Engineering High-Dependability Systems

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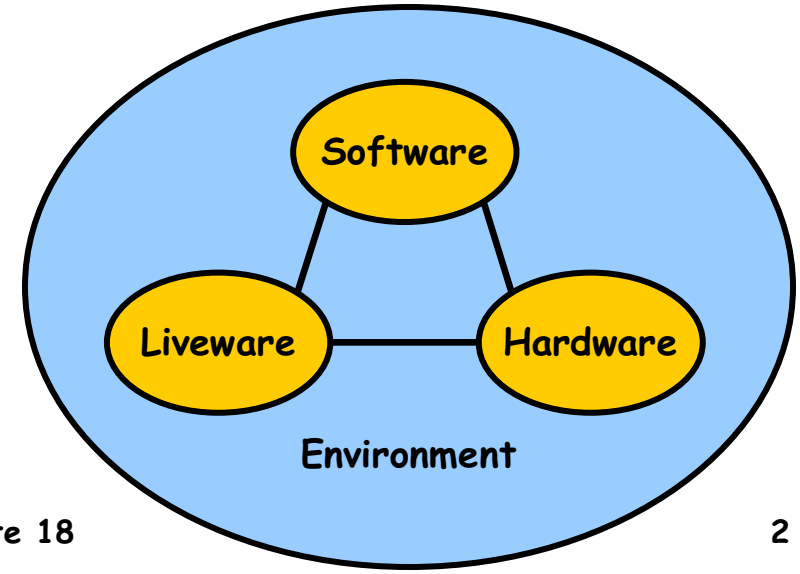
Dependability of Socio-technical Systems

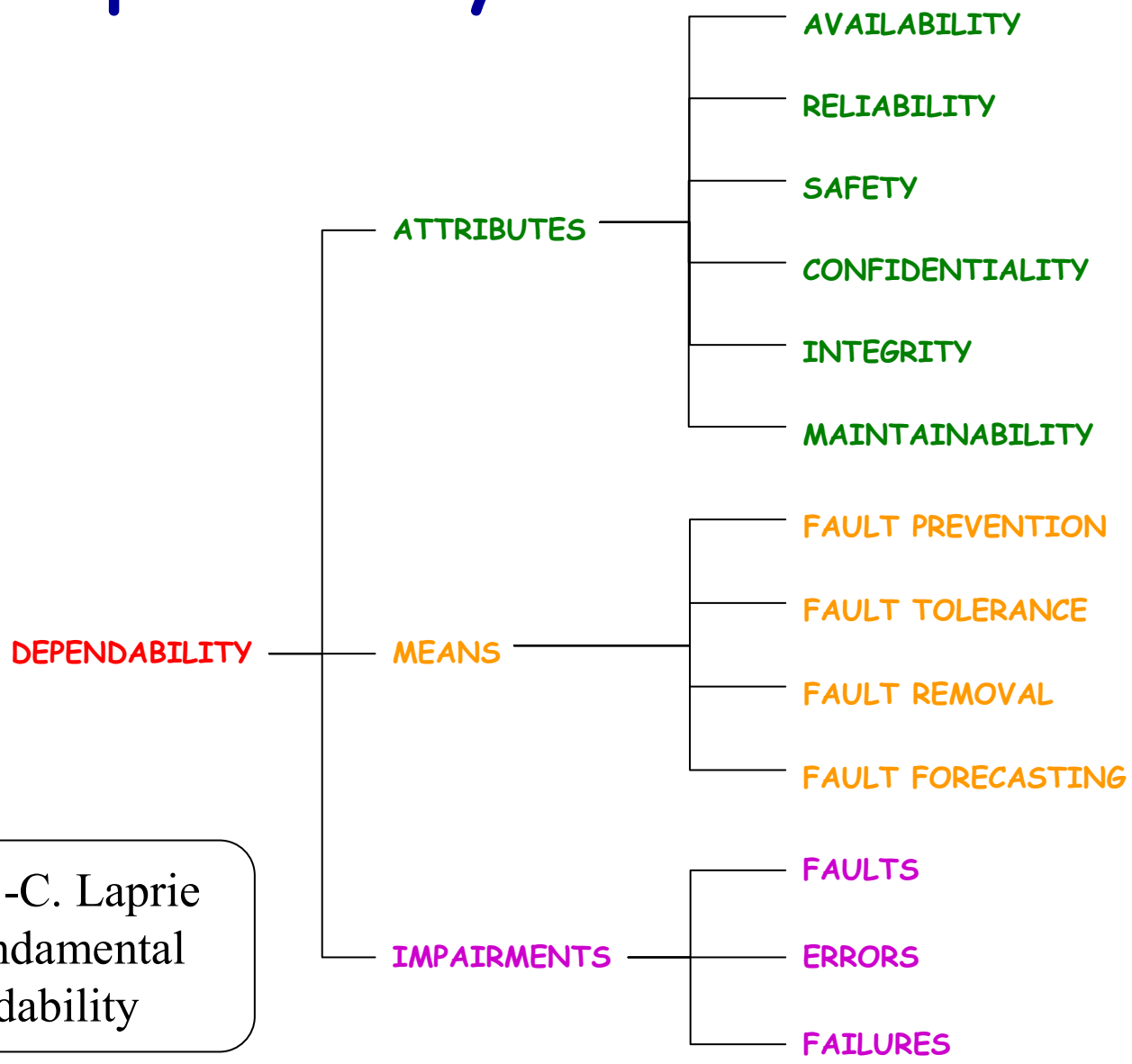
- What is Dependability? **Dependability** is that property of a computer system such that reliance can justifiably be placed on the service it delivers.
- The **service** delivered by a system is its behaviour as perceived by its user(s).
- A **user** is another system (human or physical) interacting with the system considered.

