The state of the art in fault tree modeling and analysis

Enno Ruijters

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Outline

Outline

About me

- Enno Ruijters
- PhD Student at University of Twente (Formal Methods and Tools)
- ArRangeer project
  - ProRail / STW
  - Improving railroad maintenance using Dynamic Fault Trees and Stochastic Model Checking

Introduction to fault trees

- Developed in 1961 by Nuclear Regulatory Agency
- Question: How reliable is your system?
- Now used by:

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- Question: How reliable is your system?
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Why fault trees?

- Some things really should not fail
- Risk assessment is sometimes mandatory
  - Probability of catastrophic failures?
  - Biggest risk factors?
  - Possible mitigations?

Why fault trees?

- Some things really should not fail

  Reliability Probability of failing within given time

Why fault trees?

- Some things really should not fail

Reliability	Probability of failing within given time
Availability	Proportion of time in functioning state

What do we want to know?

Qualitative:

- Insight into biggest risks
- Relatively fast to perform
- Easy to understand
- Limited information

Quantitative:

- Quantify total risk
- Quantify effect of mitigation
- Time consuming
- Hard to estimate numbers

What to we want to know?

Quantitative:

- **Reliability** $\equiv$ Probability of failure within time t
  Example: Probability of containment failure within 25 year nuclear plant lifetime

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  Example: Amazon EC2 cloud offers SLA of 99.95% uptime

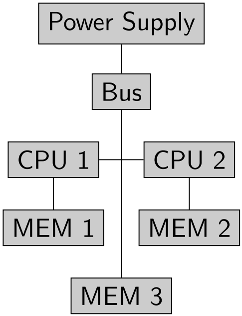
What to we want to know?

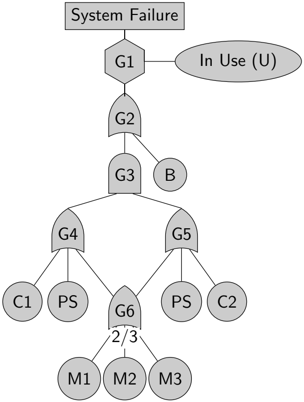
Quantitative:

- **Reliability** $\equiv$ Probability of failure within time t
  Example: Probability of containment failure within 25 year nuclear plant lifetime
- **Availability** $\equiv$ Proportion of time (in $[0, \infty\rangle$ or $[0, t]$) spent not failed
  Example: Amazon EC2 cloud offers SLA of 99.95% uptime
- **MTBF** $\equiv$ Expected time between two successive failures (in finite or infinite horizon)
  Example: How frequently will my car break down?
- Others (MTTF, ENF, etc.)

Outline

Fault tree example

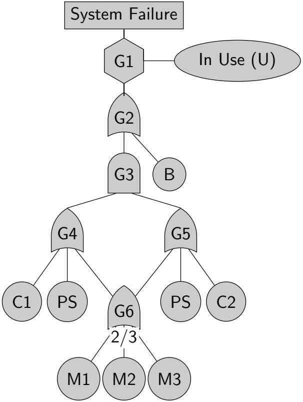




- Redundant CPUs
- 1 shared spare memory unit

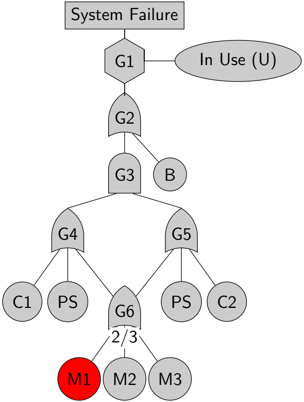
Example of fault tree failure propagation

- No failures



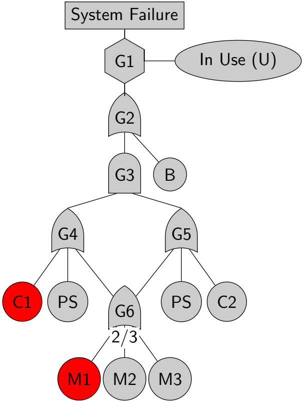
Example of fault tree failure propagation

