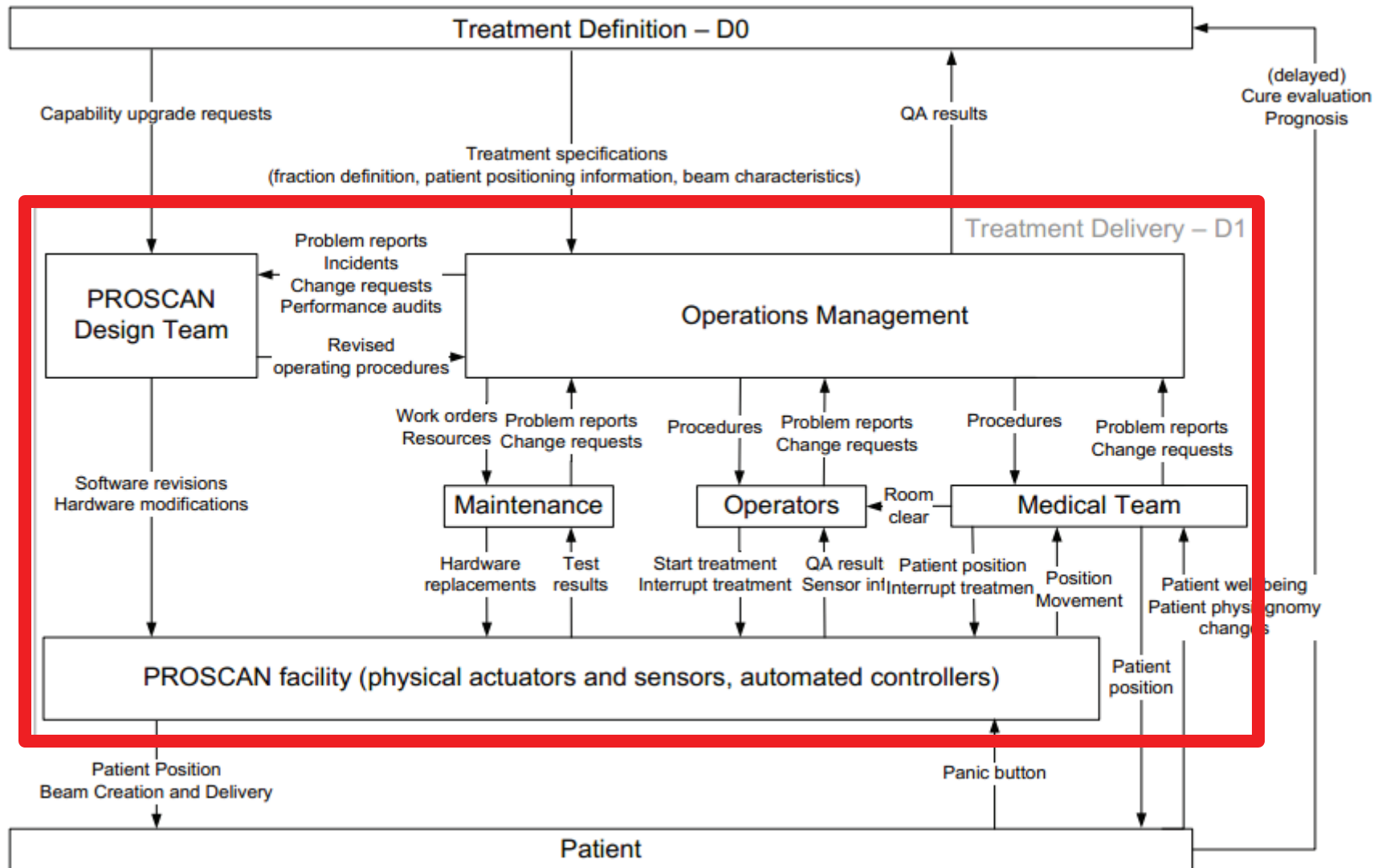
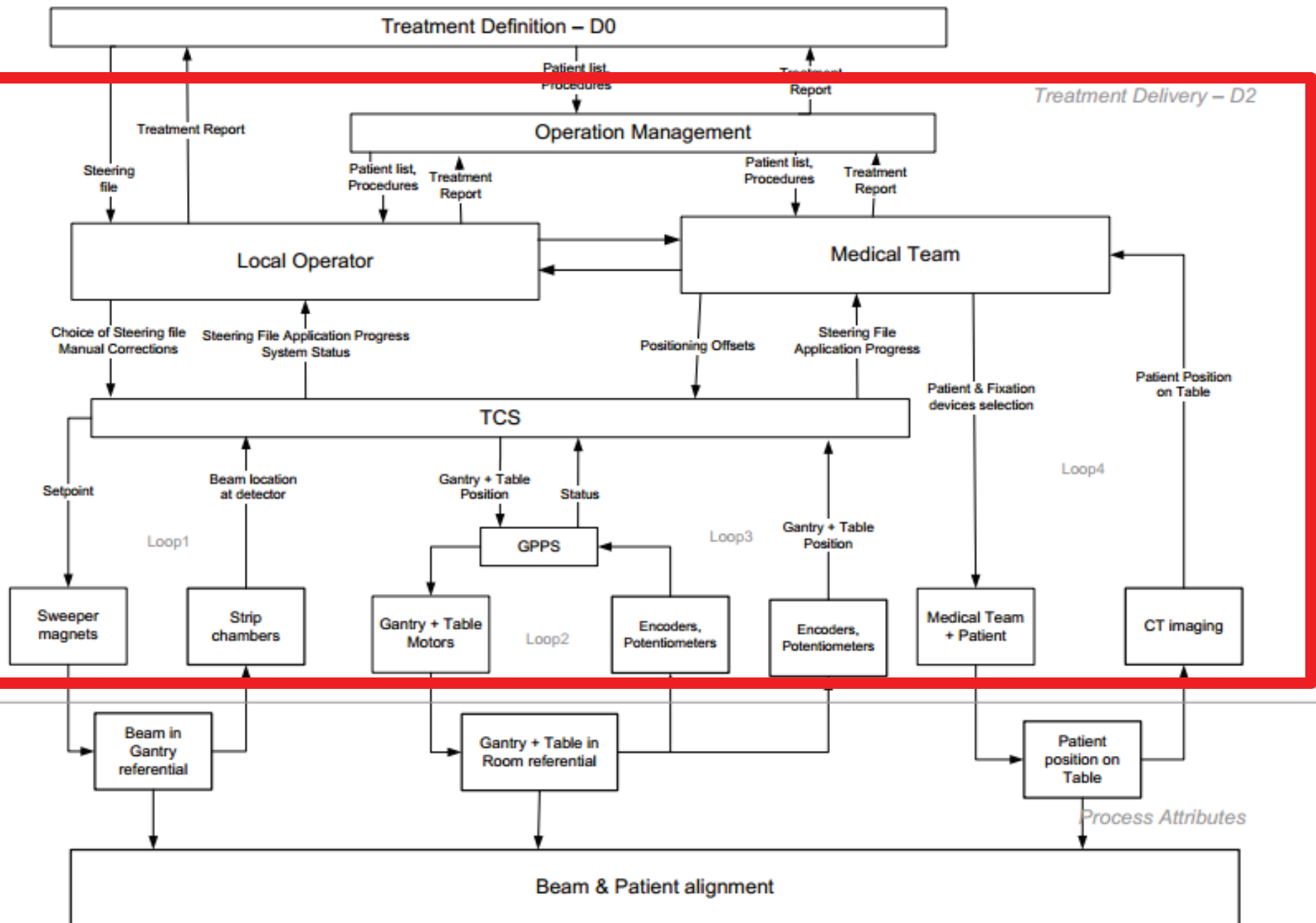


