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Tutorial T3

Engineering Safety-Related Requirements for Software-Intensive Systems

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Topics

- ❍ Importance of Safety-Related Requirements
- ❍ Automatic People Mover Example Overview
- ❍ Basic Safety Concepts
- ❍ Safety-Related Requirements:
  - ● Safety Requirements
  - ● Safety-Significant Requirements
  - ● Safety System Requirements
  - ● Safety Constraints
- ❍ A Process for Producing Safety-Related Requirements

Importance of Requirements

- Poor requirements cause more than half of all project failures:
  - Major cost overruns
  - Major schedule overruns
  - Major functionality not delivered
  - Cancelled projects
  - Delivered systems that are never used

Difficulty of Requirements

- “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, including all the interfaces to people, to machines, and to other software systems. No other part of the work so cripples the resulting system if done wrong. No other part is more difficult to rectify later.”

  F. Brooks, *No Silver Bullet*, IEEE Computer, 1987

Importance of Accidents

- Accidents can have expensive and potentially fatal repercussions:
  - Mars Climate Orbiter ($125 million)
  - Therac–25
  - Bhopal (3–10K deaths, 500K injured)

Poor Requirements Cause Accidents

- Most accidents are caused by poor requirements:
  - “For the 34 (safety) incidents analyzed, 44% had inadequate specification as their primary cause.”

    Health and Safety Executive (HSE), *Out of Control: Why Control Systems Go Wrong and How to Prevent Failure* (2nd Edition), 1995

  - “Almost all accidents related to software components in the past 20 years can be traced to flaws in the requirements specifications, such as unhandled cases.”

    Safeware Engineering, “Safety-Critical Requirements Specification and Analysis using SpecTRM”*, 2002*

Poor Requirements

- Ambiguous Requirements:
  - Developers misinterpret Subject Matter Experts intentions.
  - The system shall be safe.”
  - How safe? Safe in what way?
- Incomplete Requirements:
  - Developers must guess SME intentions.
  - The system shall do X.”
  - In what state? When triggered by what event? How often? How fast? For whom?
- Missing Requirements:
  - What shall the system do if it can’t do X?
  - Unusual combinations of conditions result in accidents.
  - What shall the system do if event X occurs when the system is simultaneously in states Y and Z?

More Problems and Challenges

- ❍ Inappropriate architecture and design constraints unnecessarily specified as requirements
  - ● Use ID and password for identification and authentication.
- ❍ Separation of requirements engineering and safety engineering:
  - ● Different disciplines with different training, books, journals, and conferences.
  - ● Different professions with different job titles.
  - ● Different fundamental underlying concepts and terminologies

Safety Engineering

- **Safety engineering** is the *engineering discipline* within *systems engineering* that lowers the *risk* of *accidental harm to valuable assets* to an *acceptable level* to *legitimate stakeholders*.

Note:

- Engineering Discipline
- Systems Engineering (not just software)
- Risk
- *Accidental* Harm
- Harm to Valuable Assets
- *Acceptable Level* of Risk
- *Legitimate* Stakeholders

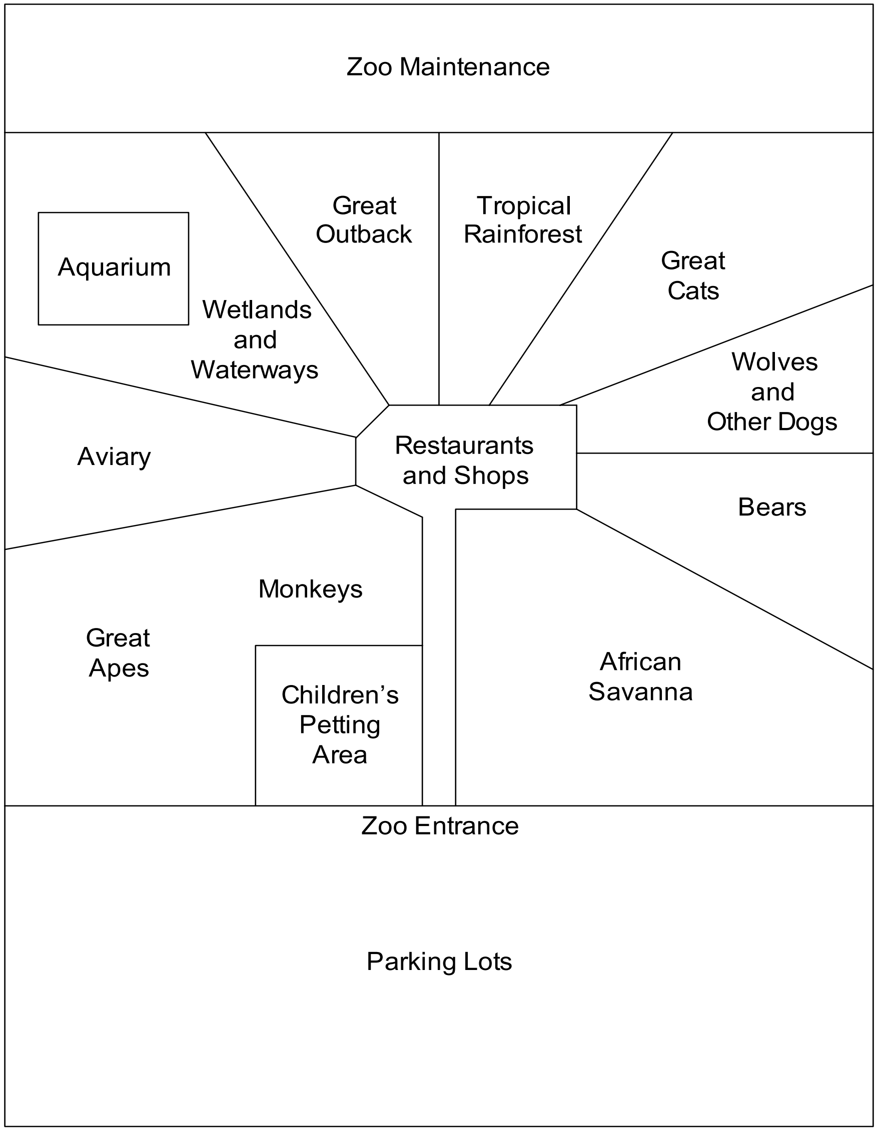
Tutorial Example: Characteristics

- Common Ongoing Example throughout Tutorial
- Safety-Critical SW-Intensive System
- Realistic Example System
- No Special Domain Knowledge Needed
- Understandable:
  - Requirements
  - Technology
  - Hazards

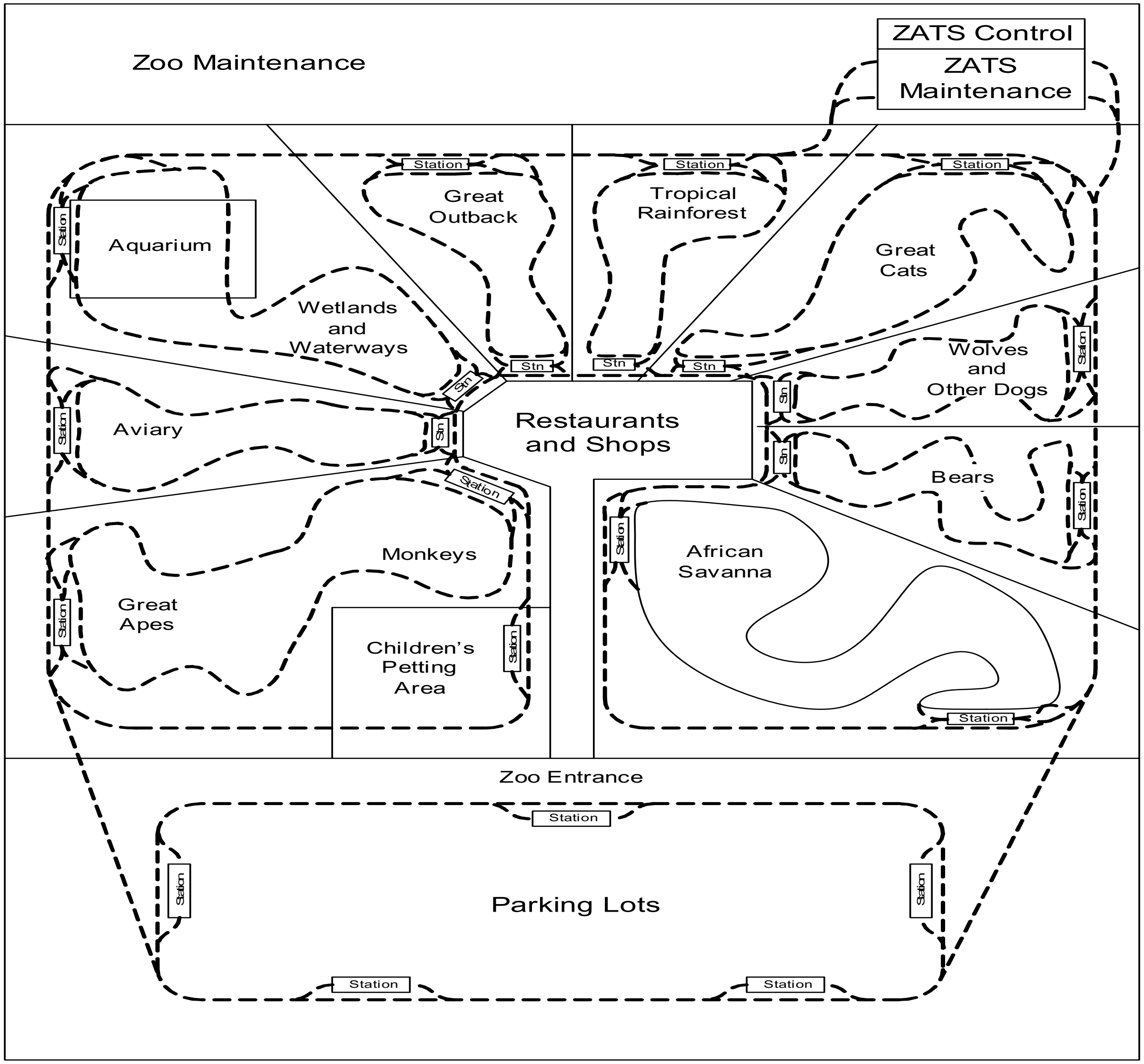
Tutorial Example: Overview

- Very Large New Zoo
- Zoo Automated Taxi System (ZATS)
- Typical Habitat
- Typical Automated Taxi Station
- ZATS Domain Model
- Taxi Object Model

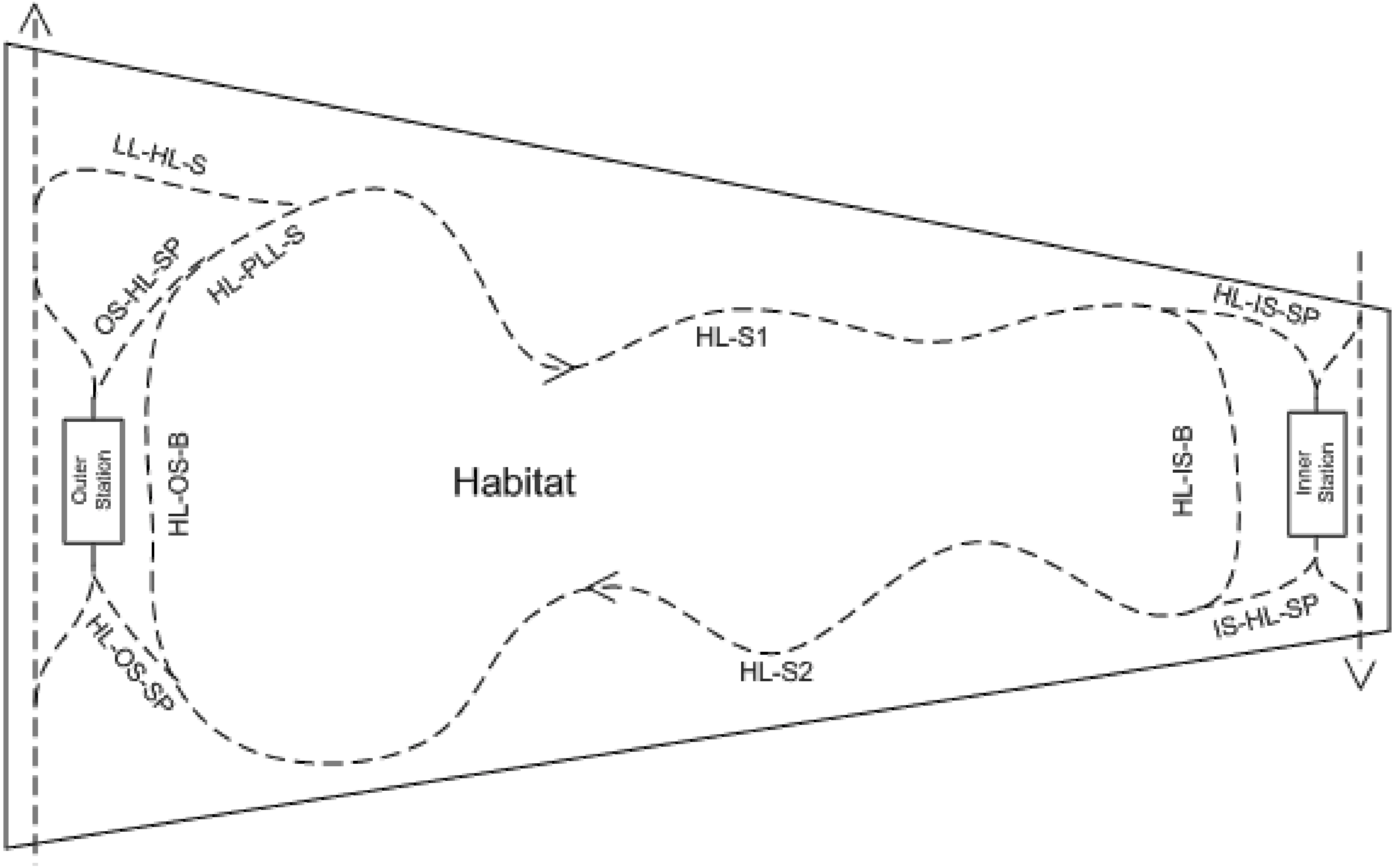
Tutorial Example: Very Large New Zoo



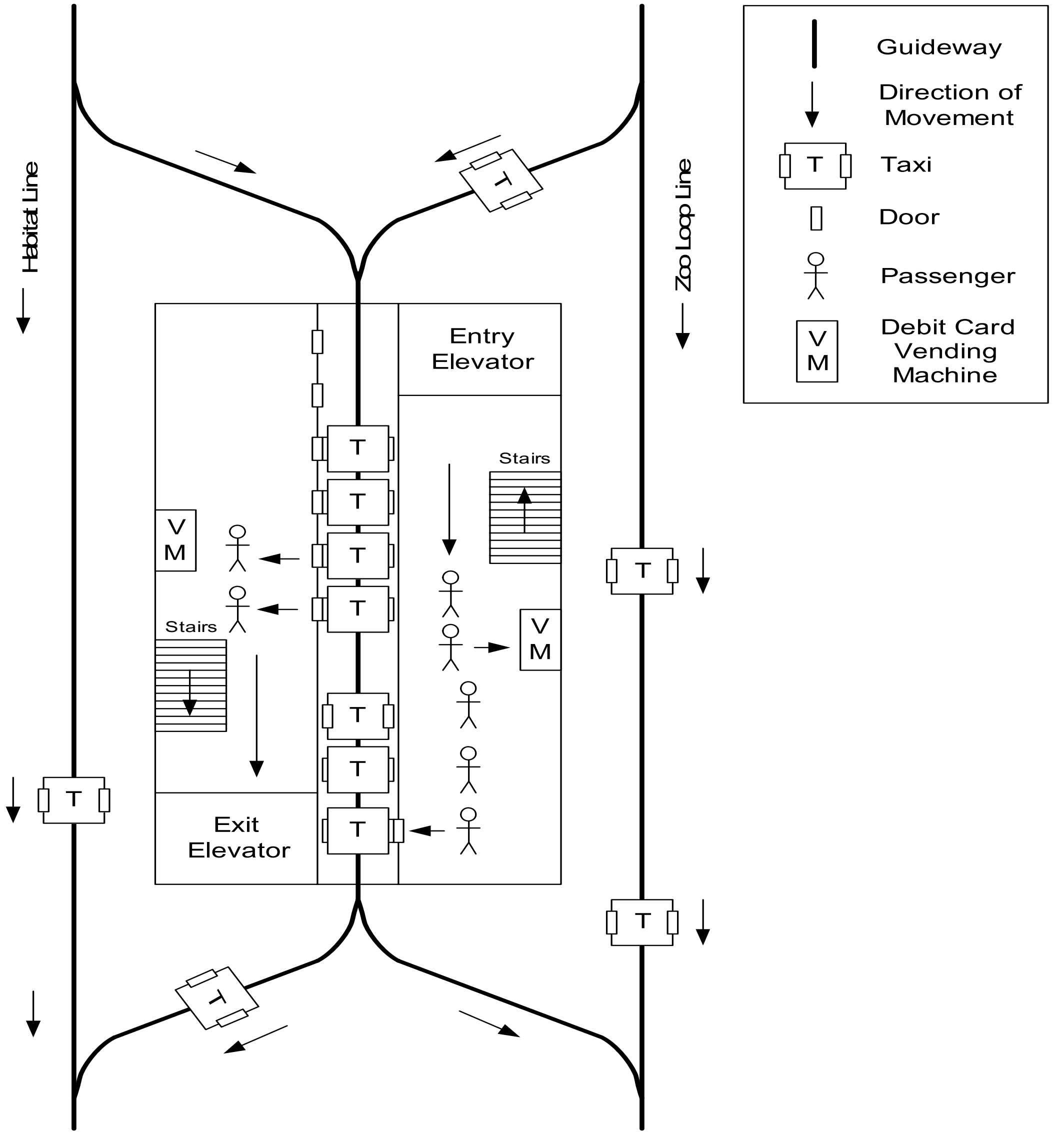
Zoo Automated Taxi System (ZATS)