(See A. Avižienis, J.-C. Laprie and B. Randell, Fundamental Concepts of Dependability)

- What are Socio-technical Systems? Systems involving humans, organizations, environment,…
- Here is a holistic view of Socio-technical Systems
- Software is a (significant) part of the "whole system"



What is Dependability?



See A. Avižienis, J.-C. Laprie and B. Randell, Fundamental Concepts of Dependability

(Some) Flavours of Dependable Systems

- **Safety-critical**: failure leads to serious injury, loss of life, or significant environmental damage
- **Security-critical**: access control, permissions and monitoring (potentially in the face of malicious attack) a key issue
- **Fault-tolerant**: system is robust - can withstand errors in, or failures of, parts of the system (e.g., auto-pilots)
- **High-reliability**: likelihood of failure-on-demand exceptional low (e.g., fire-safety shutdown systems)

What is undependability?

- "Classic" high provide failures:
  - Mars Climate Orbiter
  - Ariane 5
  - Therac 25
  - …
- What else?
  - **pervasiveness** of computers (e.g., Y2K)
  - Multiple low-criticality failures
  - Dependence of society
  - Service loss: "the system is down"
- Impact on **organizations**
  - NATS, NHS, finance,…

NASA' Mars Climate Orbiter

- Part of Mars Surveyor programme (1993)
- Developed at cost of $327.6 million (orbiter and lander)
- Launched December 1998
- Intended to enter Mars orbit September 1999. at 210km altitude
- September 23rd, attempted orbit at 57km, burned up in Martian atmosphere
- Investigation - Phase 1 Mishap Investigation report, November 1999
  - Root cause: failure to use metric units in ground software file "Small Forces"
  - Team developing SM_FORCES used English units of pounds-seconds
  - Team developing navigation software algorithm assumed metric units of Newton-seconds.
  - Project SIS (Software Interface Specification) not followed
- Contribution causes
  - Process did not adequately address transition from development to operations
  - Inadequate communication between teams
  - V&V process did not adequately address ground software

Therac 25 Radiotherapy Machine

- Therac-25 had two operating modes:
  - Low intensity (electron radiation), wide spread
  - High intensity (X-ray radiation), tight focus
- Software fault in data entry permitted high intensity, wide spread
  - X-ray generated by placing tungsten shield as "filter" for high-intensity electron beam
  - Set-up process takes considerable time
  - Changes during set-up not validated
- 6 known accidents between June 1985 and January 1987, leading to 2 confirmed deaths
- Hardware interlocks in Therac-20 removed (software error present, but caused blown fuse)

(Some) Other Major Software Failures

- London Ambulance Service
- Taurus Financial System
- CUFS (Cambridge University Financial System)
- Swanwick ATC? Proposed 1988 (for 1996), building commenced 1991, completed 1994, software working "by winter 2002"?