Figure 13 - Zooming into the Treatment Delivery group (D1)

Proton Therapy Machine Detailed Control Structure



STPA

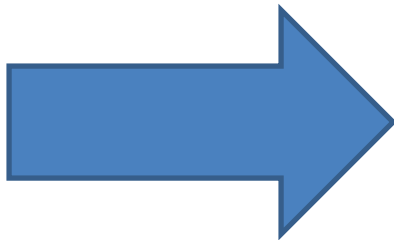
(System-Theoretic Process Analysis)



- Identify accidents and hazards

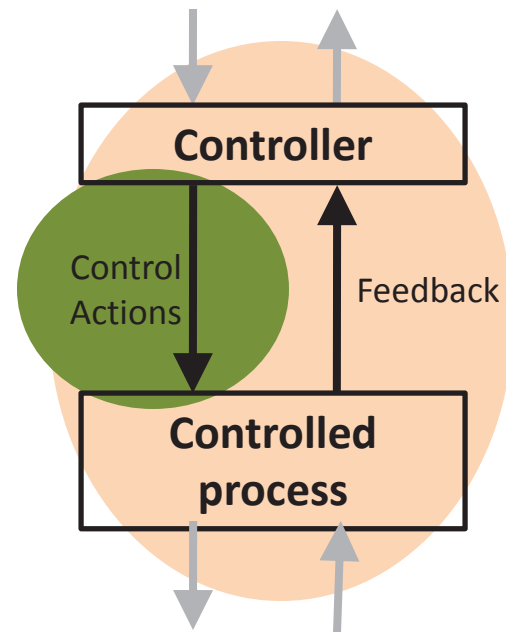


- Construct the control structure

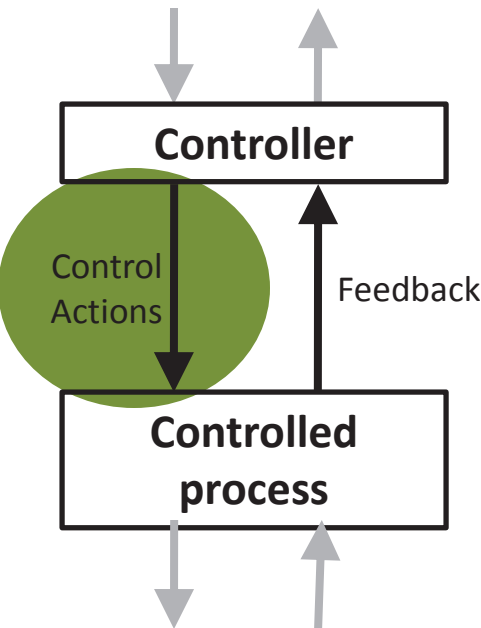


- Step 1: Identify unsafe control actions

- Step 2: Identify causal factors and control flaws



STPA Step 1: Unsafe Control Actions (UCA)



4 ways unsafe control may occur:

- A control action required for safety is not provided or is not followed
- An unsafe control action is provided that leads to a hazard
- A potentially safe control action provided too late, too early, or out of sequence
- A safe control action is stopped too soon or applied too long (for a continuous or non-discrete control action)

Control Action

	Not providing causes hazard	Providing causes hazard	Incorrect Timing/ Order	Stopped Too Soon / Applied too long