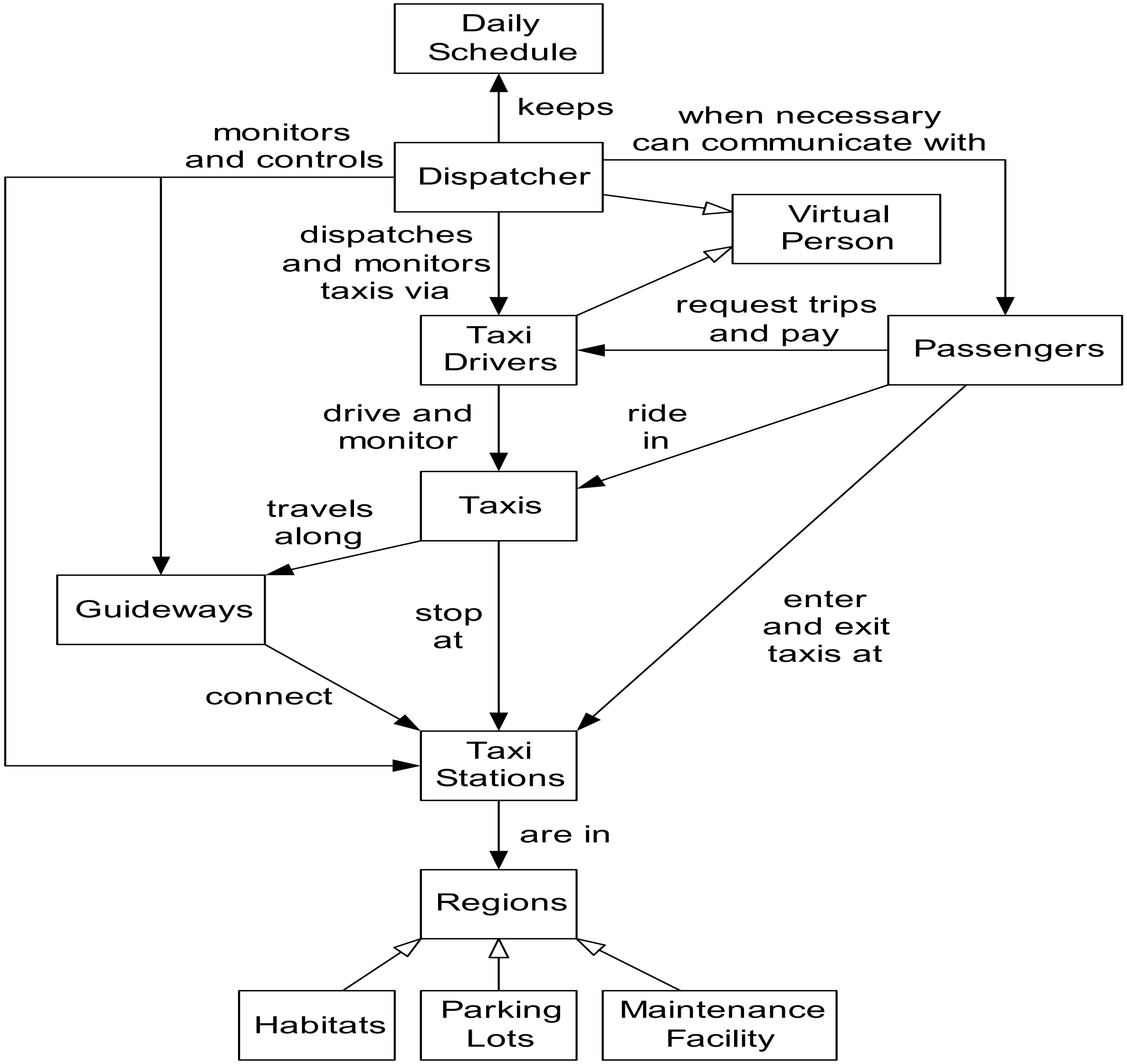
Typical Habitat



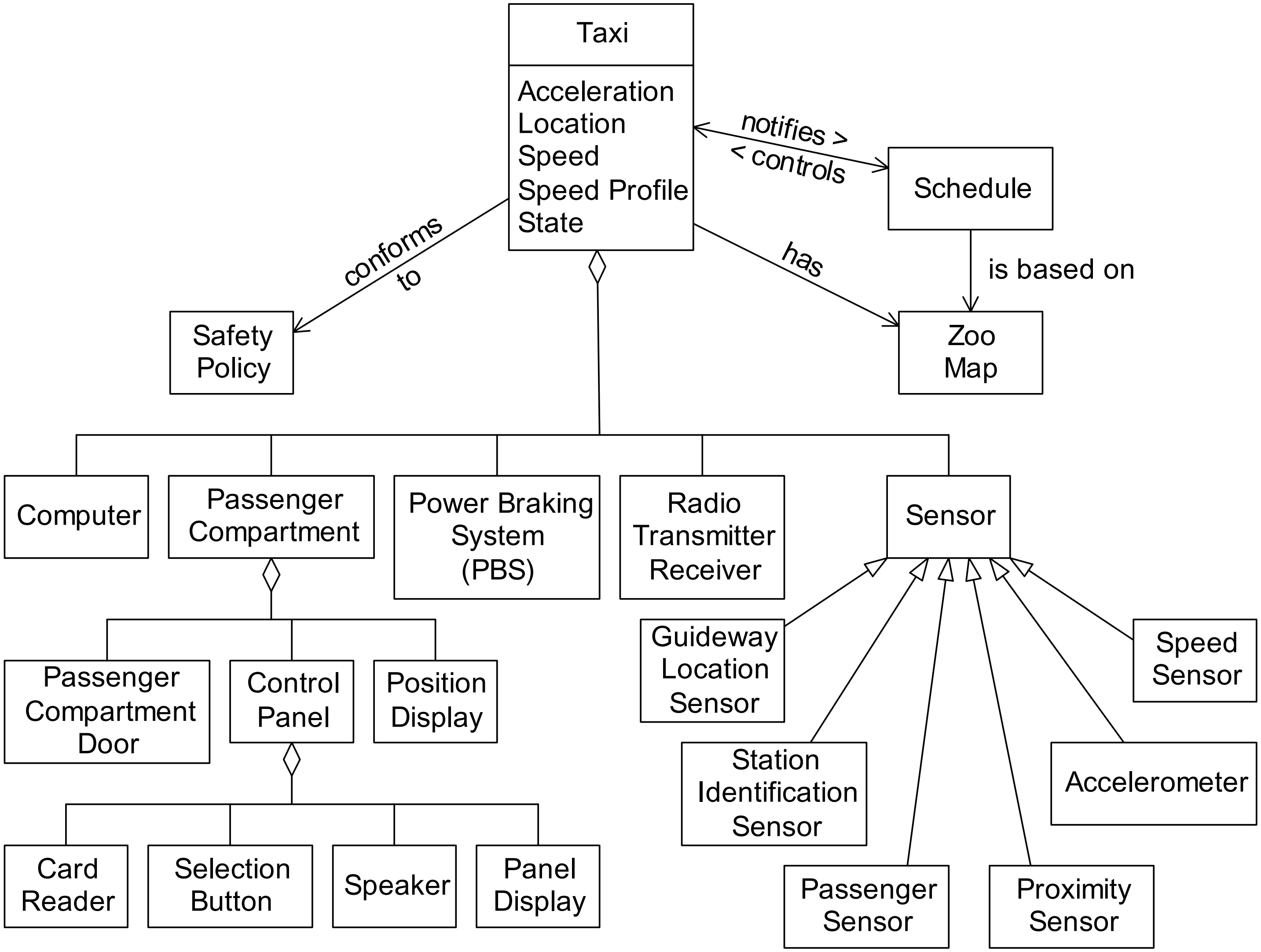
Typical Automated Taxi Station



ZATS Domain Model



Taxi Object Model

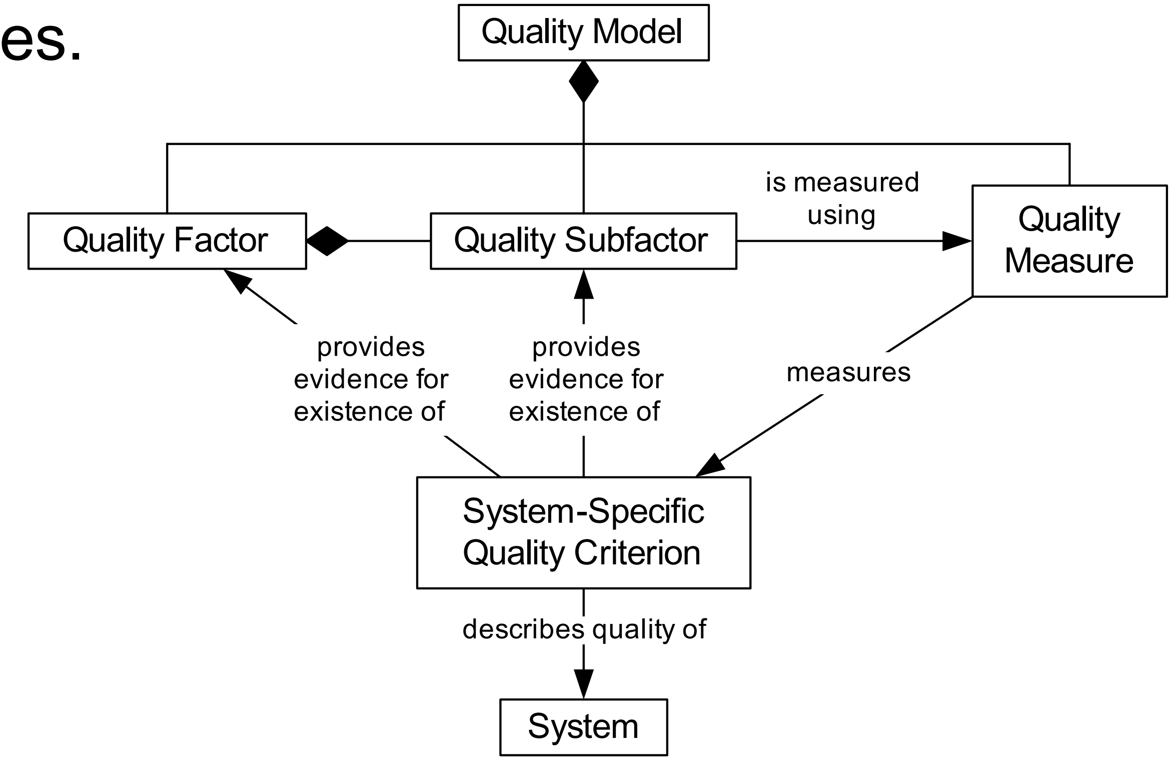


Basic Safety Concepts

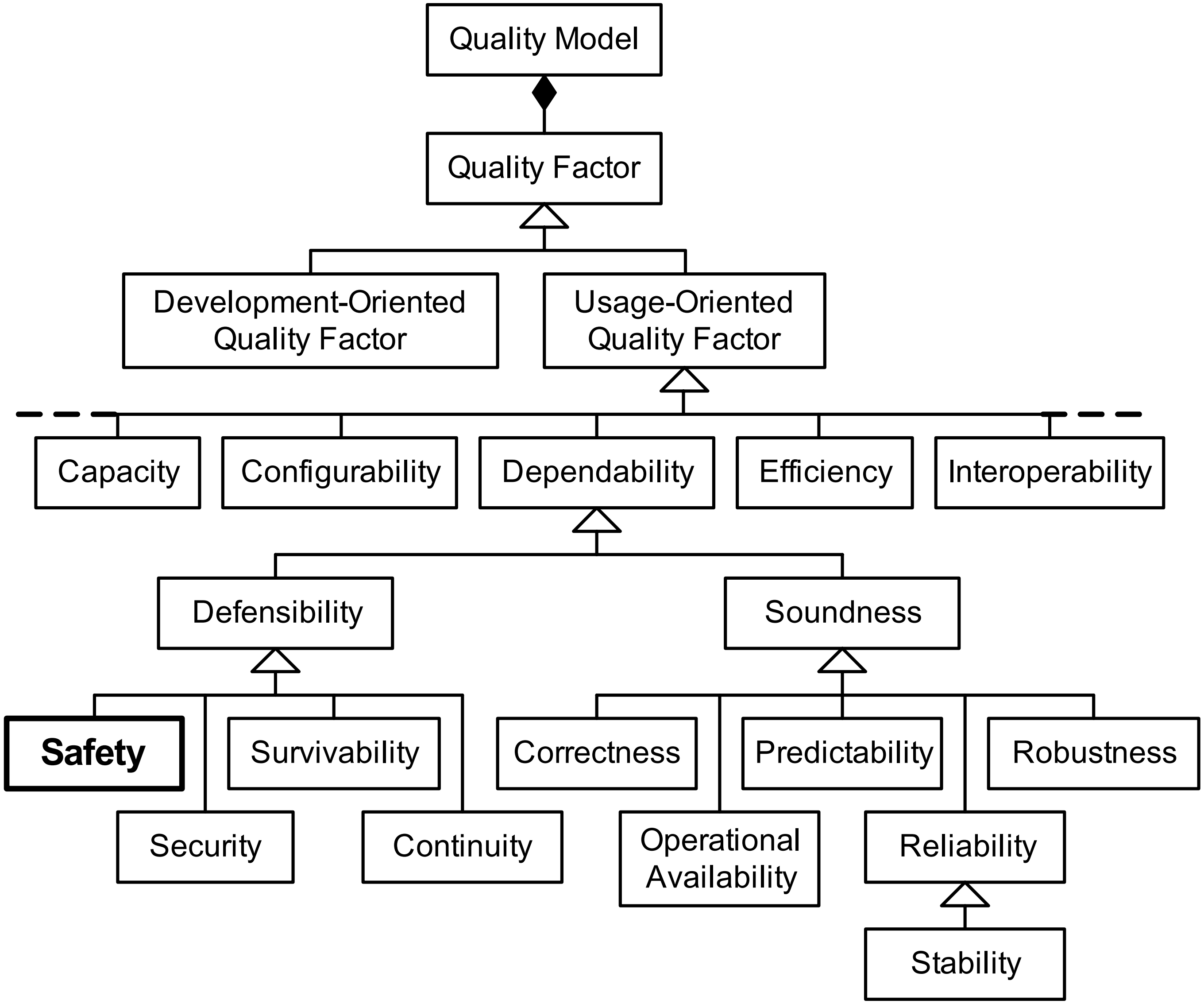
- Safety as a Quality Factor of a Quality Model
- Safety Quality Subfactors
- Valuable Assets
- Accidental Harm to Valuable Assets
- Safety Incidents (Accidents & Near Misses)
- Hazards
- Safety Risks
- Goals, Policies, and Requirements
- Safeguards (Safety Mechanisms)
- Vulnerabilities (system-internal sources of dangers)

Quality Model

- **Quality Model** – a hierarchical model (i.e., a collection of related abstractions or simplifications) for formalizing the concept of the quality of a system in terms of its quality factors, quality subfactors, quality criteria, and quality measures.