Safety Critical Systems

- Variety of industrial sectors; both regulated and (relatively) unregulated
  - Regulated
    - Hazardous manufacturing (e.g., chemical, explosives, etc.)
    - Travel and transport (e.g., air, rail, sea)
    - Energy (e.g., nuclear, petrochemical)
  - (less) regulated
    - Automotive (e.g., engine controllers, ABS, etc.)
    - Medical informatics (e.g., radiotherapy, anaesthetics, medical expert systems, etc.)
- Safety cases: "arguments" of acceptable safety of proposed system
- Focus on design for assessment
- Motivation/drivers for "safety culture"
- "whole system" issues
- Software not necessary susceptible to "traditional" engineering approaches

Regulation and Assessment

- Regulatory standards:
  - National and international
  - Generic and domain-specific
  - Independent assessment and regulatory authorities
- The safety case:
  - Pre-1990's: largely prescriptive
  - 1988: Piper-alpha; Cullen inquiry highly critical of "box ticking"
  - Post-Cullen: move to goal-setting standards

Motivation and Drivers for Safety

- Economic – cost benefit analysis (one life ~ £1-2 million)
- Responsibility
  - Developer versus assessor versus regulator
  - In-house versus 3rd party (e.g., COTS/SOUP)
- Liability, e.g., British Rail:
  - Pre-privatisation: HSE, rail regulatory authority
  - Post-privatisation: HSE, rail regulatory authority, Railtrack, 3rd party maintenance, strategic rail regulator, rail safety assessor,…
- History
  - Design for significant accidents
  - Safety culture "disaster-driven"
  - No significant automotive/medical disasters…?

Software Engineering for Safety Critical Systems

- No "new" software engineering techniques
- Adoption of traditional, physical engineering techniques
  - For design (e.g., triple modular redundancy, fault tolerance, failsafes, error recovery, etc.)
  - For analysis (e.g., hazard analysis, fault tree analysis, failure modes, effects analysis, etc.)
- …but software unlike physical systems
  - Often open and evolving
  - High functional complexity
  - Common mode failures
  - Complex dependencies
  - Software errors are all latent

The Safety Case

- A safety case is a document, or collection of documents, that presents the arguments for believing that a proposed potentially-dangerous system is acceptably safe.
- It sets out the risks involved with the operation of the process or equipment and the possible consequences of failure, and specifies what will be done (or has been done) to minimise the probability and the impact of these failures.

Design for assessment: Arguments of Software Safety

- Process versus product
  - Design process used will lead to safe system versus system produced is shown to be safe
- Quality versus quantitative
  - Claims of good quality (e.g., unsafe states not possible) versus numericdl medsures of, for example, probability of error
- Formal verification
  - Use of formal methods. However, formal models often constructed but not verified
- Adoption of traditional engineering analyses
  - HAZOPS (HAZard and Operability Studies), FMEA (Failure Modes and Effects Analysis), FTA (Fault Tree Analysis)
- Software specified standards
  - E.g., MOD 00-55, IEC 61508
- Responsibility
  - Open issue – responsibility versus liability

Safety Standards for Software

- **MOD Def.Stan. 00-55** - Procurement of Safety Critical Software in Defense Equipment
  - Requirements:
    - Safety management
    - Software engineering practice
  - Guidance:
    - Lifecycles
    - Hazard analysis
    - Risk analysis
    - V&V
    - Independent auditing
    - …

Safety Standards for Software

- **IEC 61508** - Functional Safety of electrical/electronic/programmable electronic safety related systems
  - Safety at the system level
    - The overall safety lifecycle
    - Management of functional safety
    - Hazard analysis, risk reduction and safety integrity levels
  - Hardware and architectural safety
    - Managing hardware
    - Failure probabilities
    - Integrating hardware into the safety lifecycle
  - Software safety
    - Safety related software
    - Selecting development methods and tools
    - Verification and validation

Computer-related accidental death
An empirical exploration (D. MacKenzie, 1994)

- **Computer-related** – as before
- **Accidental death** – non-deliberate (i.e., military); empirically "easy" to measure
- **Causes**
  - 4% physical (chiefly electromagnetic interference)
  - 3% software error
    - Therac-25 (2) + Patriot (28)
  - 92% failure in human-computer interaction
  - Estimated number of deaths (until end 1992): 1,100 +/- 1,000