Proton Therapy Machine Control Structure

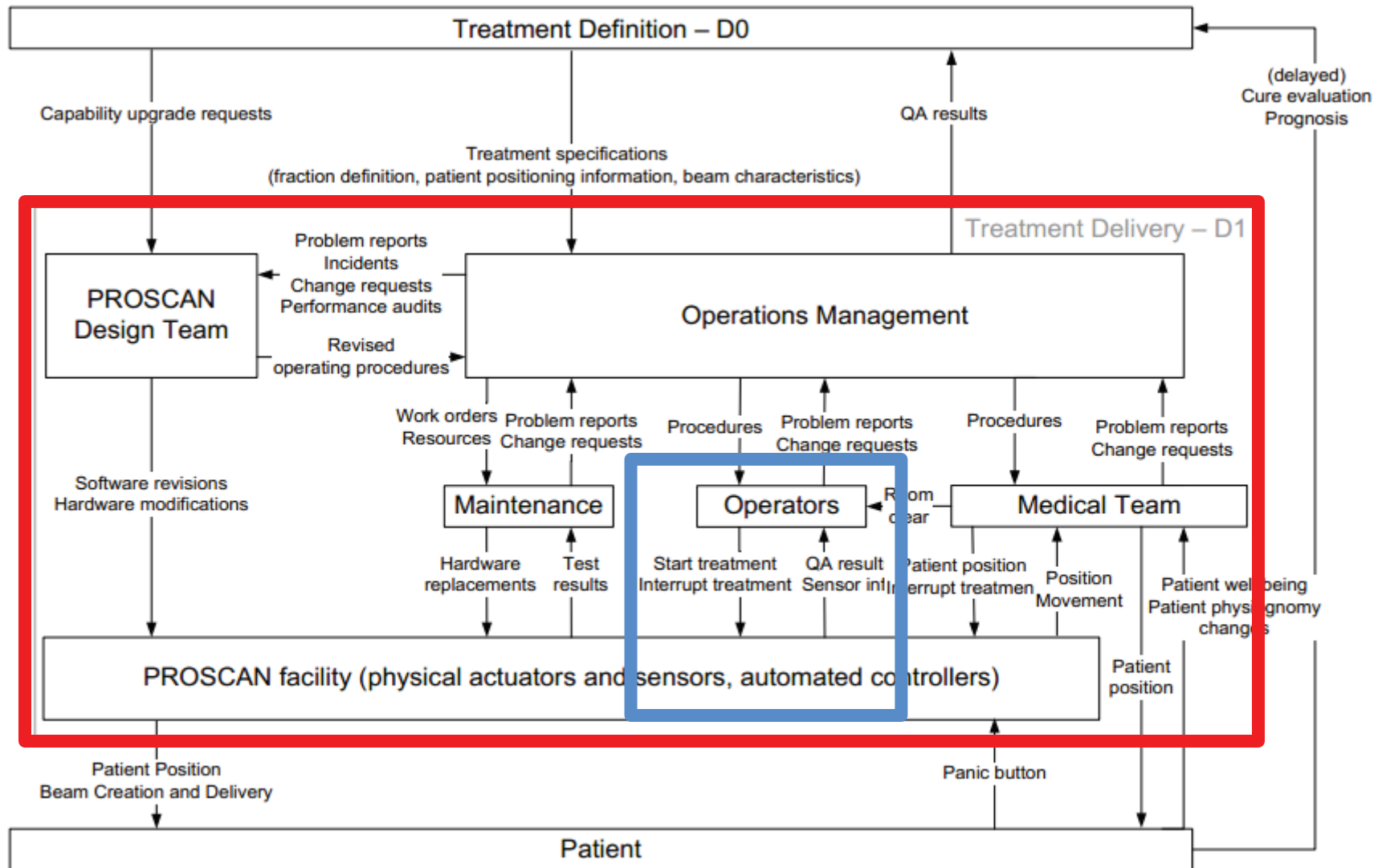
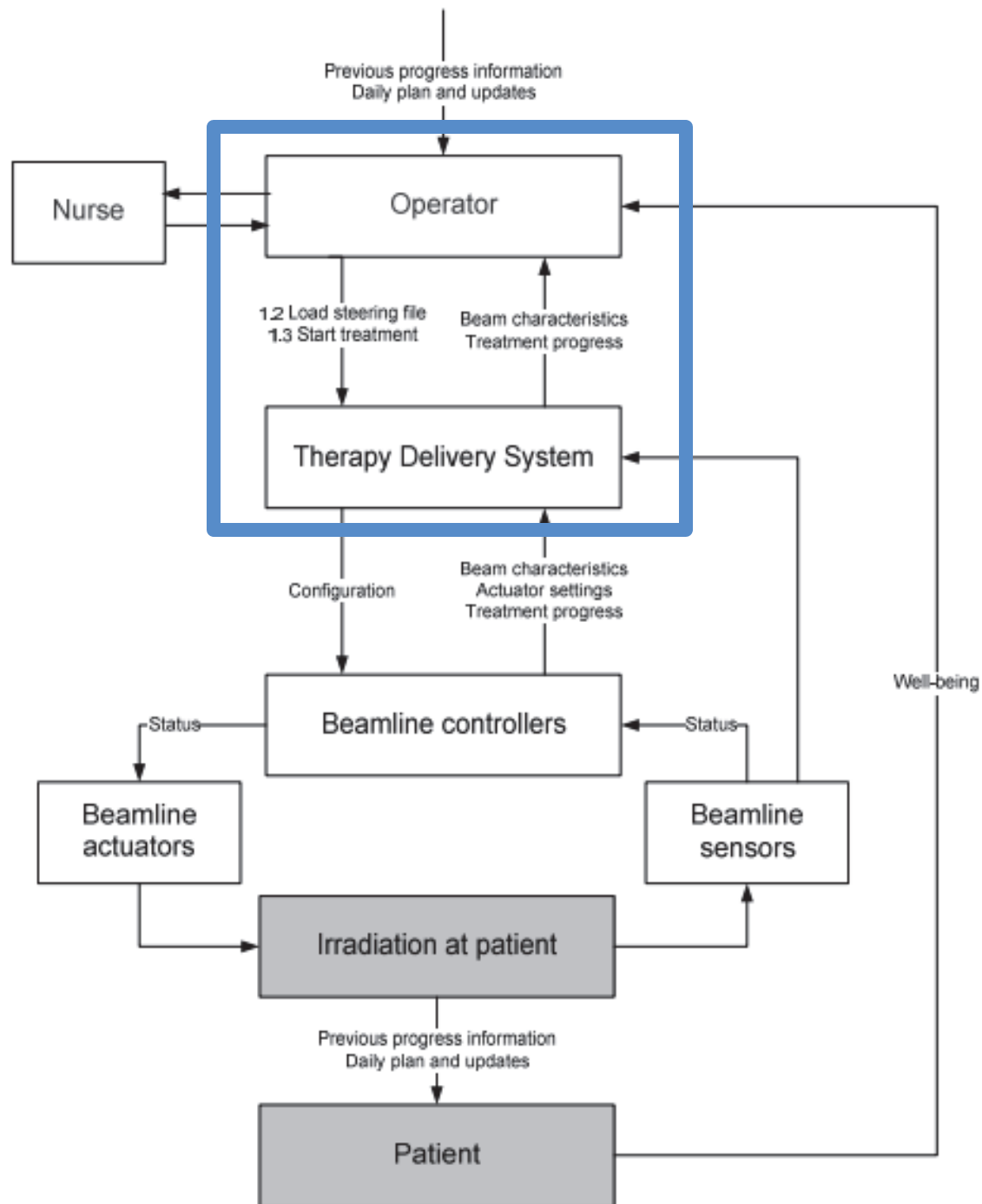