- Failure of M1



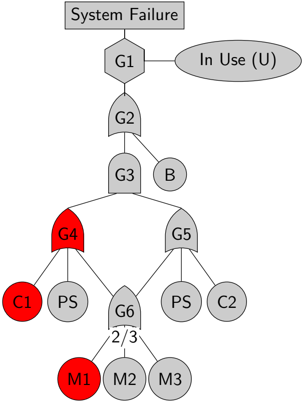
Example of fault tree failure propagation

- Failure of M1
- Failure of C1



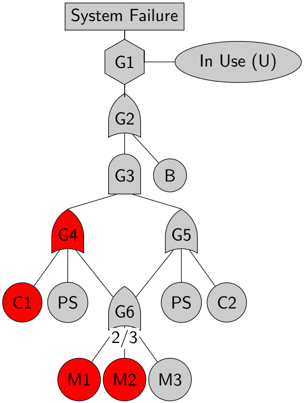
Example of fault tree failure propagation

- Failure of M1
- Failure of C1



Example of fault tree failure propagation

- Failure of M1
- Failure of C1
- Failure of M2



Example of fault tree failure propagation

- Failure of M1
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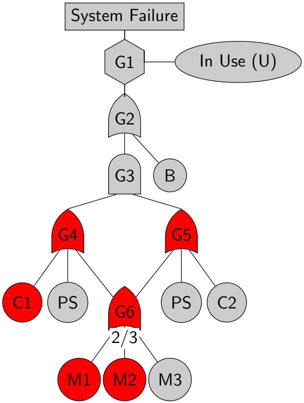

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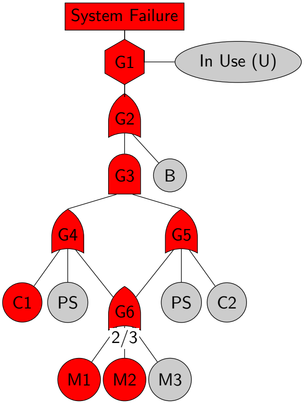


Fault tree types

Model	Reliability	Availability	MTTFF	MTTF	MTBF	MTTR	ENF
Discrete-time	+						+
Continuous-time	+	+	+				+
Repairable cont.-time	+	+	+	+	+	+	+

Table: Applicability of stochastic measures to different FT types

Quantitative analysis of static fault trees

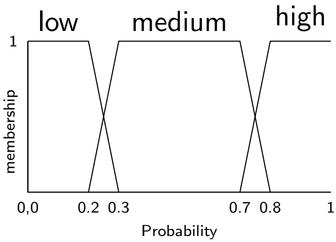
Method	Reliability	Availability	MTBF	Exact	Speed	Computable
Bottom-up method	+	+		∼	+	+
Rare-event approximation	+	+		-	+	+
Bayesian networks	+	+		+	-	+
Monte Carlo Simulation	+	+	+	-	-	+
Algebraic analysis	+	+	+	+	-	∼
Algebraic approximation	+	+	+	-	+	+

Table: Quantitative analysis for static fault trees

Outline

Fuzzy numbers

- Uncertainty and variation in BE probabilities
- Expert judgement not exact
- Possible solution: BE probabilities in fuzzy sets
- Several frameworks for computations on fuzzy numbers
- Can compute same measures as for non-fuzzy FTs.



Other uncertain FTs

- ‘Intuitionistic fuzzy set theory’: Membership function uncertain
- Probability distribution for BE failure rates
- Multi-state BE with uncertain states
- Normal distribution approximation

FTs with dependent events

- Normal FTs assume independent BEs
- Not always realistic (‘valve stuck open’ and ‘valve stuck closed’ are not independent)
- Component failures and degradation may propagate

Dependent event extensions

- Specifying mutually exclusive events
- Extended FTs
- Multiple FTs for different failure modes
- Replace BEs by Petri nets
- Boolean Driven Markov Processes

Repairable fault trees

- Simple repair model: Simultaneous independent repairs
- Problem: Limited resources for repairs in real life
- Problem: Hidden failures
- Solution method: Repairable Fault Trees
- Add repair boxes that specify when to repair what

Fault trees with temporal properties

- Static FTs do not consider timing information
- Phased systems
- Delays
- Failure sequences

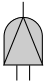
Outline

Shortcomings of fault trees

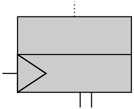
- No information about failure sequences
- Poor modeling of shared spare components
- Dependencies cause large trees
- One solution: Dynamic fault trees (DFTs)