Fatalities due to Software Error

- 1986, Therac-25
  - Radiotherapy machine
  - Two operating modes:
    - Low intensity, wide spread
    - High intensity, tight focus
  - Software error in data entry permitted high intensity, wide spread
  - Hardware interlock in Therac-20 removed
  - Overdosing leads to 2 confirmed deaths
- 1991, Patriot anti-Scud missile system
  - Internal clock uses tenths of seconds
  - Binary rounding error known
  - Long run times not anticipated
  - 25th February: Alpha Battery in uniterrupted operation for over 100 hours; unable to track Scud missiles; 28 US servicemen killed
  - 26th February: software fix arrives

Fatalities due to Human-computer Interaction Failures

- 1992, A320 airbus crashes after over-rapid descent, 87 die. "Glass cockpit" descent display of 3.3 (thousands of feet per minute) wrongly interpreted as angle – Airbus denies responsibility (although interface changed subsequently).
- Similar incidents
  - Habsheim 1988, Bangalore 1990, Moscow 1991, Nagoya 1994, Toulouse 1994, Paris 1994,….
- 1998, USS Vincennes shoots down Iran Air airliner, all 290 on board die: weapon system human interface deemed "not optimal"

Lufthansa Airbus A320 Crash, Warsaw

- 14 Sept. 1993, flight DLH 2904 from Frankfurt overruns runway on landing at Warsaw Airport, Poland
  - co-pilot and 1 passenger die, 54 people hospitalised
- Autopilot found to have prevented reverse thrust braking for 9 seconds
- Specification of checks to sever (height, wheel-spin, weight on both wheels)
- Dangers of in-flight reverse thrust activation: May 1991, Boening 767 brought down over Thailand, killing all on board
- Pilot error/specification error? Airbus denies responsibility (although code subsequently changed)

Fatalities due to Human-computer Interaction Failures

- 1992, London Ambulance Service Computer Aided Despatch Systems
  - primarily management failure, claims of 20-30 deaths
- 1982-1991, North Staffs. Royal Infirmary radiotherapy
  - Double error-correction leads to underdosing of around 1,000 patients, 401 die
  - Clinical verdict is "tens rather than hundreds" due to double error-correction
- 1994, Toulouse: Airbus A330 stalls during testing. Flight level set at 2,000ft instead of 7,000ft
  - 7 dead including Airbus chief test pilot
  - Attitudes to "safety envelope" different from Airbus and Boeing

Where is the danger?

- Software does not directly cause fatalities
- **Interaction** between software and physical world
- All **software errors latent**; present in specification
  - Requirements missed, incorrect or misunderstood
  - Failure to correctly implement specification rarer, e.g., NASA Galileo/Voyager mission critical software

How Dangerous is Software?

- Estimated number of deaths (until end 1992): 1,100 +/- 1,000
- Compare with UK road deaths for 1992 alone: 4,274
- Human **perception of risk** and danger complicated
  - Degree of personal control
  - Anticipated benefit
  - Availability of data
- **Hypothesis**: software is safe, because we believe it to be dangerous

Where does SEOC1 fit in?
Software Engineering versus Physical Engineering

- **Art**, **Craft**, **Science**???
  - **Science**: strong theoretical foundation, knowledge-based teaching
  - **Craft**: little theory, skill-based apprentices
  - **Art**: highly subjective, innate ability crucial
- Errors are **latent** (often in requirements or specification)
- Physical system convex, e.g., beam is tested for 100kg load and 1000kb load, can assume will carry any load between 100-1000kg
- Software not convex, but structured
  - Can partition system; e.g., independence of failures in interface and operation (c.f., Therac-25)

SEOC1 and Dependability
Process, Assessment and Components

- **Process oriented assessment**
  - E.g., lifecycle models, project planning and management, structured test plans,…
  - Combining qualitative and quantitative modelling and assessmment
- **Avoiding failure in communication**
  - During design (c.f., Mars Climate Orbiter)
  - During assessment (c.f., Voyager and Galileo; Arianne 5)
  - Validation as well as verification (c.f., LASCAD)
- **(reuse of) trusted/tested components**
  - E.g., 3rd party developers of high-dependability components
- **Principled composition of components**
  - Theory of composition, e.g., independence of failures in component