Figure 13 - Zooming into the Treatment Delivery group (D1)

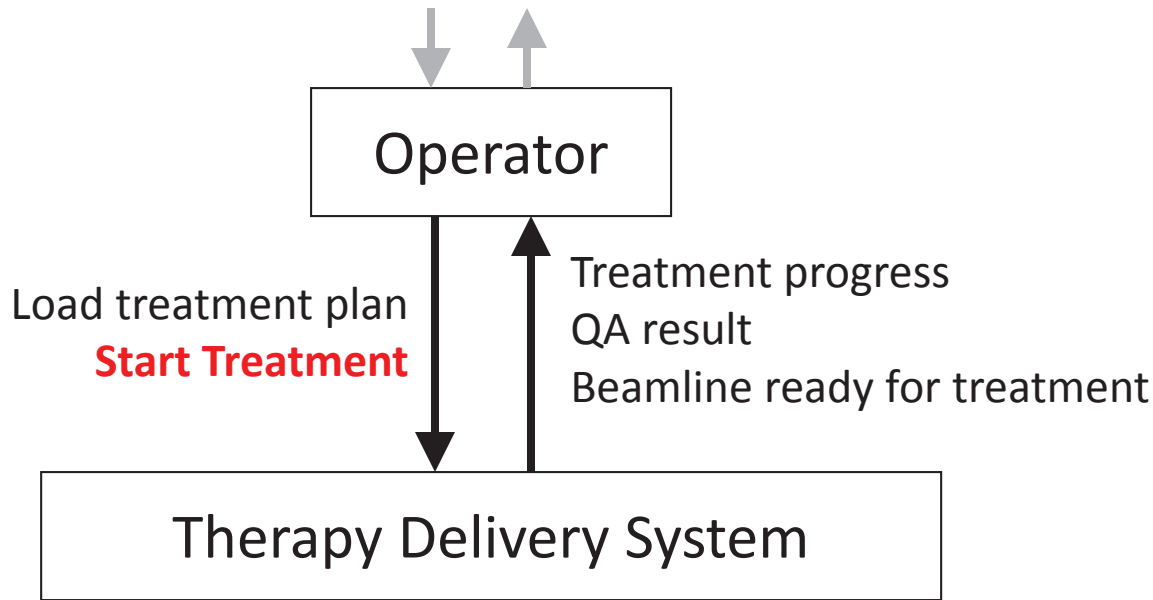
Unsafe Control Actions

Start Treatment Command

- Not provided causes hazard?
- Providing causes hazard?
- Too early/late?
Wrong order?
- Stopped too soon,
applied too long?



Step 1: Identify Unsafe Control Actions



System Hazards

- H-R1. Patient tissues receive more dose than clinically desirable
- H-R2. Patient tumor receives less dose than clinically desirable
- H-R3. Non-patient (esp. personnel) is unnecessarily exposed to radiation
- H-R4. Equipment is subject to unnecessary stress

Control Action	Not providing causes hazard	Providing causes hazard	Too early/too late, wrong order	Stopped too soon/ applied too long
Start Treatment Command		Operator provides Start Treatment cmd while personnel is in room (↑H-R3)		

Structure of an Unsafe Control Action

Example:

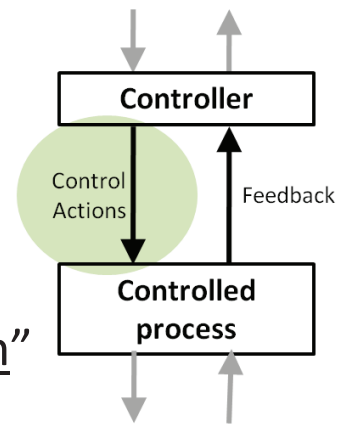
“Operator provides start treatment cmd while personnel is in room”

Source Controller

Type

Control Action

Context



Four parts of an unsafe control action

- Source Controller: the controller that can provide the control action
- Type: whether the control action was provided or not provided
- Control Action: the controller’s command that was provided / missing
- Context: conditions for the hazard to occur
 - (system or environmental state in which command is provided)