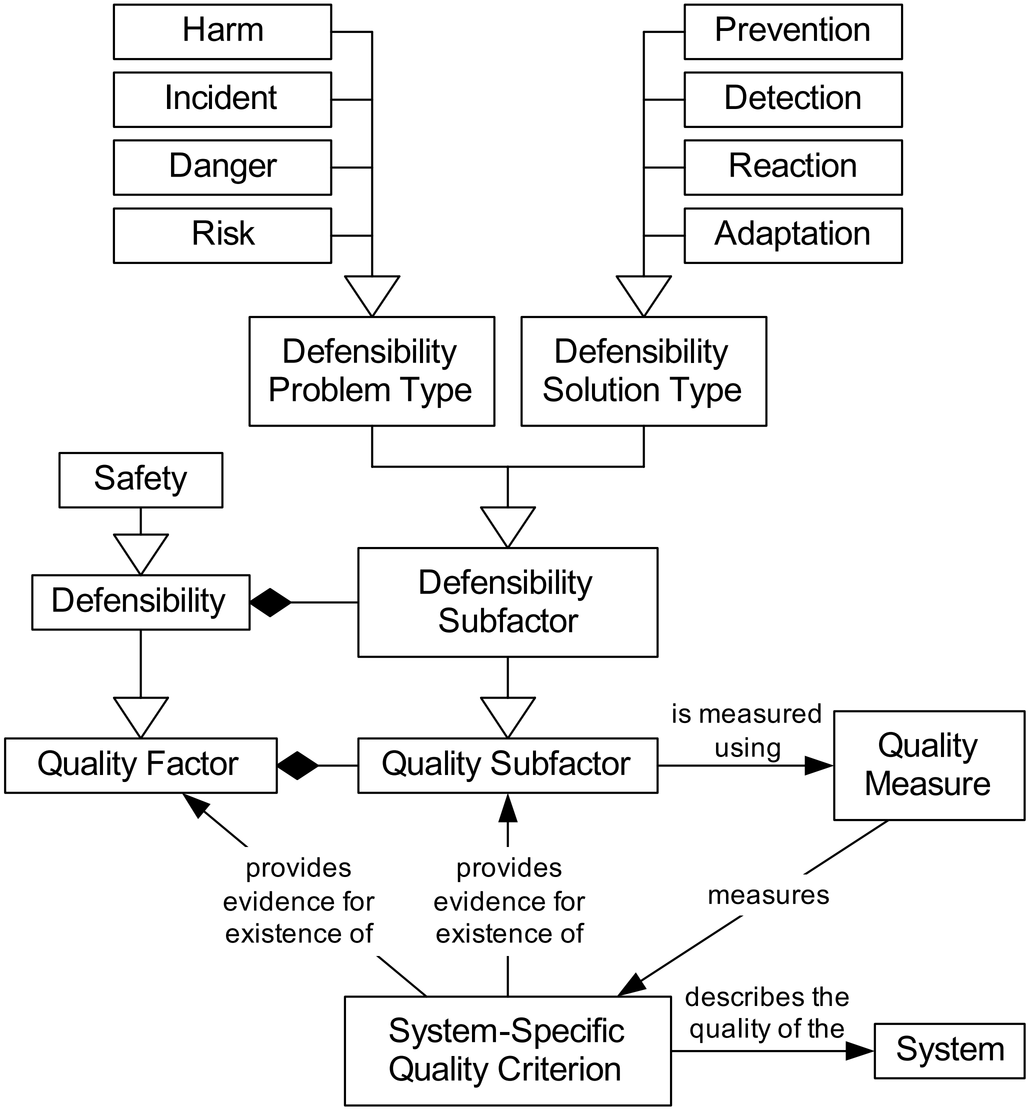
Quality Factors



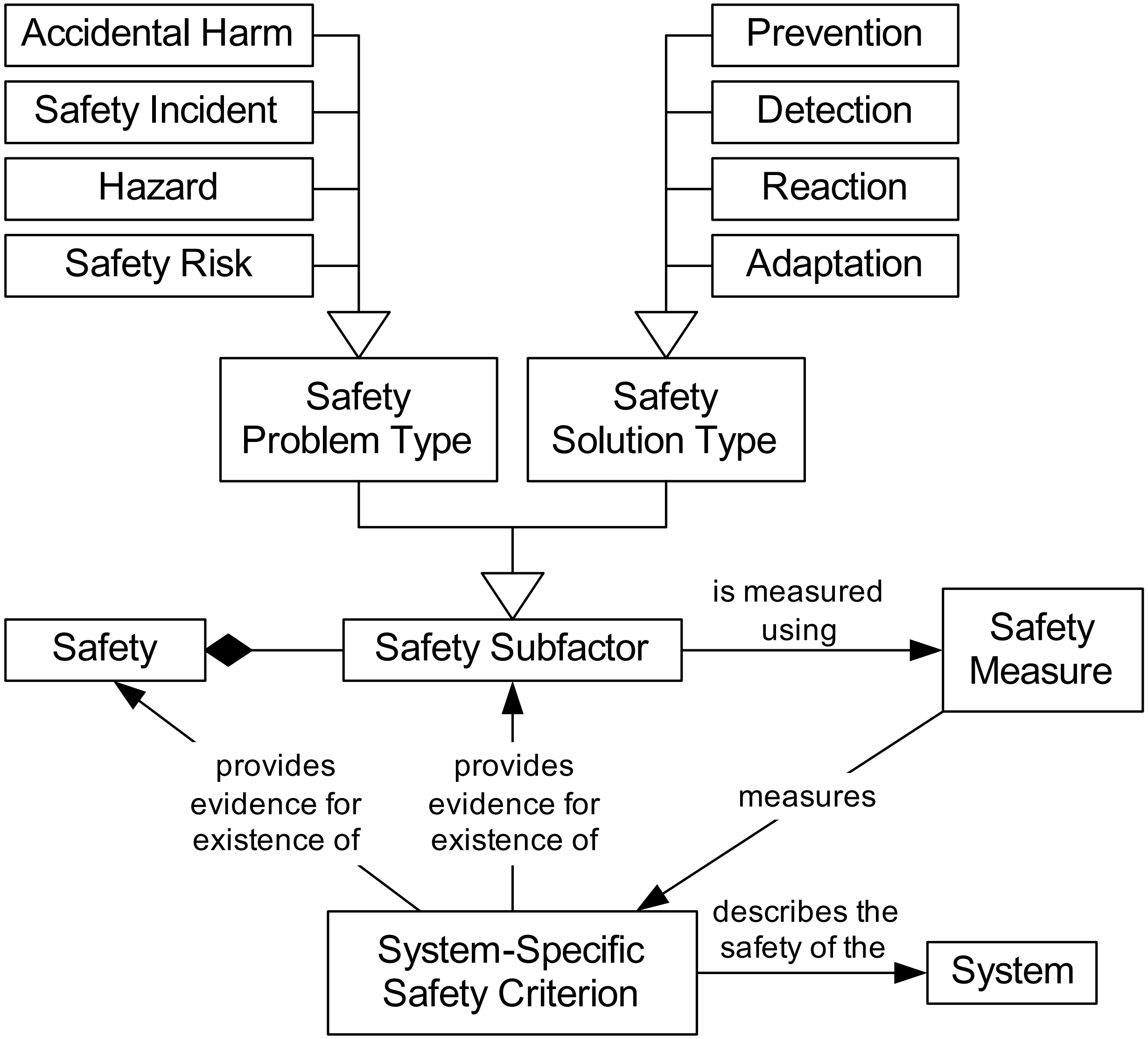
Safety as a Quality Factor

- **Safety** is the quality factor capturing the *degree* to which:
  - A*ccidental harm* to valuable assets is prevented, detected, reacted, and adapted
  - *Accidents* (and near misses) are eliminated or their negative consequence mitigated
  - *Hazards* are eliminated or mitigated
  - *Safety risks* are acceptably low

Defensibility Subfactors

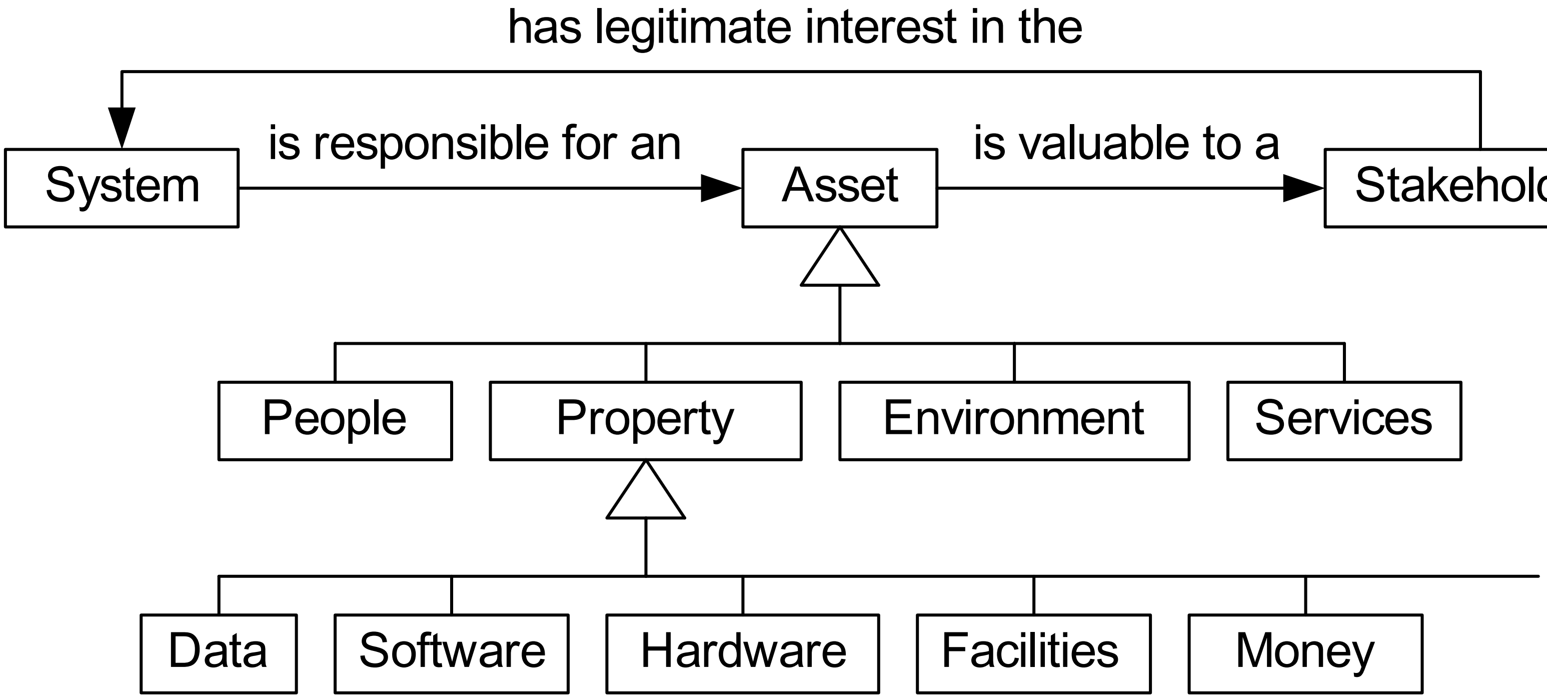

Harm
Incident
Danger
Risk
Prevention
Detection
Reaction
Adaptation
Defensibility Problem Type
Defensibility Solution Type
Safety
Defensibility
Defensibility Subfactor
Quality Factor
Quality Subfactor
is measured using
Quality Measure
provides evidence for existence of
provides evidence for existence of
measures
System-Specific Quality Criterion
describes the quality of the
System

Safety Subfactors



Valuable Assets

- A valuable **asset** is anything of *significant* value to a *legitimate stakeholder* that should be protected from *accidental* (or malicious) harm by the system.

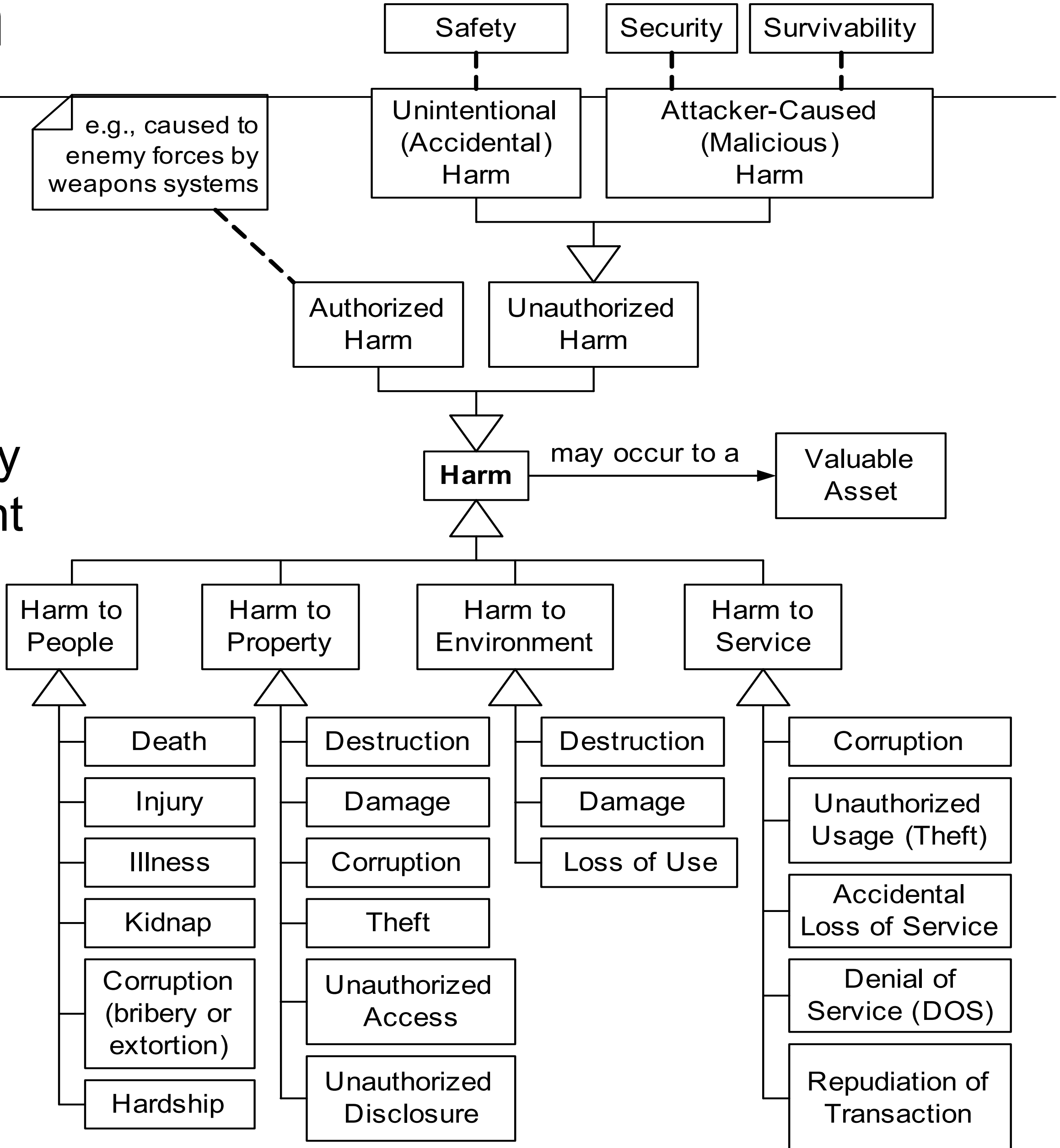


ZATS Valuable Assets

- What are the Valuable Assets for which ZATS is responsible for protecting against accidental harm?
- How valuable are these assets to the Zoo (and society)?

Accidental Harm

- **Harm** is any significant negative consequence to a valuable asset
- **Accidental harm** is any harm due to an accident



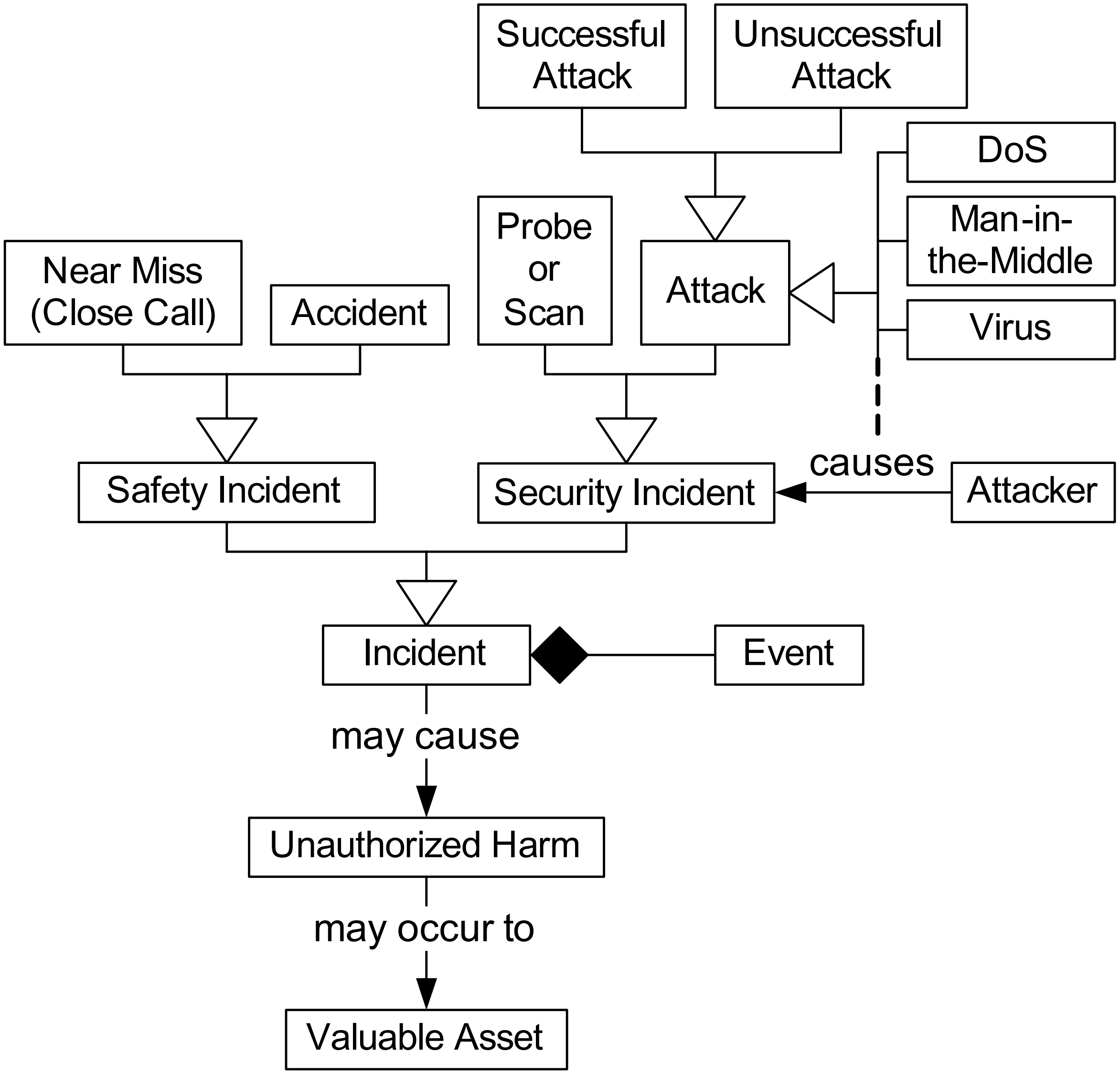
ZATS Harm to Valuable Assets

- What kinds of accidental harm can occur to the Valuable Assets for which ZATS is responsible?
- How should these kinds of harm be categorized in terms of harm severity, and how should the categories be defined?
  - Catastrophic
  - Critical
  - Major
  - Minor
  - Negligible

Safety Incidents

- An **incident** is an unplanned (but not necessarily unexpected) series of one or more related *events* that either did cause or could have caused (accidental or malicious) harm to one or more valuable assets
  - A **safety incident** is an incident involving actual or potential accidental harm

Incidents and their Relationships



ZATS Safety Incidents

❍ What kinds of safety incidents can occur if not prevented?