Dynamic fault trees

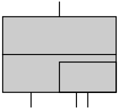
Three new gates:



PAND gate

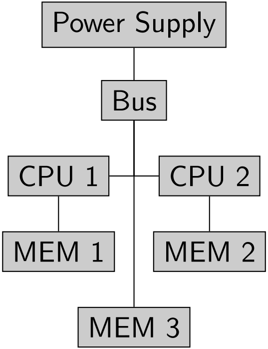


FDEP gate



SPARE gate

DFT Example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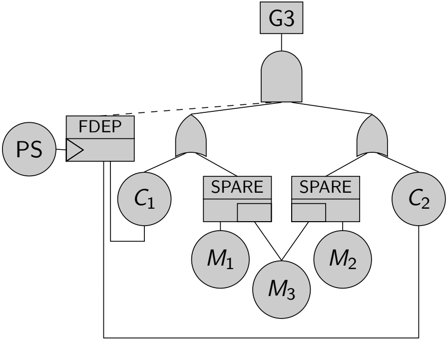
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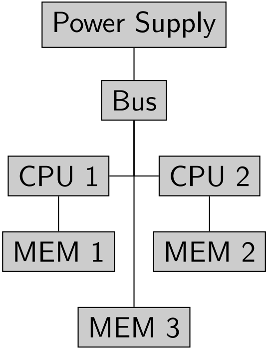
DFT Example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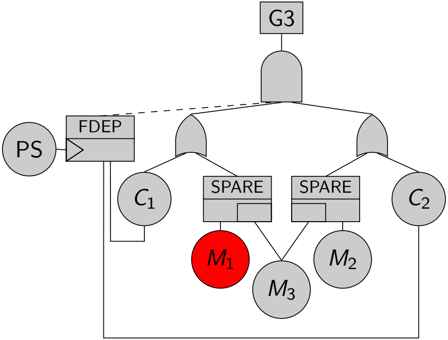
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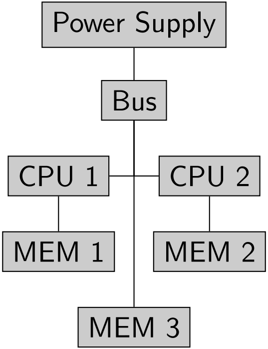
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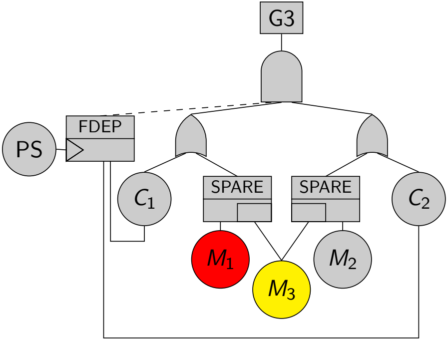
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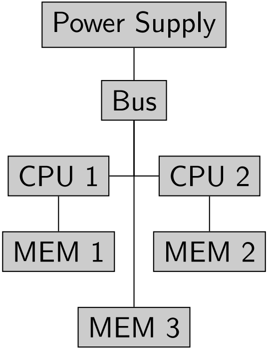
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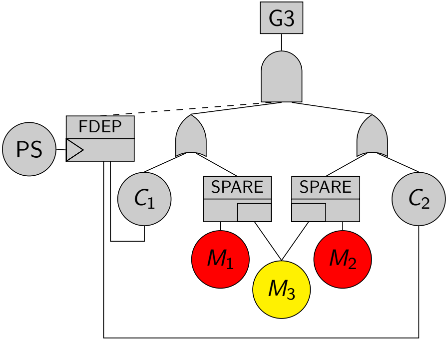
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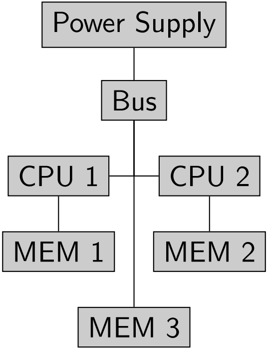