Unsafe control action summary

- UCA1. Treatment is started while personnel is in room (↑H-R3)
- UCA2. Treatment is started while patient is not ready to receive treatment (↑H-R1, H-R2)
 - Note: This includes “wrong patient position”, “patient feeling unwell”, etc.
- UCA3. Treatment is started when there is no patient at the treatment point (↑H-R2)
- UCA4. Treatment is started with the wrong treatment plan (↑H-R1,H-R2)
- UCA5. Treatment is started without a treatment plan having been loaded (↑H-R1,H-R2)
- UCA6. Treatment is started while the beamline is not ready to receive the beam (↑H-R1, H-R4)
- UCA7. Treatment is started while not having mastership (↑H-R1, H-R2, H-R3)
- UCA8. Treatment is started while facility is in non-treatment mode (e.g. experiment or trouble shooting mode) (↑H-R1, H-R2)
- UCA9. Treatment start command is issued after treatment has already started (↑H-R1, H-R2)
- UCA10. Treatment start command is issued after treatment has been interrupted and without the interruption having adequately been recorded or accounted for (↑H-R1, H-R2)
- UCA11. Treatment does not start while everything else is otherwise ready (↑H-R1, H-R2)

Component Safety Constraints

Unsafe Control Action

Component Safety Constraint

Treatment is started while personnel is in room



Treatment must not be started while personnel are in the room

Treatment is started while the beamline is not ready to receive the beam



Treatment must not start before beamline is fully configured

Treatment is started when there is no patient at the treatment point



Treatment must not start until when patient is at the treatment point

Treatment is started without a treatment plan having been loaded



Treatment must not start until a new treatment plan has been loaded

STPA

(System-Theoretic Process Analysis)



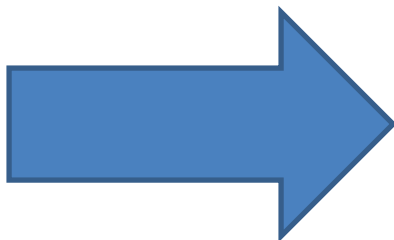
- Identify accidents and hazards



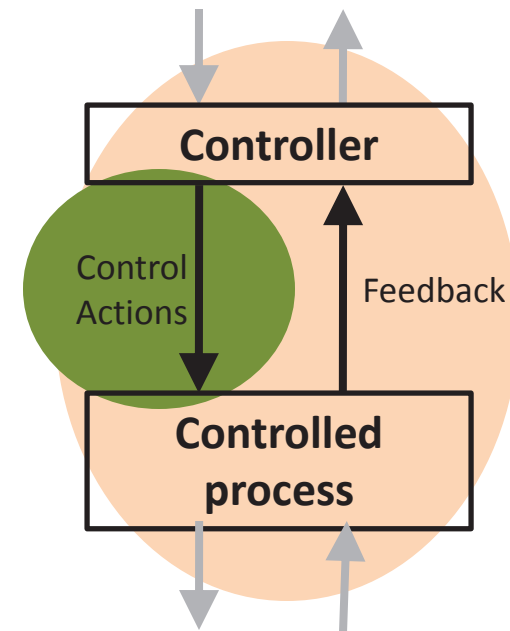
- Construct the control structure



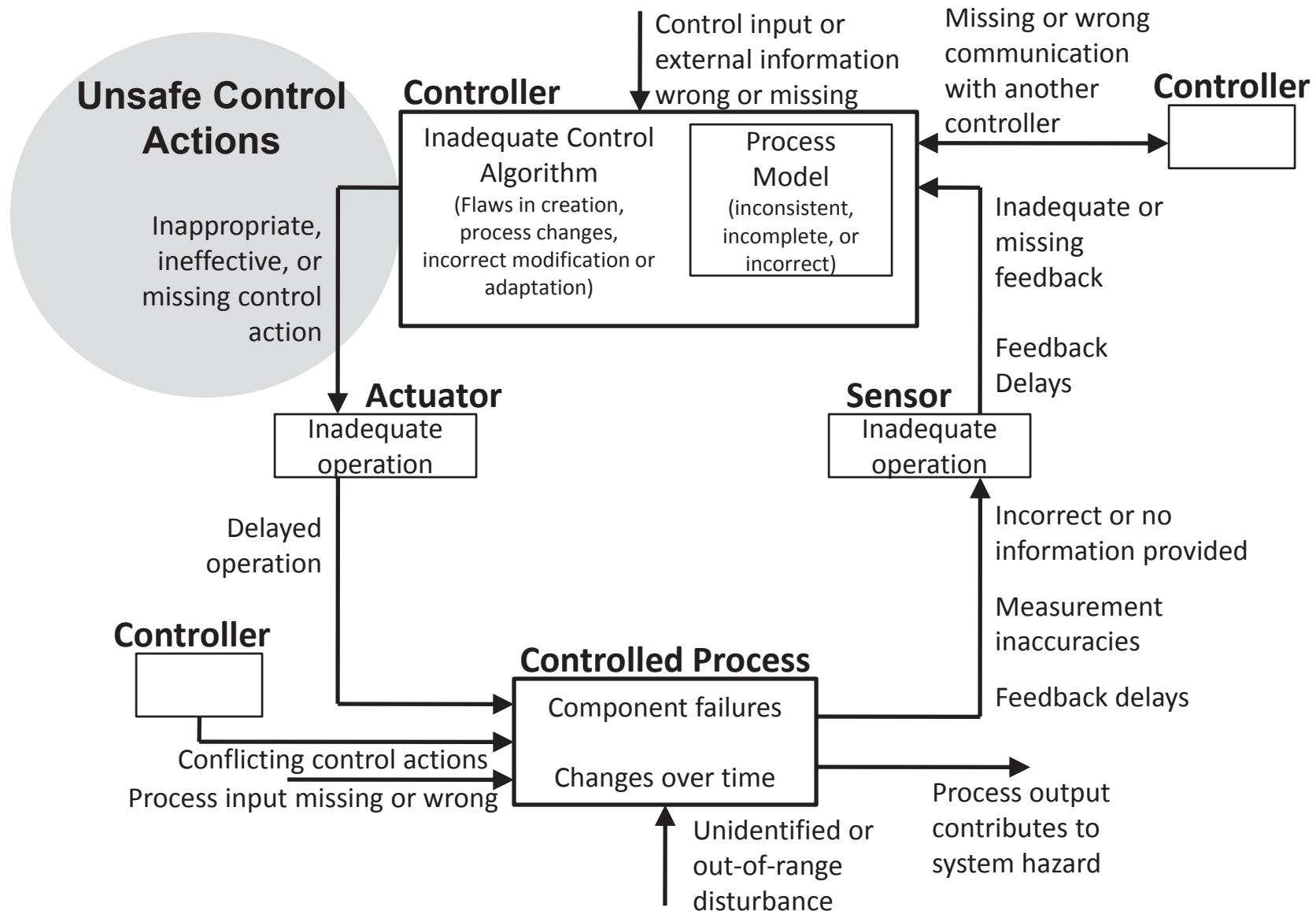
- Step 1: Identify unsafe control actions