- Accidents
- Near misses

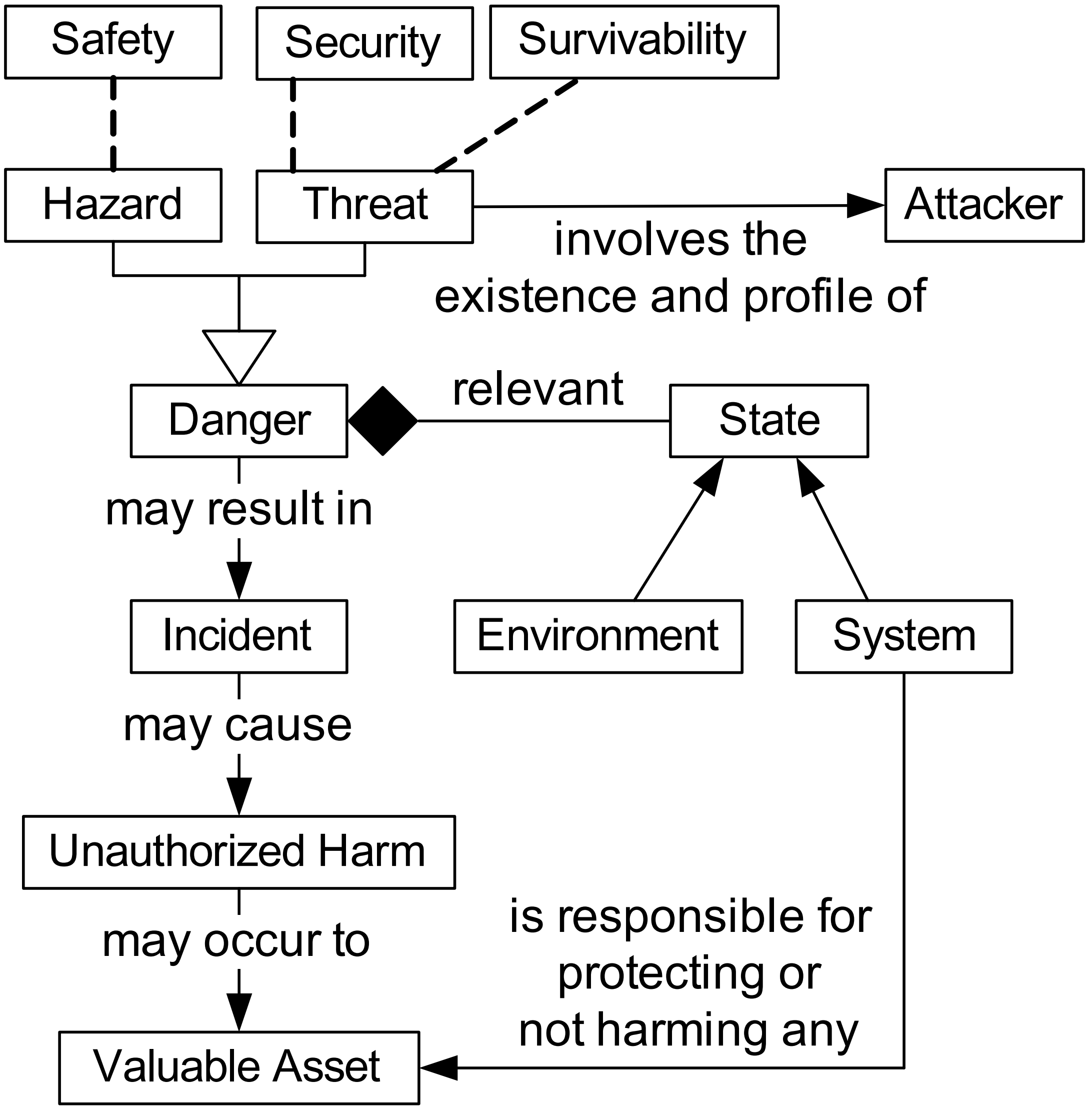
❍ What kind of harm can these accidents cause to what valuable assets?

❍ How likely can these safety incidents be allowed to be?

Safety Hazards

- **Danger** (Defensibility) is one or more conditions, situations, or states of a system that in conjunction with condition(s) in the environment of the system can cause or contribute to the occurrence of an *incident*:
  - ***Hazard*** (Safety) is a danger that can cause or contribute to the occurrence of an safety incident.
  - **Threat** (Security and Survivability) is a danger that can cause or contribute to the occurrence of security or security incident (i.e., a vulnerability combined with an attacker with means, motive, and opportunity).

Dangers and their Relationships

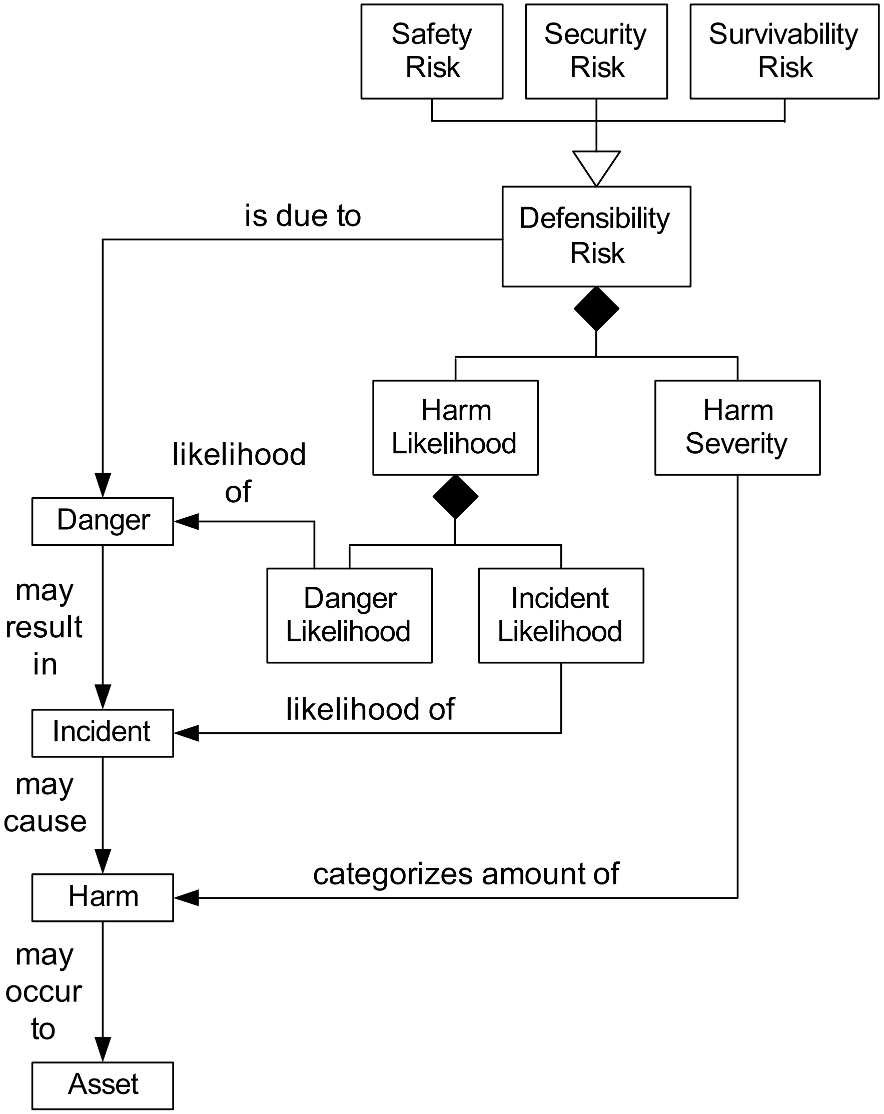


ZATS Hazards

- What kinds of ZATS hazards (hazardous conditions) might exist?
- What kinds of safety incidents can these hazards cause?
- What kinds of events can cause these safety hazards to exist?
- Can the existence of these hazards be detected?

Safety Risks

- **Risk** is the combination of the severity of harm to a valuable asset with the likelihood that the harm will occur.
- **Harm severity** is usually set *conservatively* to the maximum credible category of harm.
- The likelihood of harm is the likelihood of danger multiplied by the likelihood that the danger results in a harm-causing incident (e.g., accident or attack).



Safety Risk Matrix

- Safety Risks can be categorized (for example) as:
  - Intolerable
  - Undesirable
  - As Low As Reasonably Practical (ALARP)
  - Acceptable

Safety Risks/ Safety Integrity Levels(SILs)					
	Frequency of Accident/ Hazard Occurrence				
Harm Severity	**Frequent**	**Probable**	**Occasional**	**Remote**	**Implausible**
Catastrophic	Intolerable	Intolerable	Intolerable	Undesirable	ALARP
Critical	Intolerable	Intolerable	Undesirable	ALARP	ALARP
Major	Undesirable	Undesirable	ALARP	ALARP	Acceptable
Minor	Undesirable	ALARP	ALARP	Acceptable	Acceptable
Negligible	ALARP	ALARP	ALARP	Acceptable	Acceptable

ZATS Safety Risks

- How would you develop a safety matrix for ZATS?
  - How would you categorize and define harm severity?
  - How would you categorize and define likelihood?
- How would you categorize, define, and assign safety risks to the safety risk matrix cells?
- What would be some of the ramifications of your choices?

Safety Goals

- **Safety Goals** are high-level stakeholder desires regarding safety:
  - "The system must be safe."
  - "There can be no serious accidents."
  - "The system will never kill or injure its users."
- Goals are typically ambiguous or unrealistic (i.e. impossible to guarantee).
- Goals are *not* requirements.
- A *major* problem is safety goals that are specified as if they were verifiable requirements.

ZATS Safety Goals

- What do you think some of the safety goals for the ZATS should be?
- Are they realistic and verifiable?
- Do different stakeholders have different safety goals?

Safety Policies

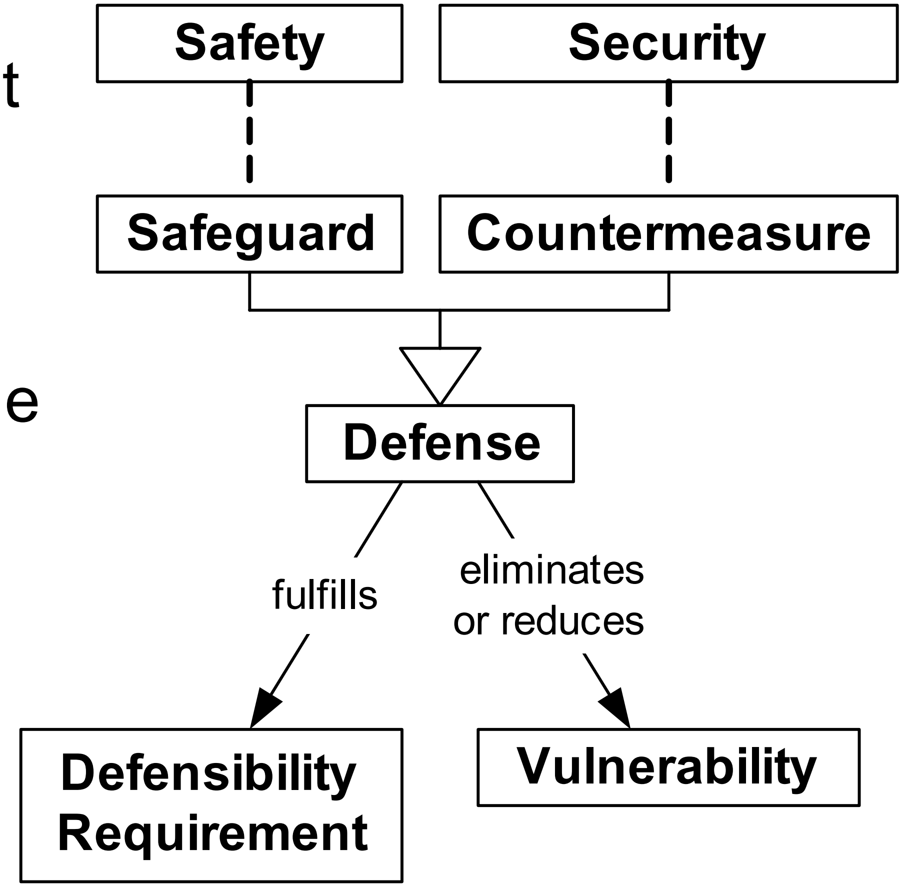
- **Policy** – a strategic decision that establishes a desired goal.
- **Safety policy** – a policy that *establishes* a safety goal:
  - “The overall responsibility for safety must be identified and communicated to all stakeholders.”
  - “A hazard analysis shall be performed during early in the project.”
  - “All users will have safety training.”
- Tend to be process rather than product oriented.
- Safety policies are collected into safety policy documents.
- In practice, safety policies are confused with requirements and policy documents may sometimes include requirements. Why is this a problem?

Requirements

- A **requirement** is a statement that formally specifies a necessary capability or characteristic of a business enterprise, application (system or SW), component, or application domain.
- Good requirements must be:
  - Mandatory (i.e., required)
  - Cohesive
  - Consistent
  - Correct
  - Feasible
  - Relevant
  - Unambiguous
  - Uniquely Identifiable
  - Verifiable and Validatable
  - What, not how (architecture, design, or implementation)

Safeguards (Safety Mechanisms)

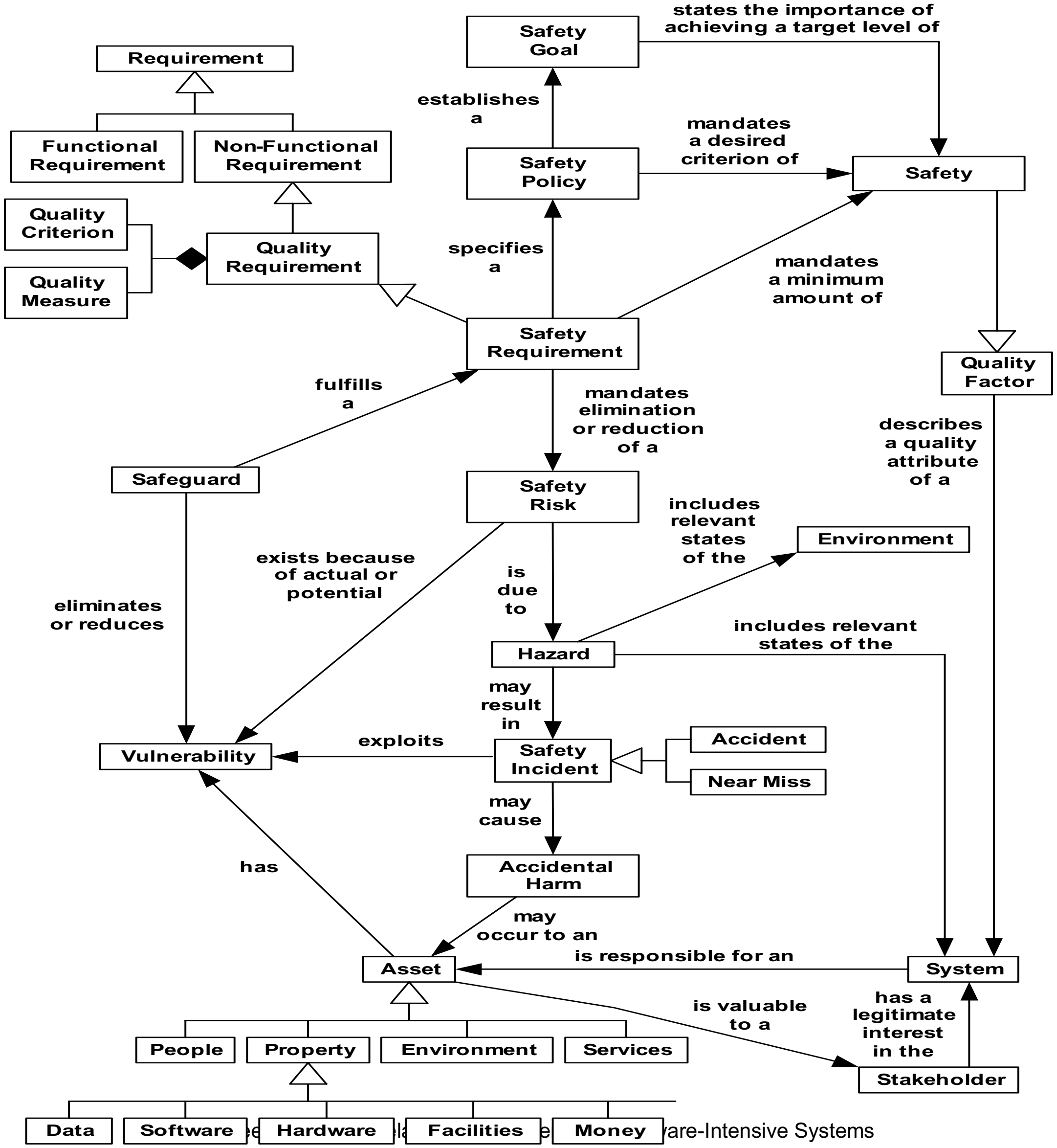
- A **safeguard** is a kind of defense that fulfills a safety-related requirement and thereby eliminates or reduces the impact of a safety vulnerability.
- A safeguard is a part of the system (e.g., component, procedure, training)
- Only relevant to requirements if specified as safety constraints.



Safety Vulnerabilities

- A **safety vulnerability** is a weakness in the architecture, design, implementation, integration, or deployment of a system that enables a hazard to exist or an accident to occur.
- Only relevant to requirements if a requirement needs to be specified to prevent the vulnerability or mitigate its negative consequences
- For example, if taxi doors did not have locks or lock sensors.