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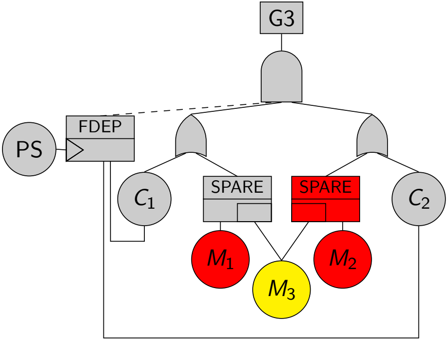
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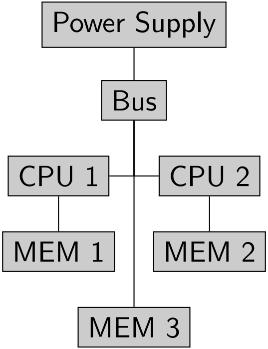
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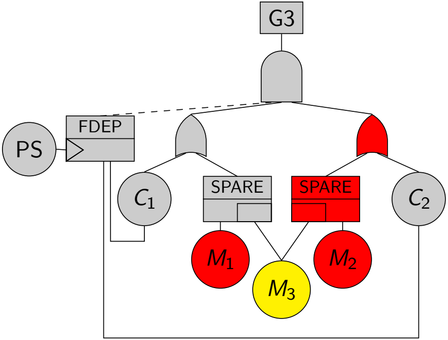
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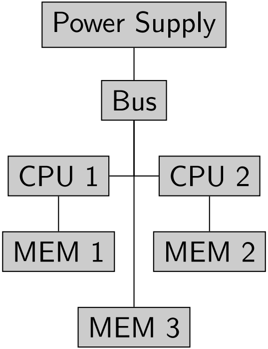
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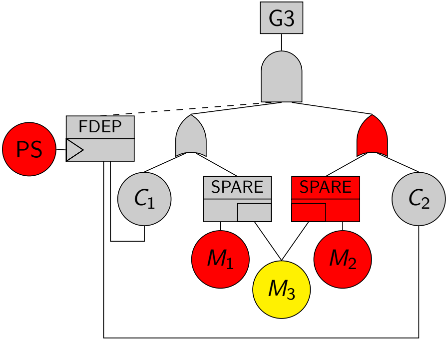
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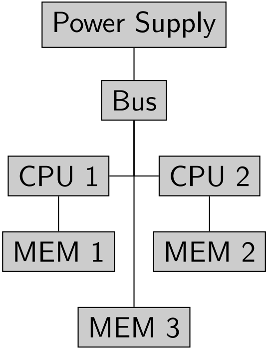
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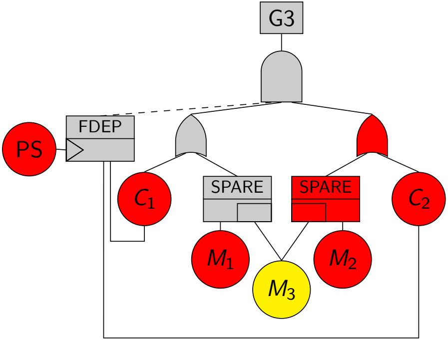
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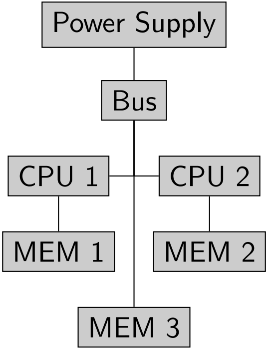
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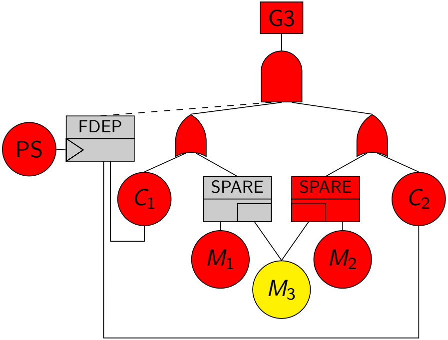
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Outline

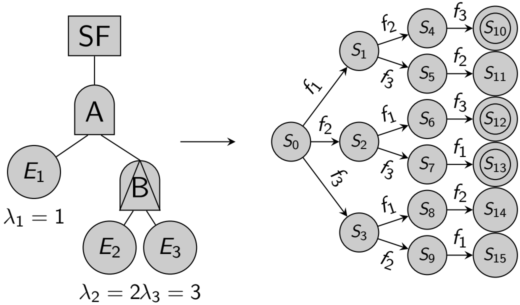
Quantitative analysis of dynamic fault trees