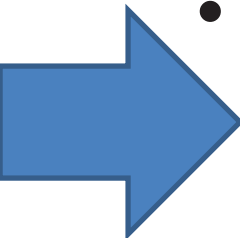
- Step 2: Identify causal factors and control flaws



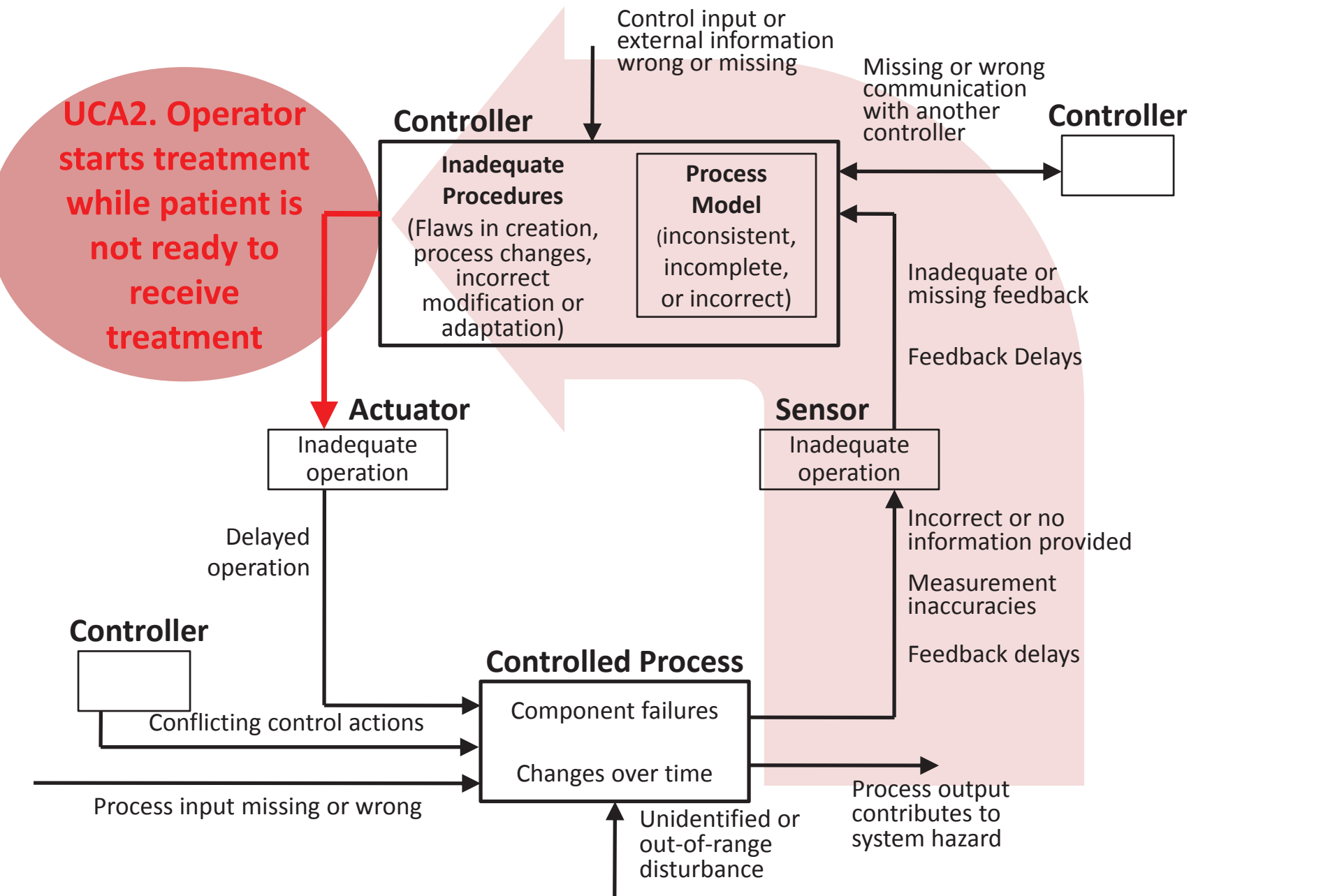
STPA Step 2: Identify Control Flaws



STPA Step 2: Identify Causal Factors

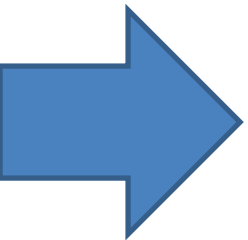
- 
- Select an Unsafe Control Action
 - A. Identify causal factors that explain how it could happen
 - Develop causal accident scenarios
 - B. Identify causal factors that explain how control actions may not be followed or executed properly
 - Develop causal accident scenarios
 - Identify controls and mitigations for the accident scenarios