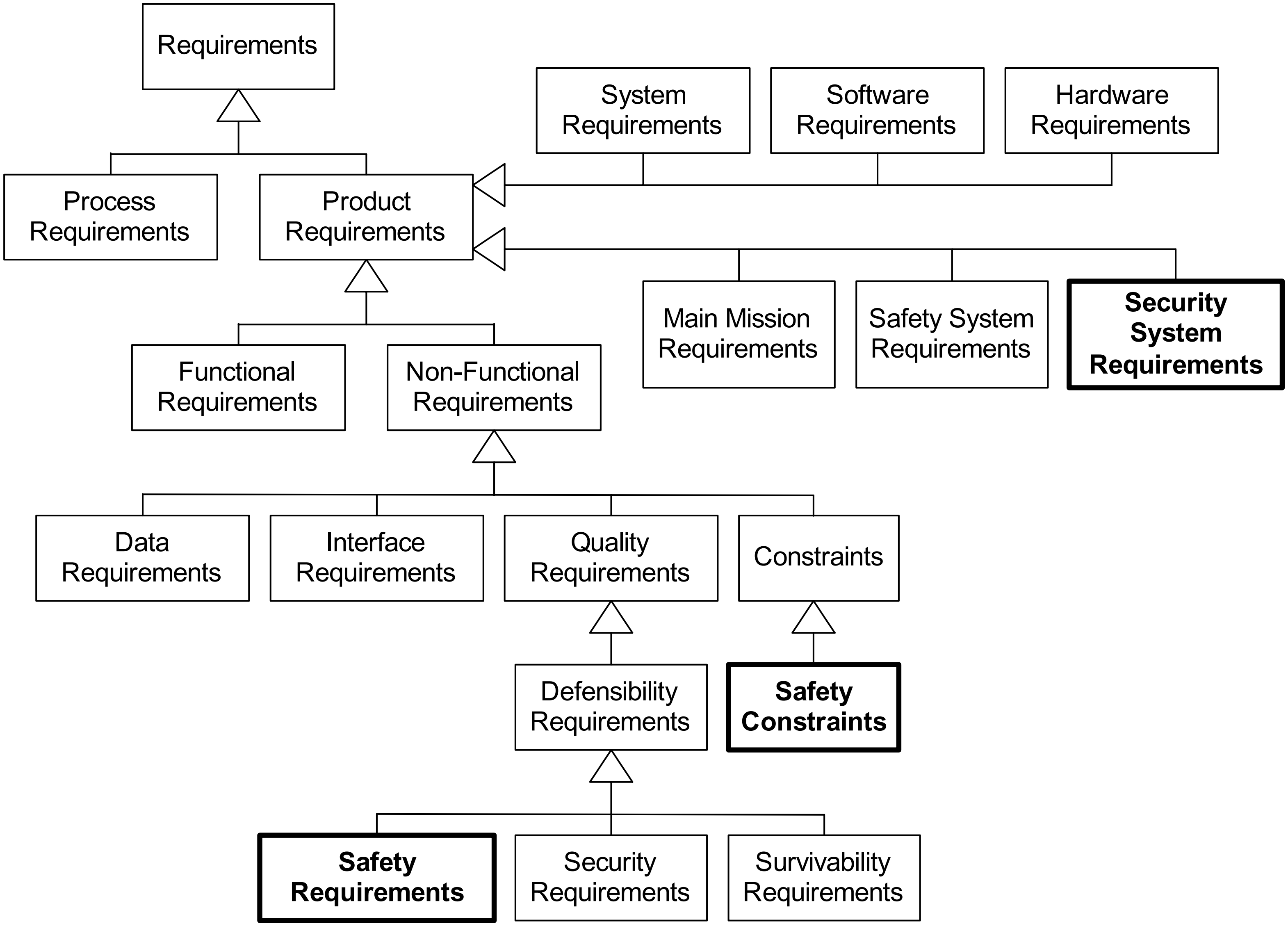
Putting the Safety Concepts Together



Safety-Related Requirements

- Safety Requirements
- Safety-Significant Requirements
- Safety System Requirements
- Safety Constraints

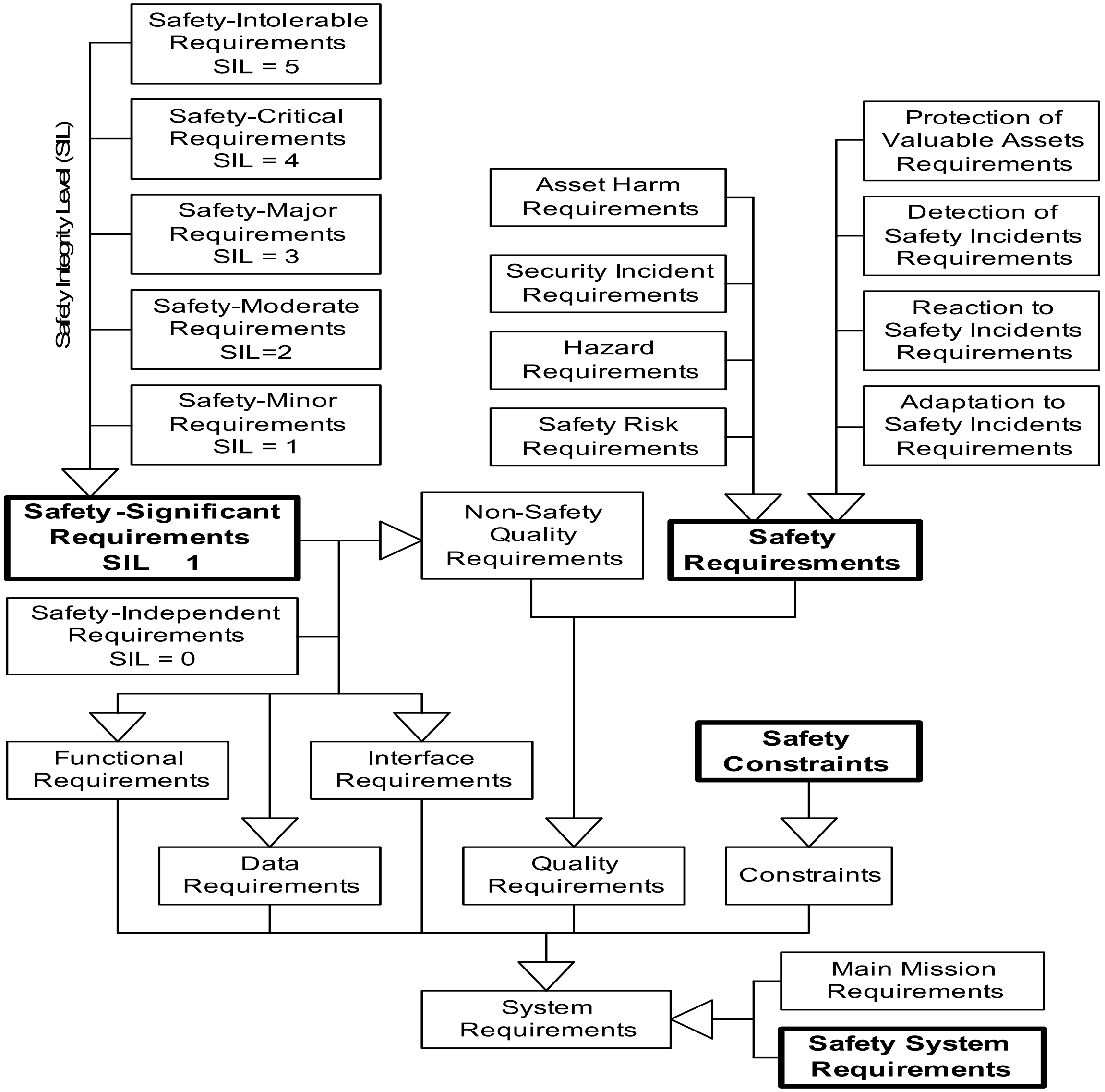
Types of Requirements



Safety-Related Requirements

- ***Safety-Related Requirements*** are any system requirements having *significant safety ramifications*:
  - **Safety Requirements** are requirements that specify mandatory amounts of pairs of subfactors of the safety quality factor.
  - **Safety-Significant Requirements** are non-safety primary mission requirements with significant safety ramifications.
  - **Safety System Requirements** are requirements for safety systems or subsystems (as opposed to primary mission requirements).
  - **Safety Constraints** are constraints intended to ensure a minimum level of safety.

Safety-Related Requirements

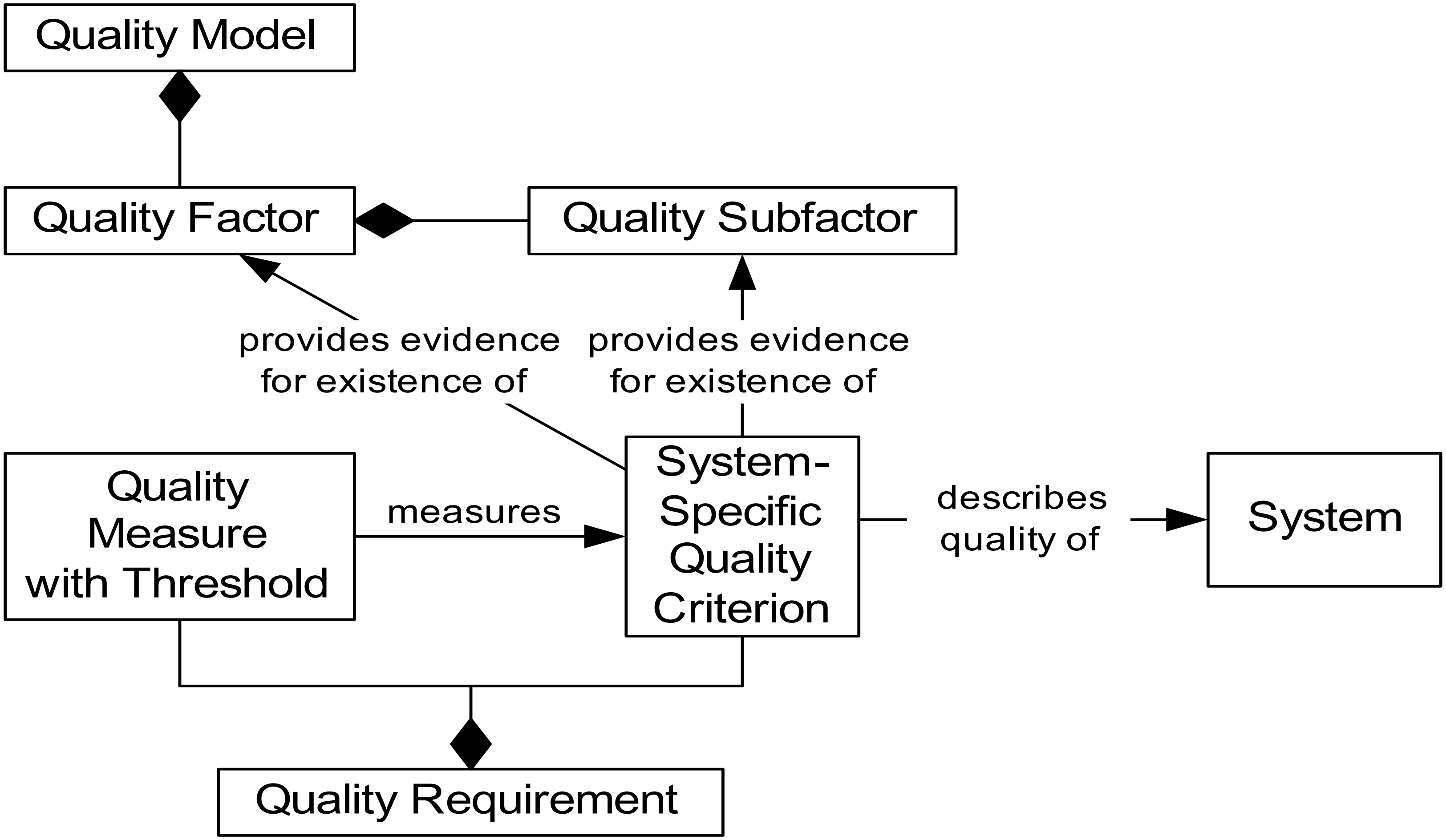

Safety Integrity Level (SIL)
Safety-Intolerable Requirements SIL = 5
Safety-Critical Requirements SIL = 4
Safety-Major Requirements SIL = 3
Safety-Moderate Requirements SIL=2
Safety-Minor Requirements SIL = 1
Asset Harm Requirements
Security Incident Requirements
Hazard Requirements
Safety Risk Requirements
Protection of Valuable Assets Requirements
Detection of Safety Incidents Requirements
Reaction to Safety Incidents Requirements
Adaptation to Safety Incidents Requirements
Safety -Significant Requirements SIL 1
Non-Safety Quality Requirements
Safety Requiresments
Safety-Independent Requirements SIL = 0
Functional Requirements
Interface Requirements
Safety Constraints
Data Requirements
Quality Requirements
Constraints
Main Mission Requirements
System Requirements
Safety System Requirements

[Pure] Safety Requirements

- A safety requirement is a kind of defensibility requirement because safety is a type of defensibility.
  (Safety requirements are like security requirements.)
- Safety requirements specify minimum required amounts of:
  - Safety
  - A quality subfactor of safety:
    - Defensibility Problem Type:
      Accidental Harm, Safety Incident, Hazard, Safety Risk
    - Defensibility Solution Type:
      Prevention, Detection, Reaction, Adaptation
- A safety requirement is a combination of a safety criterion and a minimum threshold on a safety measure.

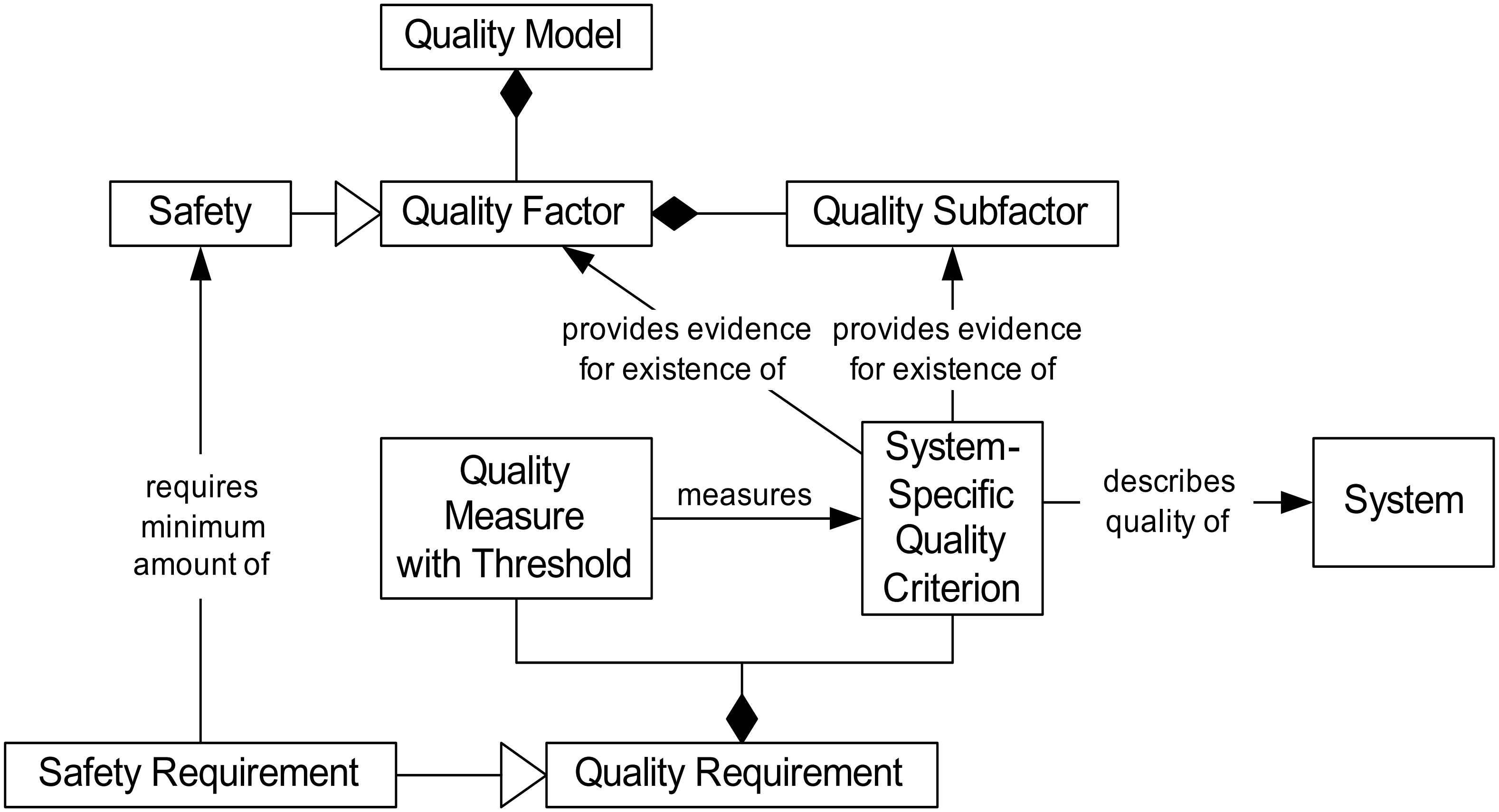
Quality Requirements

- Quality Requirements are based on a quality model:


Quality Model
Quality Factor
Quality Subfactor
provides evidence for existence of
provides evidence for existence of
Quality Measure with Threshold
measures
System-Specific Quality Criterion
describes quality of
System
Quality Requirement

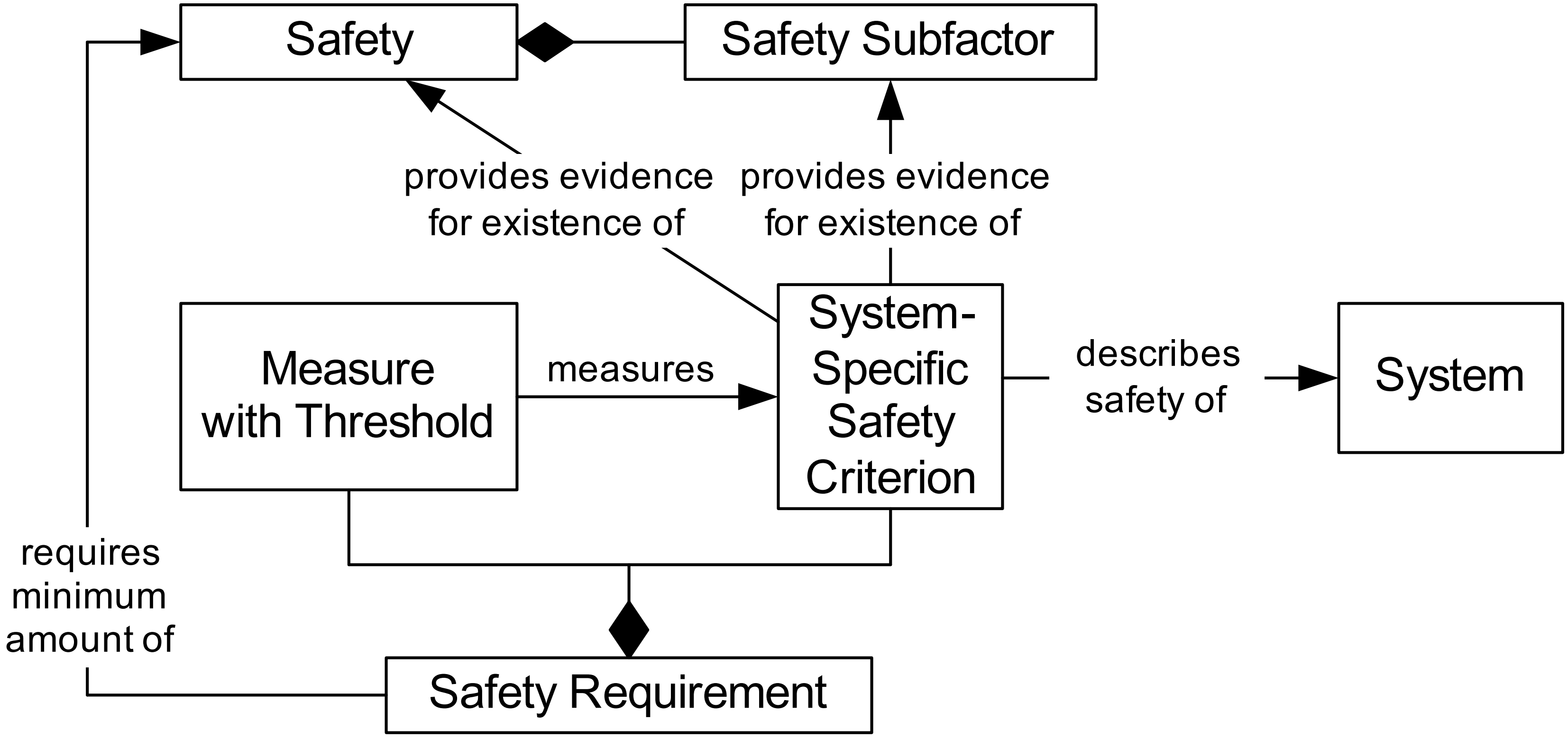
Safety Requirements

- Safety Requirements are a kind of quality requirement.