Method	Reliability	Availability	MTBF	Exact	Deterministic	Speed
Markov Chains	+	+		+	∼	-
I/O IMC	+	+		+		+
Petri Nets	+	+		+	∼	+
Dynamic Bayesian Networks	+	+		-	∼	-
Monte Carlo Simulation	+	+	+	-		-
Algebraic analysis	+	+	+	+		-

Table: Quantitative analysis for dynamic fault trees

DFT analysis: Markov chain

Analysis by markov chain:



DFT analysis: Markov chain

Advantages:

- Exact semantics
- No nondeterminacy
- Reuse of existing modelcheckers (PRISM, etc.)

DFT analysis: Markov chain

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- Exact semantics
- No nondeterminacy
- Reuse of existing modelcheckers (PRISM, etc.)

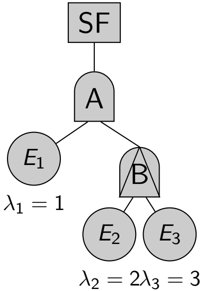
Disadvantages:

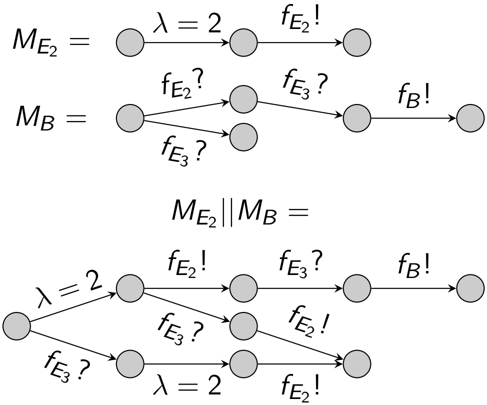
- Semantics are ca. 20 pages long
- Combinatorial explosion

DFT analysis: Compositional Markov Analysis

- *Input/Output Interactive Markov Chains* exist of gates and basic events
- Input/Output signals allow parallel composition
- Models of FT elements are composed into one large model

DFT analysis: I/O IMC example





DFT analysis: Compositional Markov Analysis

Advantages:

- Semantics easier to understand
- Intermediate minimization reduces state-space explosion
- Easy to add new gates or events
- Can model nondeterminacy

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Advantages:

- Semantics easier to understand
- Intermediate minimization reduces state-space explosion
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Disadvantages:

- Still has state-space explosion
- Nondeterminacy

Outline

Importance of maintenance

Importance of maintenance

When to do maintenance

- Preventive maintenance
- Corrective maintenance

Effect of maintenance

On component:

- 'As good as new' replacement
  - example: Replace battery
- Reduced failure rate
  - example: Oil change

Effect of maintenance on system

Positive:

- Correct failure (corrective)
- Reduce failure rate (preventive)

Effect of maintenance on system

Positive:

- Correct failure (corrective)
- Reduce failure rate (preventive)

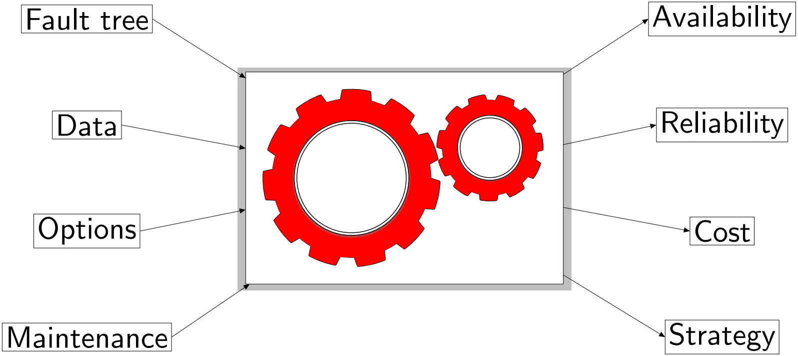
Negative:

- Cost
- Downtime

Maintenance strategy

- What maintenance actions to do on which components?
- When to perform preventive maintenance?
  - Type of schedule (clock based, etc.)
  - Frequency
- How to react to failures?

Project goal



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