Step 2A: Potential causes of UCAs

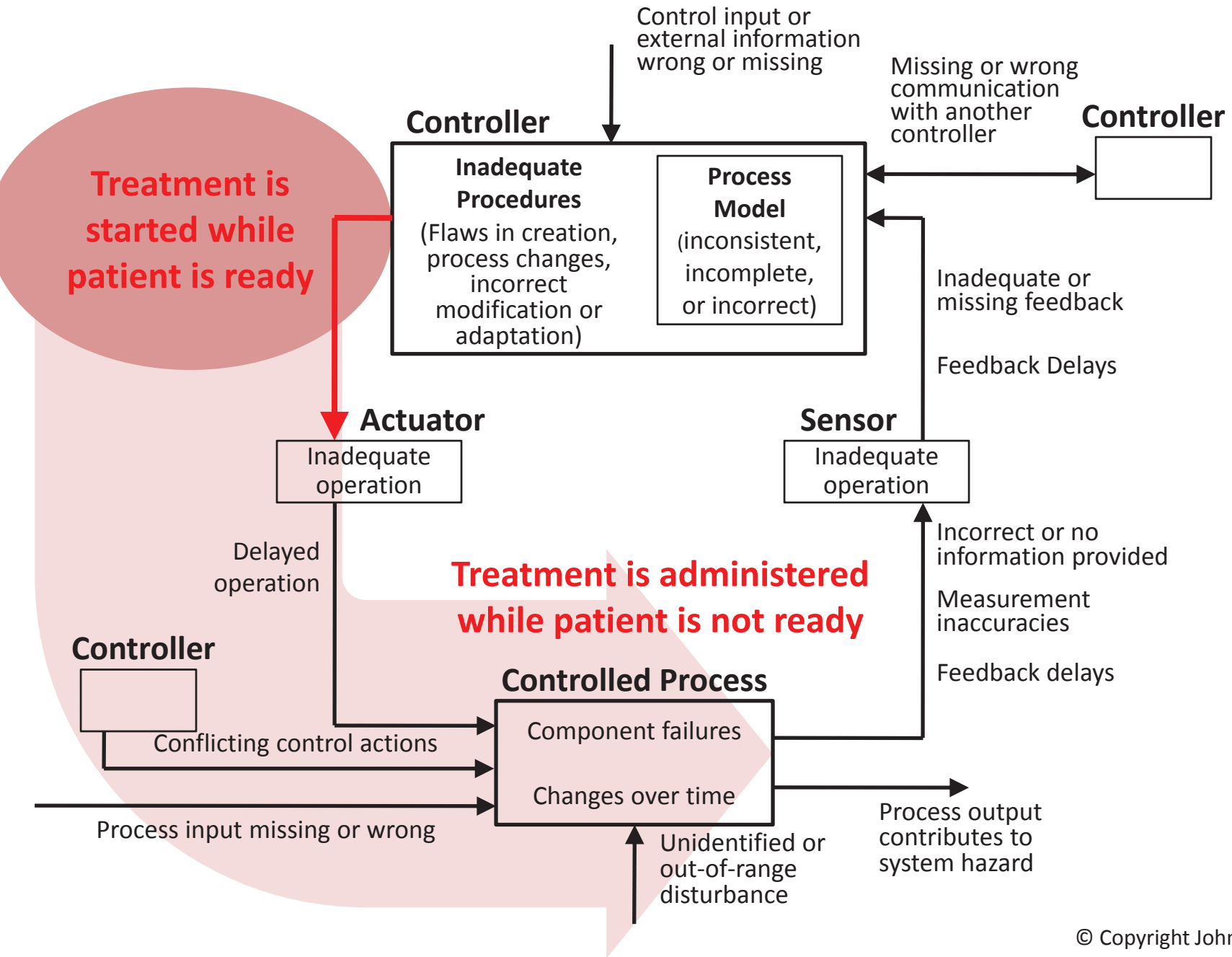


STPA Step 2: Identify Causal Factors

- Select an Unsafe Control Action
 - A. Identify causal factors that explain how it could happen
 - Develop causal accident scenarios
 - B. Identify causal factors that explain how control actions may not be followed or executed properly
 - Develop causal accident scenarios
- Identify controls and mitigations for the accident scenarios

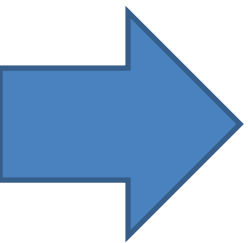


Step 2B: Potential control actions not followed



STPA Step 2: Identify Causal Factors

- Select an Unsafe Control Action
 - A. Identify causal factors that explain how it could happen
 - Develop causal accident scenarios
 - B. Identify causal factors that explain how control actions may not be followed or executed properly
 - Develop causal accident scenarios



Identify controls and mitigations for the accident scenarios

Example Controls for Causal Scenarios

- **Scenario 1** – Operator provides Start Treatment command when there is no patient on the table or patient is not ready. Operator was not in the room when the command was issued, as required by other safety constraints. Operator was expecting patient to have been positioned, but table positioning was delayed compared to plan (e.g. because of delays in patient preparation or patient transfer to treatment area; because of unexpected delays in beam availability or technical issues being processed by other personnel without proper communication with the operator).
- **Controls:**
 - Provide operator with direct visual feedback to the gantry coupling point, and require check that patient has been positioned before starting treatment (M1).
 - Provide a physical interlock that prevents beam-on unless table positioned according to plan

Example Controls for Causal Scenarios

- **Scenario 2** — Operator provides start treatment command when there is no patient. The operator was asked to turn the beam on outside of a treatment sequence (e.g. because the design team wants to troubleshoot a problem, or for experimental purposes) but inadvertently starts treatment and does not realize that the facility proceeds with reading the treatment plan and records the dose as being administered.
- **Controls:**
 - Reduce the likelihood that non-treatment activities have access to treatment-related input by creating a non-treatment mode to be used for QA and experiments, during which facility does not read treatment plans that may have been previously been loaded (M2);
 - Make procedures (including button design if pushing a button is what starts treatment) to start treatment sufficiently different from non-treatment beam on procedures that the confusion is unlikely.