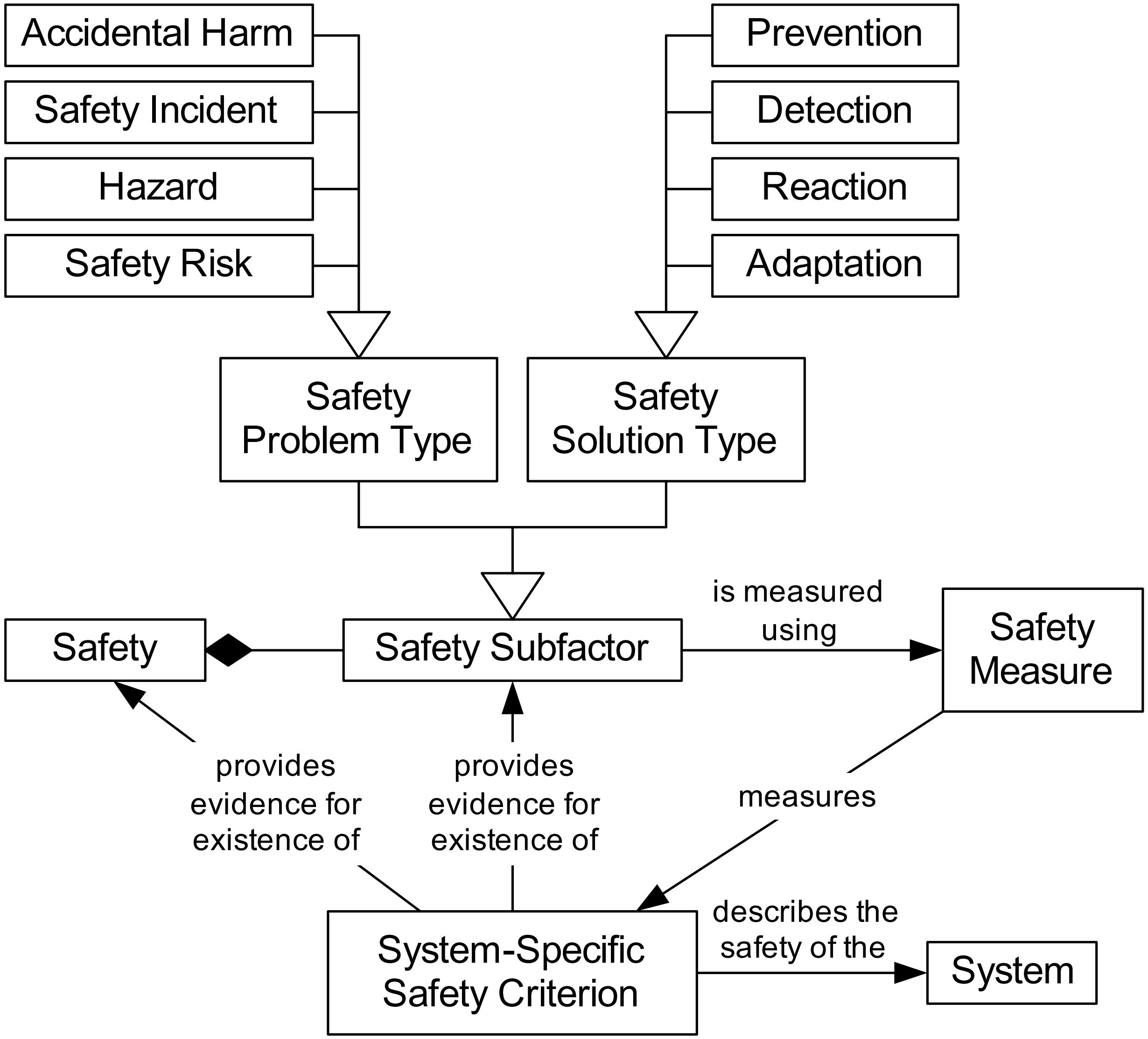

Quality Model
Safety
Quality Factor
Quality Subfactor
provides evidence for existence of
provides evidence for existence of
requires minimum amount of
Quality Measure with Threshold
measures
System-Specific Quality Criterion
describes quality of
System
Safety Requirement
Quality Requirement

Safety Requirements (Simplified)

❍ Previous figure with supertypes removed for simplicity:


Safety
Safety Subfactor
provides evidence for existence of
provides evidence for existence of
Measure with Threshold
measures
System-Specific Safety Criterion
describes safety of
System
requires minimum amount of
Safety Requirement

Based on Safety Subfactors



Safety Requirements

- Based on the previous figure, there are twelve types of safety requirements:
  - Accidental harm prevention, detection, and reaction
  - Safety incident prevention, detection, and reaction
  - Hazard prevention, detection, and reaction
  - Safety risk prevention, detection, and reaction

Example Safety Requirements

- “The system shall not cause more than X amount of accidental harm per year.”
- “The system shall not cause more than X safety incidents (accidents, near misses) per passenger mile traveled.”
- “The system shall not cause hazard X to exist more than Y percent of the time.”
- “The system shall not allow a safety risk level of X to exist.”
- “The system shall detect accidents of type X Y percent of the time.”
- “The system shall react to accidents of type X by performing Y.”

ZATS Safety Requirements

- What are some reasonable ZATS safety requirements related to *preventing*:
  - Accidental harm to valuable assets?
  - Safety incidents from occurring?
  - Hazards from existing?
  - Safety risks from being too high?
- How about:
  - *Detecting* accidental harm, safety incidents, hazards, and risks?
  - *Reacting* to the detection of harm, incidents, hazards, and risks?
  - *Adapting* ZATS to better handle future harm, safety incidents, hazards, and risks?

Safety-Significant Requirements

- Are identified based on safety (hazard) analysis
- Subset of non-safety requirements:
  - Functional Requirements
  - Data Requirements
  - Interface Requirements
  - Non-safety Quality Requirements
  - Constraints
- Safety Integrity Level (SIL) is not 0:
  - May have minor safety ramifications
  - May be safety-critical
  - May have intolerable safety risk

SILs and SEALs

- **Safety Integrity Level** – a category of required safety for safety-significant requirements.
- **Safety Evidence Assurance Level** – a category of required evidence needed to assure stakeholders (e.g., safety certifiers) that the system is sufficiently safe (i.e., that it has achieved its required SIL).
- **SILs** are for requirements
- **SEALs** are for components that collaborate to fulfill requirements (e.g., architecture, design, coding, testing)

Safety-Significant Requirements (cont)

- Require enhanced Safety Evidence Assurance Levels (SEALs) including more rigorous development process (including better requirements engineering):
  - Formal specification of requirements
  - Fagan inspections of requirements
- Too often SEALs only apply to design, coding, and testing:
  - Safe subset of programming language
  - Design inspections
  - Extra testing

Example Safety-Significant Requirements

- Requirements for controlling elevator doors:
  - Keep doors closed when moving
  - Not crush passengers
- Requirements for firing missiles from military aircraft:
  - When to arm missile
  - Controlling doors providing stealth capabilities
  - Detecting weight-on-wheels
- Requirements for chemical plant:
  - Mixing and heating chemicals
  - Detecting temperature and pressure

ZATS Safety-Significant Requirements

- What are some reasonable ZATS functional requirements with safety ramifications?
- What is a reasonable data requirement with safety ramifications?
- What is a reasonable interface requirement with safety ramifications?
- What SIL level (e.g., intolerable, undesirable, tolerable, insignificant) should be assigned to these safety-significant requirements?

Safety System Requirements

- Systems or components strictly added for safety:
  - Emergency core coolant system for nuclear power plant
  - Fire detection and suppression system for aircraft
  - Emergency full pump cut off for gas station
  - Emergency stop for escalators
- All requirements for such systems are safety-related

Example Safety System Requirements

- “Except when the weapons bay doors are open or have been open within the previous 30 seconds, the weapons bay cooling system shall maintain the temperature of the weapons bay below X° C.”
- “The Fire Detection and Suppression System (FDSS) shall detect smoke above X ppm in the weapons bay within 5 seconds.”
- “The FDSS shall detect temperatures above X° C in the weapons bay within 2 seconds.”
- “Upon detection of smoke or excess temperature, the FDSS shall alert the pilot within 1 second and begin fire suppression.”

ZATS Safety System Requirements

- Would the ZATS system need a safety subsystem?
- If so, what would that subsystem be and what would a few of its requirements be?

Safety Constraints

- A constraint is any engineering decision that has been chosen to be mandated as a requirement. For example:
  - Architecture constraints
  - Design constraints
  - Implementation (e.g., coding) constraints
  - Testing constraints
- A safety constraint is any constraint primarily intended to ensure a minimum level of safety
  (e.g., a mandated safety control).
- Safety standards often mandate best practices safety constraints.

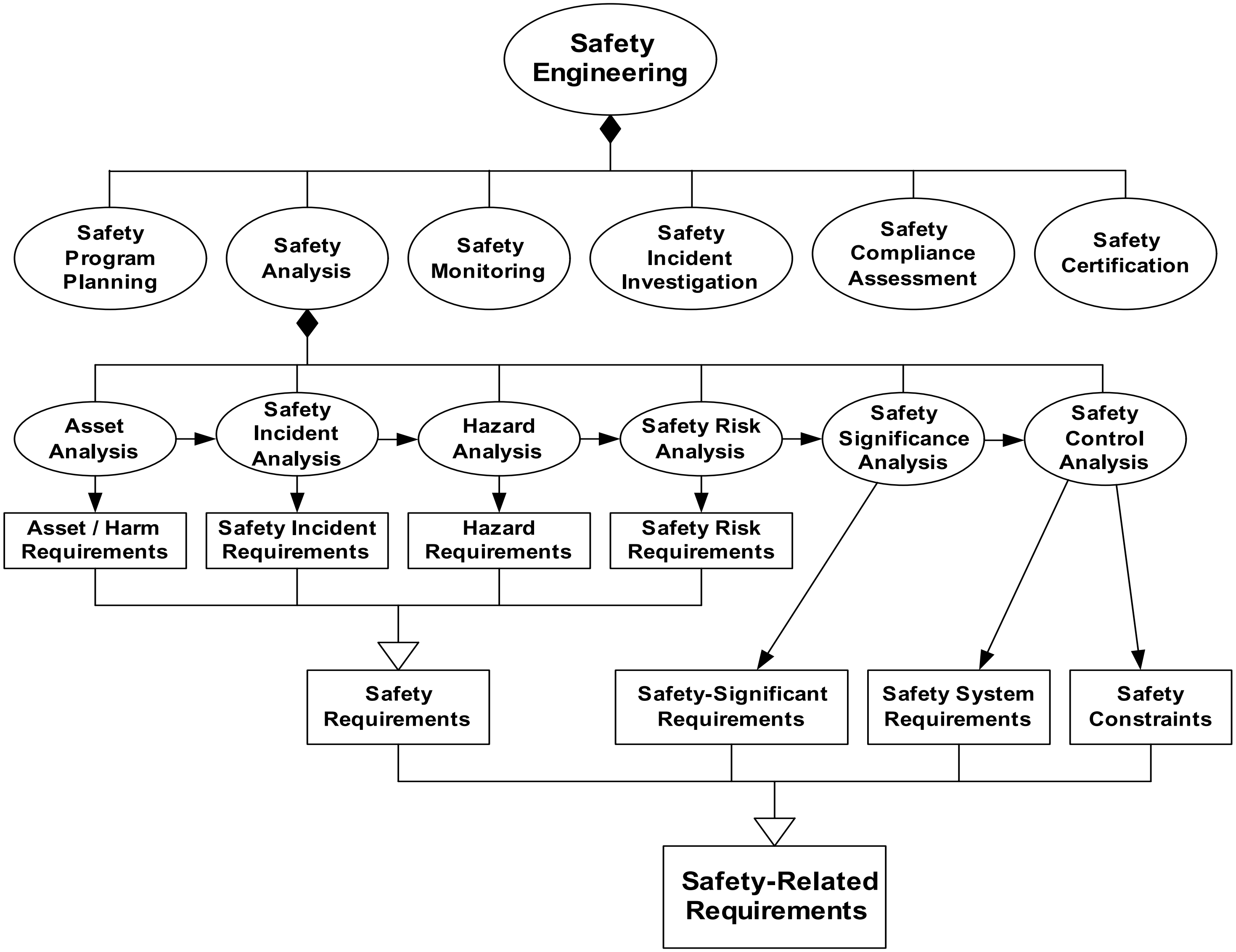
Example Safety Constraints

- “When the vehicle is stopped in a station with the doors open for boarding, the horizontal gap between the station platform and the vehicle door threshold shall be no greater than 25 mm (1.0 in.) and the height of the vehicle floor shall be within plus/minus 12 mm (0.5 in.) of the platform height under all normal static load conditions…” Automated People Mover Standards – Part 2: Vehicles, Propulsion, and Braking (ASCE 21-98)
- “Oils and hydraulic fluids shall be flame retardant, except as required for normal lubrication.”

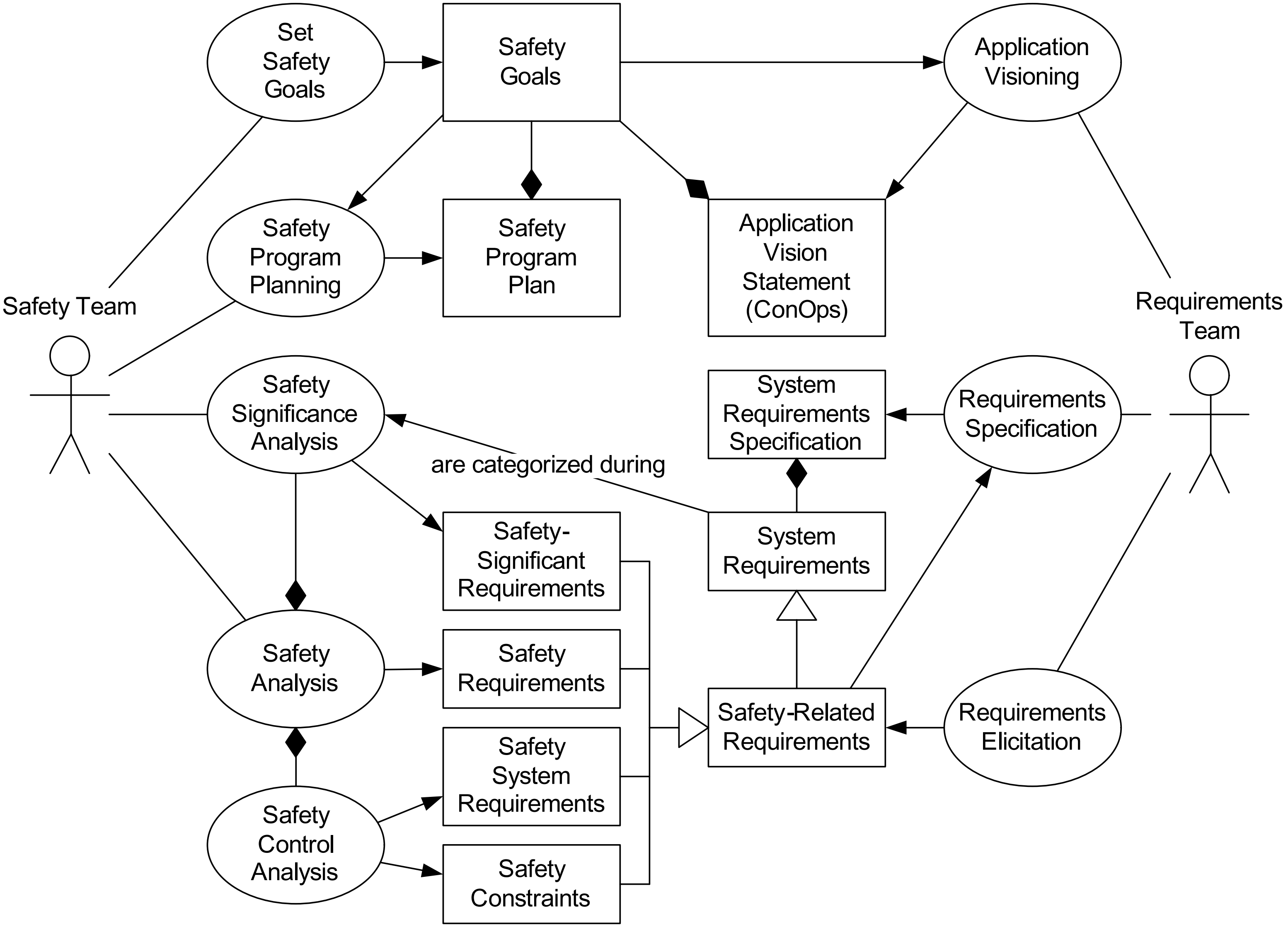
ZATS Safety Constraints

- What would be reasonable safety constraints to specify on the ZATS system?

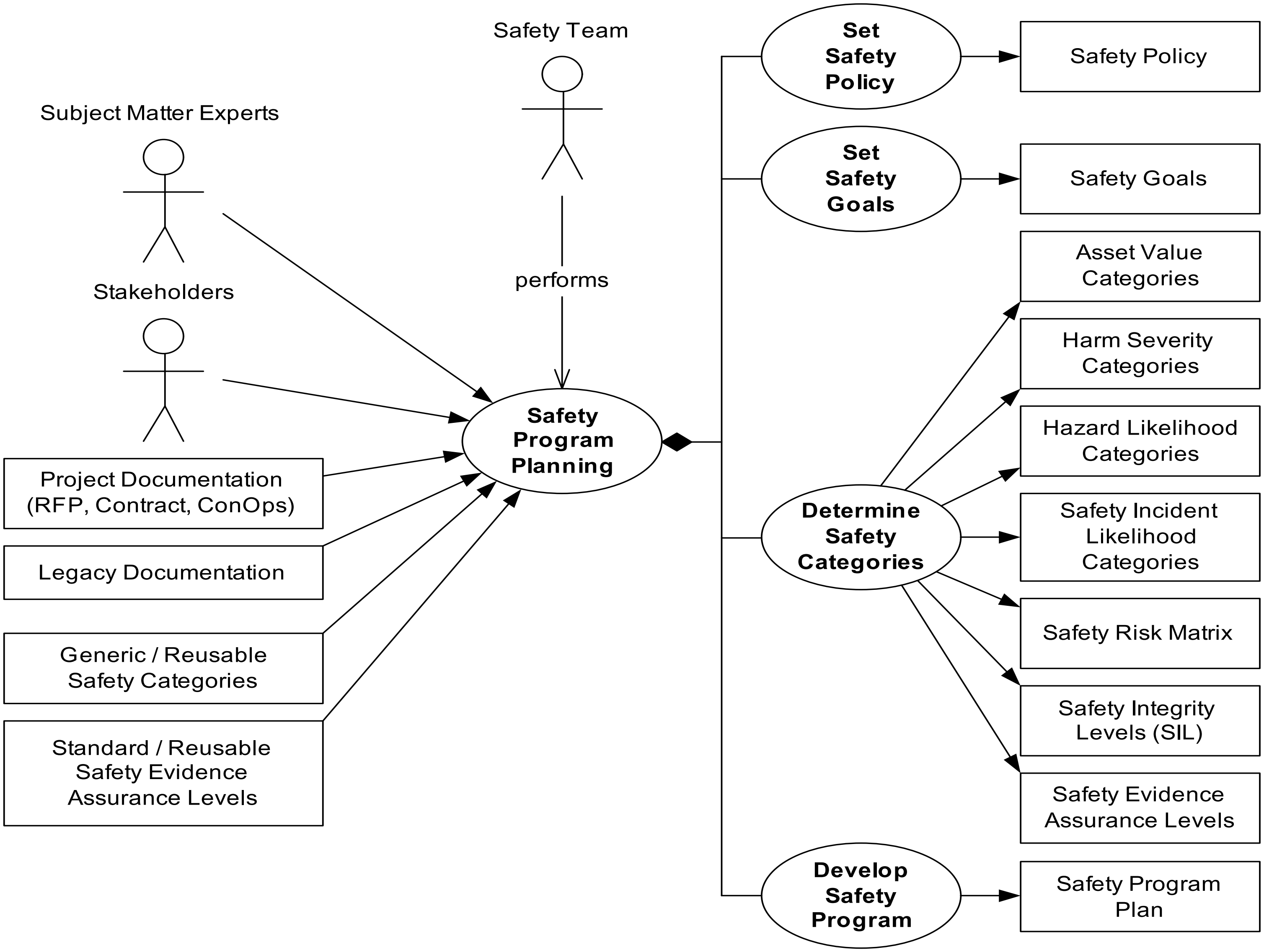
Safety Engineering Process



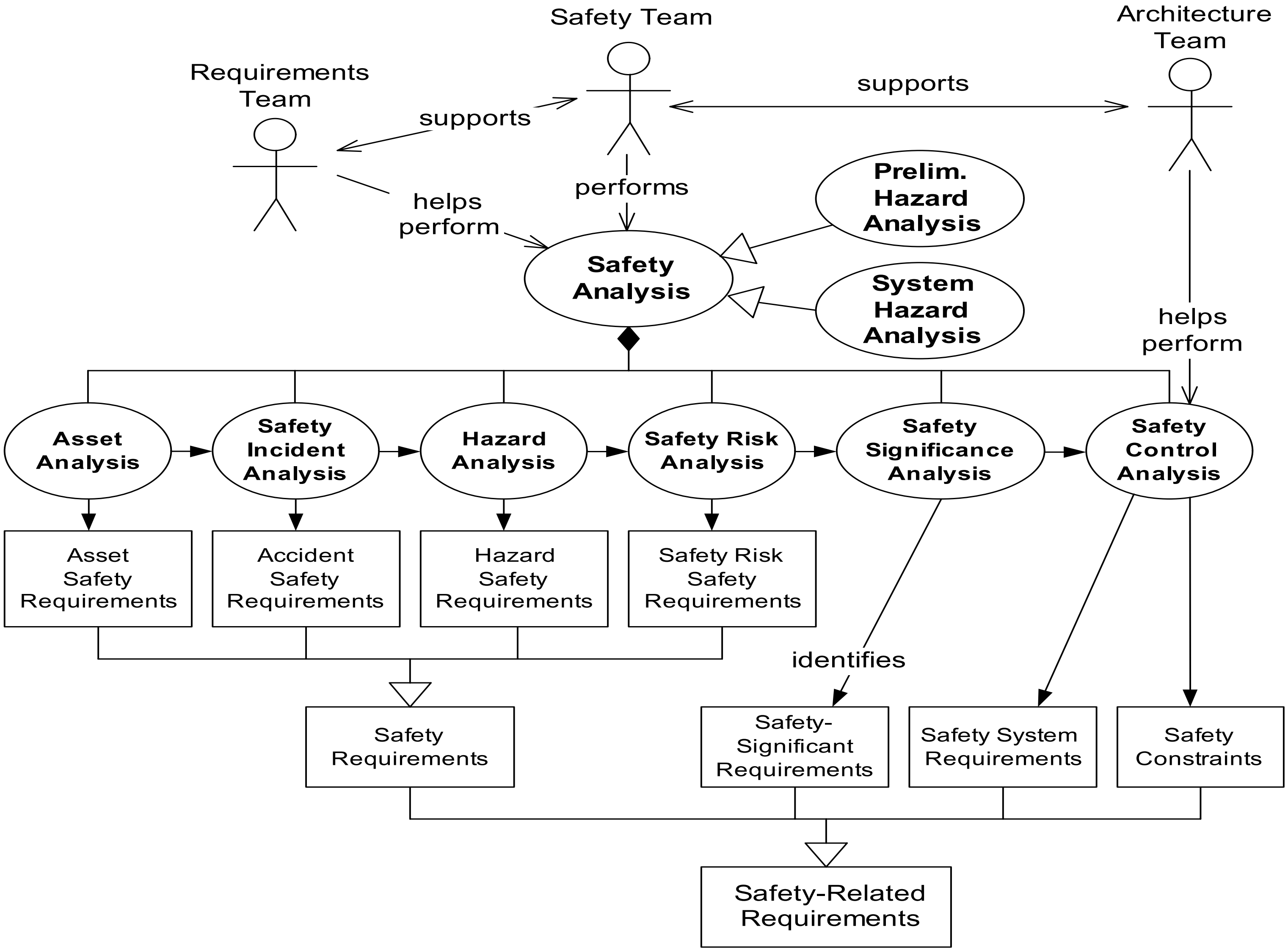
Safety & Requirements Engineering



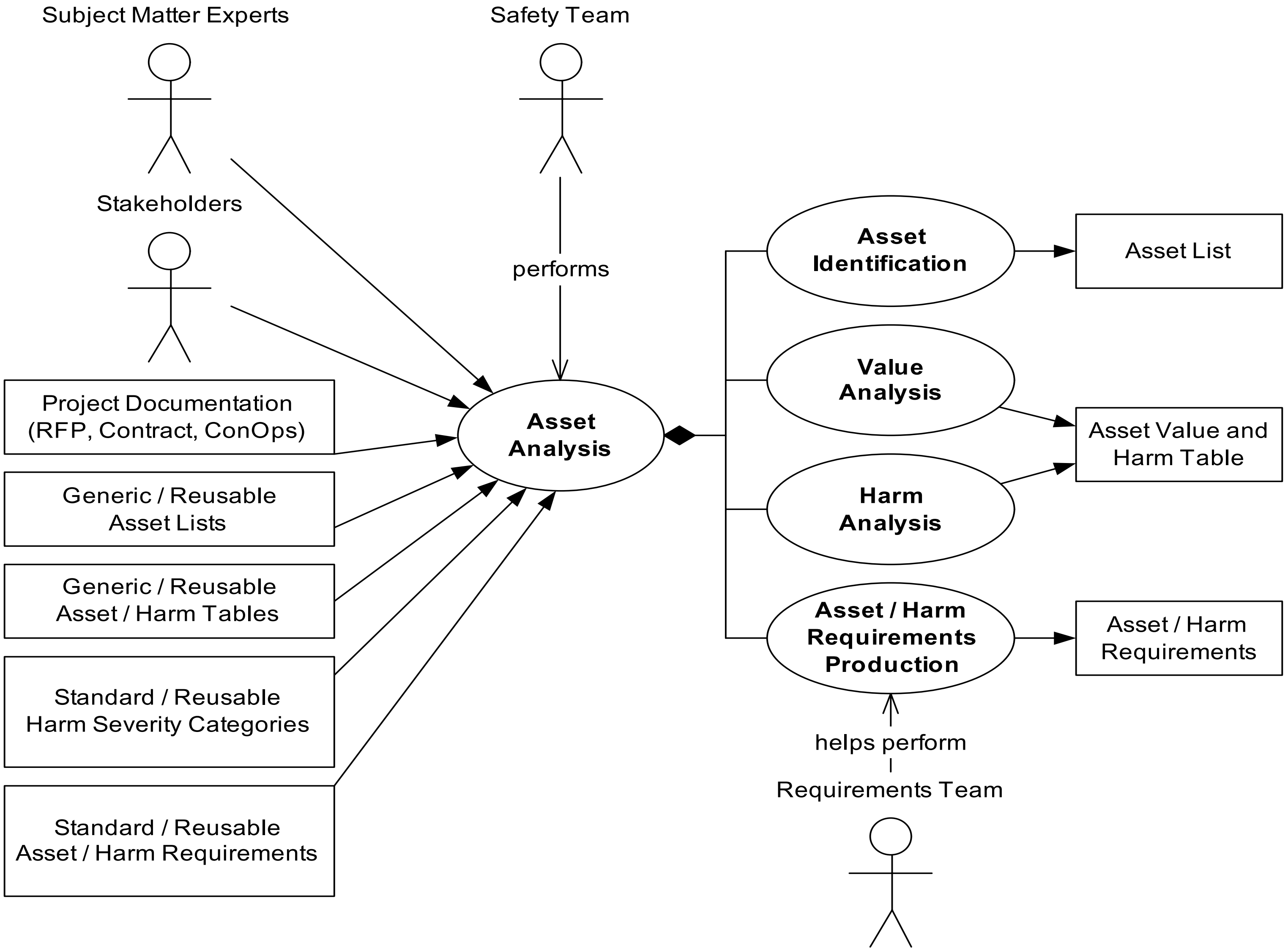
Safety Program Planning


Safety Team
Subject Matter Experts
Stakeholders
performs
Safety Program Planning
Project Documentation (RFP, Contract, ConOps)
Legacy Documentation
Generic / Reusable Safety Categories
Standard / Reusable Safety Evidence Assurance Levels
Set Safety Policy
Set Safety Goals
Determine Safety Categories
Develop Safety Program
Safety Policy
Safety Goals
Asset Value Categories
Harm Severity Categories
Hazard Likelihood Categories
Safety Incident Likelihood Categories
Safety Risk Matrix
Safety Integrity Levels (SIL)
Safety Evidence Assurance Levels
Safety Program Plan