Example Controls for Causal Scenarios

Command not followed

- **Scenario 3** — The operator provides the Start Treatment command, but it does not execute properly because the proper steering file failed to load (either because operator did not load it, or previous plan was not erased from system memory and overwriting is not possible) or the system uses a previously loaded one by default.
- **Controls:**
 - When fraction delivery is completed, the used steering file could for example be automatically dumped out of the system's memory (M4).
 - Do not allow a Start Treatment command if the steering file does not load properly
 - Provide additional checks to ensure the steering file matches the current patient (e.g. barcode wrist bands, physiological attributes, etc.)

How does STPA compare?

- MIT: TCAS
 - Existing high quality fault tree done by MITRE for FAA
 - MIT comparison: STPA captured everything in fault tree, plus more
- JAXA: HTV
 - Existing fault tree reviewed by NASA
 - JAXA comparison: STPA captured everything in fault tree, plus more
- EPRI: HPCI/RCIC
 - Existing fault tree & FMEA overlooked causes of real accident
 - EPRI comparison: Blind study, only STPA found actual accident scenario
- NRC: Power plant safety systems
 - Proposed design that successfully completed Final Safety Analysis Report
 - STPA found additional issues that had not been considered
- Safeware: U.S. Missile Defense Agency BMDS
 - Existing hazard analysis per U.S. military standards
 - Safeware comparison: STPA captured existing causes plus more
 - STPA took 2 people 3 months, MDA took 6 months to fix problems
- Automotive: EPS
 - Compare STPA results to FMECA using SAE J1739
- MIT: NextGen ITP
 - Existing fault tree & event tree analysis by RTCA
 - MIT comparison: STPA captured everything in fault tree, plus more
- MIT: Blood gas analyzer
 - Existing FMEA found 75 accident causes
 - STPA by S.M. student found 175 accident causes
 - STPA took less effort, found 9 scenarios that led to FDA Class 1 recall

MIT March Workshop (free)

Industries:

Automotive
Oil and Gas
Space
Aviation
Defense
Nuclear
Healthcare and Healthcare IT
Medical Devices
Academia
Insurance
Academia (Education)
Hydropower
Chemicals
Software/Computing
Government
Industrial Automation
Electric Utility
Security
Think Tank
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Maritime (security)
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Pharmaceuticals
Internet

Organizations:

General Motors
Ford
Nissan Motor Company
Toyota
Draper Lab
Volpe National Transportation
Research Center

The Boeing Company
Boeing Environment Health
and Safety
Boeing Engineering and
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Embraer
U.S. Nuclear Regulatory
Commission
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GE Aviation
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University of Alabama in
Huntsville
Liberty Mutual Safety Research
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ITA (Instituto Tecnológico de
Aeronautica)
Jeppesen
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Applied Sciences
Dutch Safety Agency
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BC Hydro
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Institute of Aeronautics and
Space (IAE), Brazil
Shell Oil
University of Braunschweig
Stiki
Reykjavik University

National Nuclear Energy
Commission, Brazil
FAA
U.S. Department of
Transportation
U.S. Air Force
U.S. Navy
IPEV (Institute for Research
and Flight Testing), Brazil
Japan Aerospace Exploration
Agency (JAXA)
U.S. Department of Energy
Rockwell Automation
Democritus University of
Thrace
Dependable Management
ILF Consulting Engineers
JETRO (Japan)
Alliance for Clinical Research
Excellence and Safety
Washington CORE
Florida Institute of Technology
U.S. Navy Strategic Systems
Programs
IPEN (Institute for Nuclear and
Energy Research), Brazil
Duke Energy
Synensis
Japan MOT Society
Tufts University
Southern Company
U.S. Army Aviation Engineering
U.S. Army Corps of Engineers
(Kansas City District)

University of Houston, Clear
Lake
Lincoln Lab
Hanscom AFB
U.S. Army Research,
Development, and Engineering
Command
McMaster University
Bechtel
Kyushu University (Japan)
Analog Devices
Cummins
University of Massachusetts
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Syracuse Safety Research
National Civil Aviation Agency
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Toyota Central R&D Labs
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Hospital
AstraZeneca
STM (Defense Technology
Engineering and Trading Corp.,
Turkey)
Varian Medical Systems
Fort Hill Group
TUBITAK-UZAY (Scientific and
Technological Research Council
of TURKEY-Space Technologies
Research Institute)
Cranfield University (U.K.)

U.S. Air Force Test Pilot School
NASA/Bastion Technologies
U.S. Customs and Border
Protection
Second Curve Systems
Vequria
Akamai Technologies
Canadian Dept. of Defense
(DND)
University of Virginia
MSAG
Novartis
U.S. Coast Guard
EPRI (Electric Power Research
Institute)
Sandia National Laboratories
Lawrence Livermore National
Laboratories
Tapestry Solutions
Kansas State University
Systems Planning and Analysis
Zurich University of Applied
Sciences
IBM
Lawrence Berkeley National
Laboratory (LBNL)
U.S. Navy School of Aviation
Safety
JAMSS (Japanese Manned
Space Systems)
U.S. Chemical Safety Board

mit.edu/psas

For more information...

- Email: jthomas4@mit.edu
- Website
 - mit.edu/psas
 - Free annual MIT conference in March
 - Presentations with cross-industry examples available
- Classes
 - Tutorials
 - Training
 - Project-focused workshops
- Radiation therapy application
 - “SYSTEMS THEORETIC HAZARD ANALYSIS (STPA) APPLIED TO THE RISK REVIEW OF COMPLEX SYSTEMS: AN EXAMPLE FROM THE MEDICAL DEVICE INDUSTRY”, Antoine, 2012
 - Includes more examples