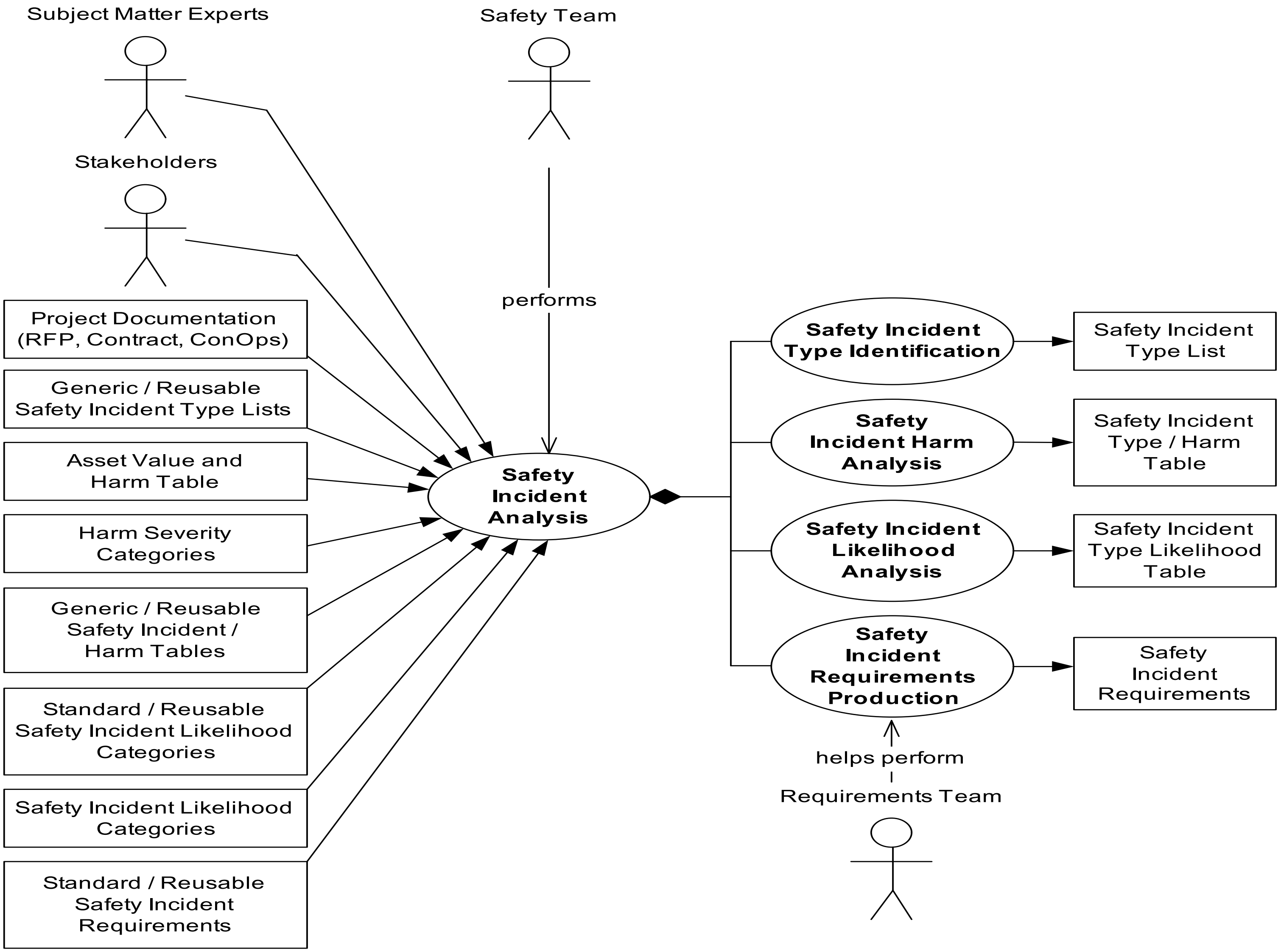
Safety Analysis



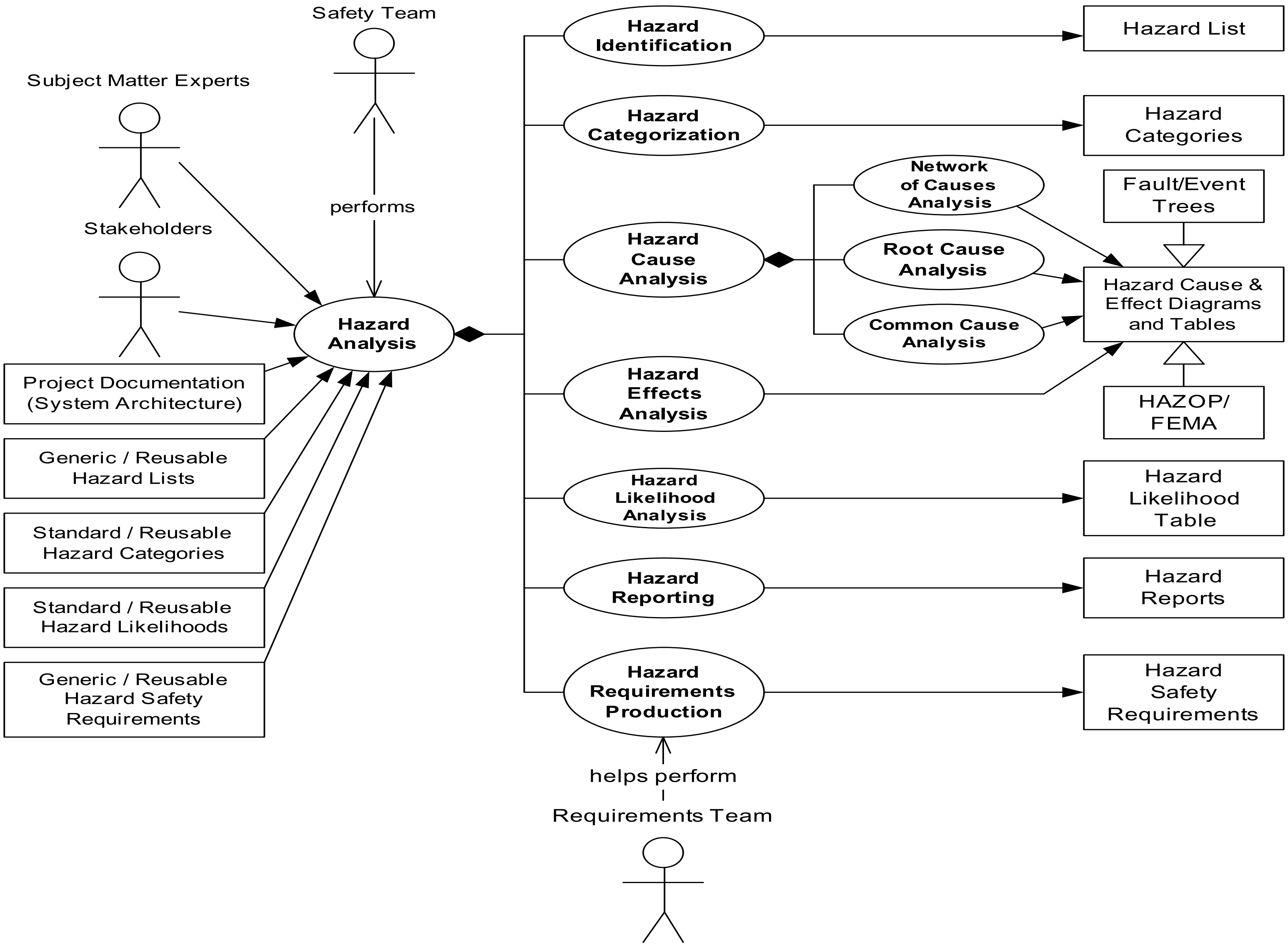
Asset Analysis


Subject Matter Experts
Safety Team
Stakeholders
performs
Project Documentation (RFP, Contract, ConOps)
Generic / Reusable Asset Lists
Generic / Reusable Asset / Harm Tables
Standard / Reusable Harm Severity Categories
Standard / Reusable Asset / Harm Requirements
Asset Analysis
Asset Identification
Value Analysis
Harm Analysis
Asset / Harm Requirements Production
Asset List
Asset Value and Harm Table
Asset / Harm Requirements
helps perform
Requirements Team

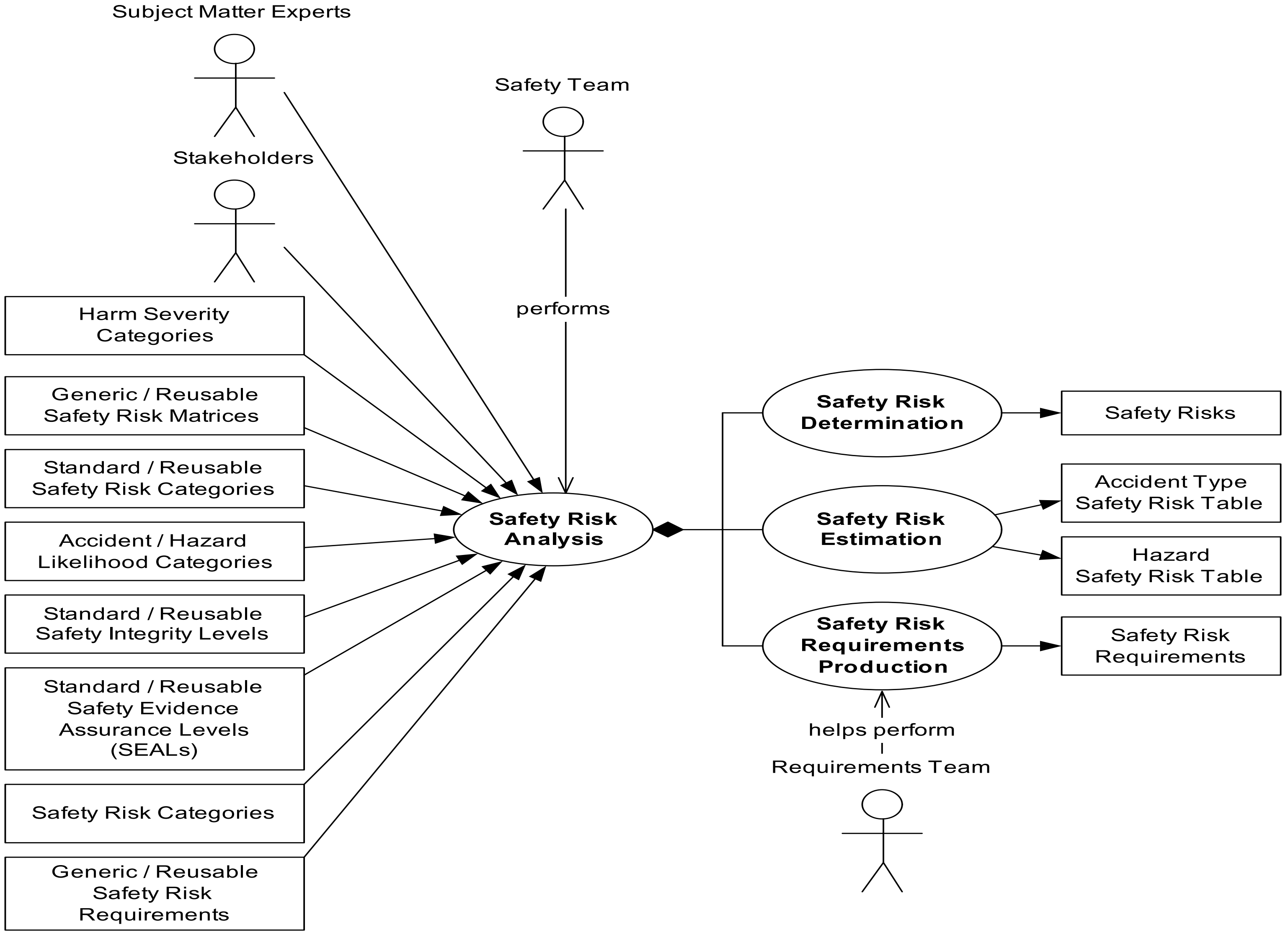
Safety Incident Analysis


Subject Matter Experts
Safety Team
Stakeholders
performs
Project Documentation (RFP, Contract, ConOps)
Generic / Reusable Safety Incident Type Lists
Asset Value and Harm Table
Harm Severity Categories
Generic / Reusable Safety Incident / Harm Tables
Standard / Reusable Safety Incident Likelihood Categories
Safety Incident Likelihood Categories
Standard / Reusable Safety Incident Requirements
Safety Incident Analysis
Safety Incident Type Identification
Safety Incident Harm Analysis
Safety Incident Likelihood Analysis
Safety Incident Requirements Production
Safety Incident Type List
Safety Incident Type / Harm Table
Safety Incident Type Likelihood Table
Safety Incident Requirements
helps perform
Requirements Team

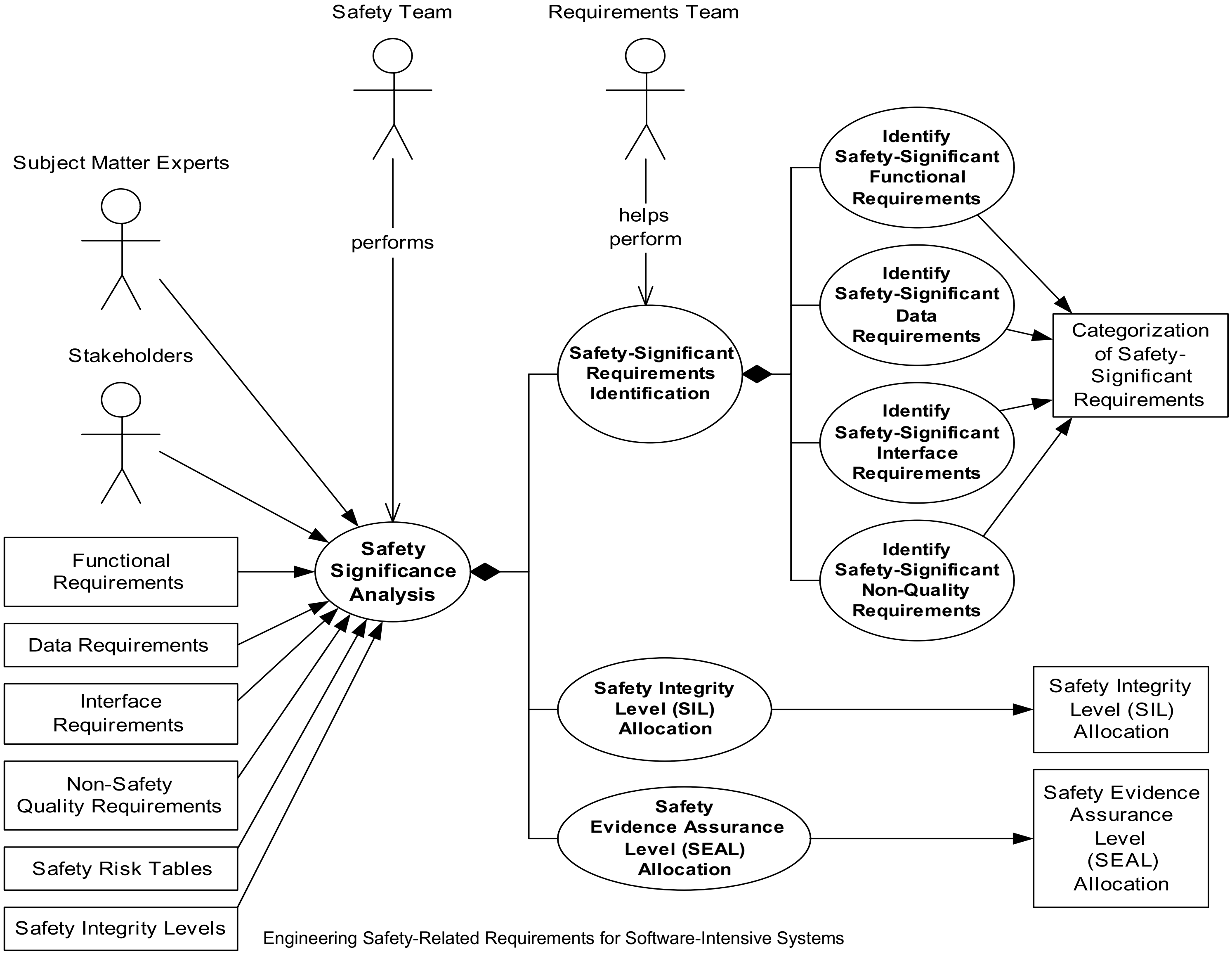
Hazard Analysis


Safety Team
Subject Matter Experts
Stakeholders
performs
Hazard Analysis
Project Documentation (System Architecture)
Generic / Reusable Hazard Lists
Standard / Reusable Hazard Categories
Standard / Reusable Hazard Likelihoods
Generic / Reusable Hazard Safety Requirements
Hazard Identification
Hazard Categorization
Hazard Cause Analysis
Network of Causes Analysis
Root Cause Analysis
Common Cause Analysis
Hazard Effects Analysis
Hazard Likelihood Analysis
Hazard Reporting
Hazard Requirements Production
helps perform
Requirements Team
Hazard List
Hazard Categories
Fault/Event Trees
Hazard Cause & Effect Diagrams and Tables
HAZOP/ FEMA
Hazard Likelihood Table
Hazard Reports
Hazard Safety Requirements

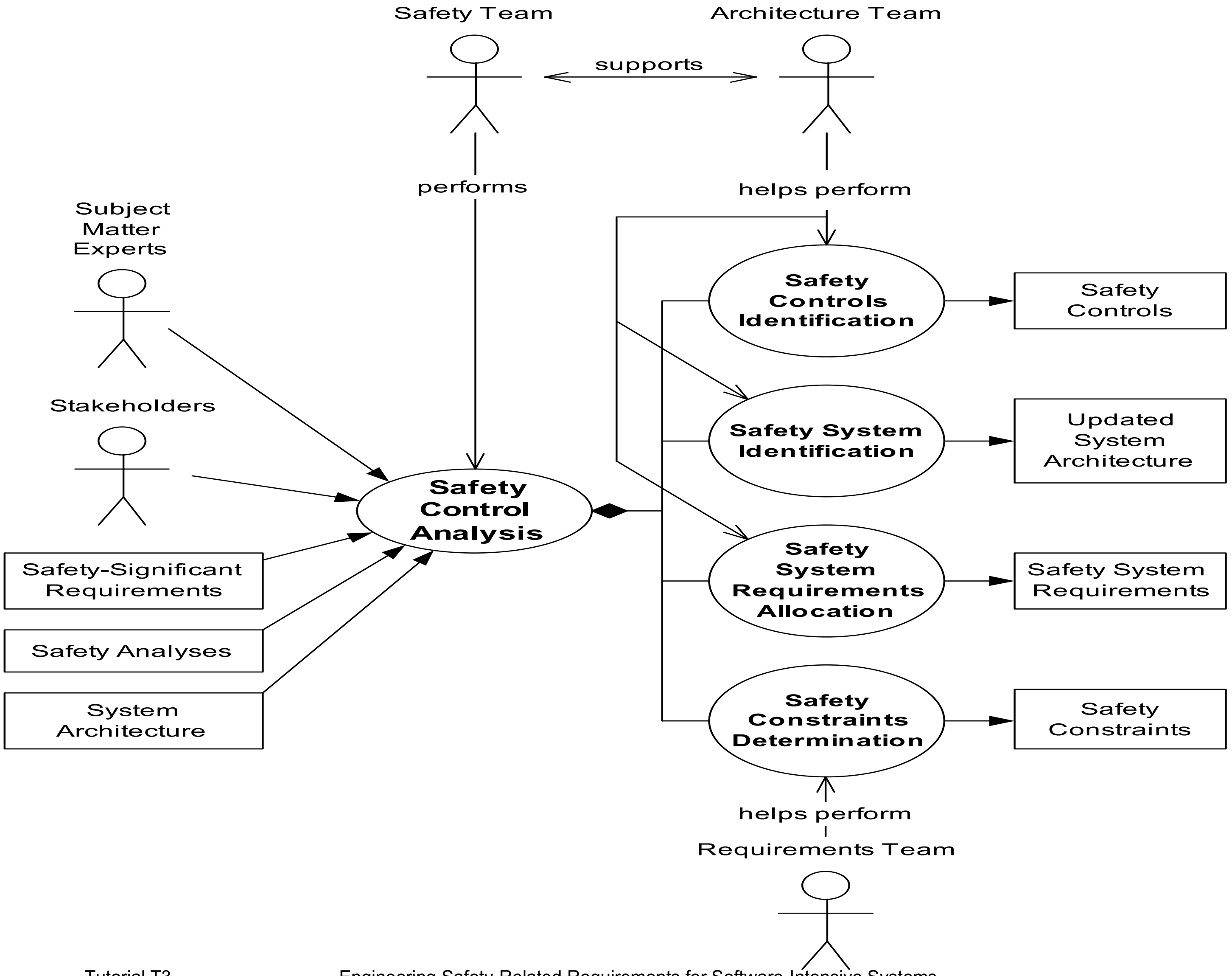
Safety Risk Analysis


Subject Matter Experts
Safety Team
Stakeholders
performs
Harm Severity Categories
Generic / Reusable Safety Risk Matrices
Standard / Reusable Safety Risk Categories
Accident / Hazard Likelihood Categories
Standard / Reusable Safety Integrity Levels
Standard / Reusable Safety Evidence Assurance Levels (SEALs)
Safety Risk Categories
Generic / Reusable Safety Risk Requirements
Safety Risk Analysis
Safety Risk Determination
Safety Risk Estimation
Safety Risk Requirements Production
Safety Risks
Accident Type Safety Risk Table
Hazard Safety Risk Table
Safety Risk Requirements
helps perform
Requirements Team

Safety-Significance Analysis


Safety Team
Requirements Team
Subject Matter Experts
Stakeholders
performs
helps perform
Safety Significance Analysis
Functional Requirements
Data Requirements
Interface Requirements
Non-Safety Quality Requirements
Safety Risk Tables
Safety Integrity Levels
Safety-Significant Requirements Identification
Identify Safety-Significant Functional Requirements
Identify Safety-Significant Data Requirements
Identify Safety-Significant Interface Requirements
Identify Safety-Significant Non-Quality Requirements
Categorization of Safety-Significant Requirements
Safety Integrity Level (SIL) Allocation
Safety Integrity Level (SIL) Allocation
Safety Evidence Assurance Level (SEAL) Allocation
Safety Evidence Assurance Level (SEAL) Allocation

Safety Control Analysis


Safety Team
Architecture Team
supports
performs
helps perform
Subject Matter Experts
Stakeholders
Safety-Significant Requirements
Safety Analyses
System Architecture
Safety Control Analysis
Safety Controls Identification
Safety System Identification
Safety System Requirements Allocation
Safety Constraints Determination
Safety Controls
Updated System Architecture
Safety System Requirements
Safety Constraints
helps perform
Requirements Team

Conclusion

- Engineering safety-significant requirements requires concepts, methods, techniques, and expertise from *both* requirements engineering and safety engineering.
- There are multiple types of safety-related requirements that have different forms and that need to be analyzed and specified differently.
- Look for my upcoming book by the same title.
- For more information, check out my repository of over 1,100 free open source reusable process components including many on safety at www.opfro.org.