Unmasking Fault Tolerance: Masking vs. Non-masking Fault-tolerant Systems

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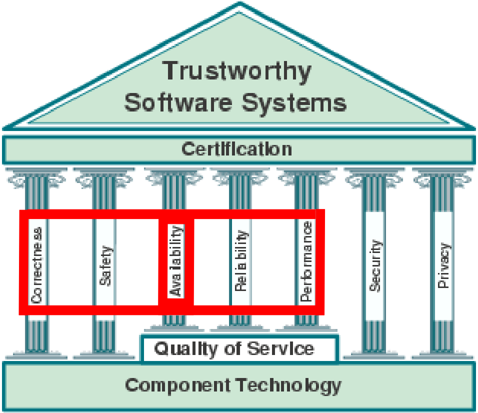
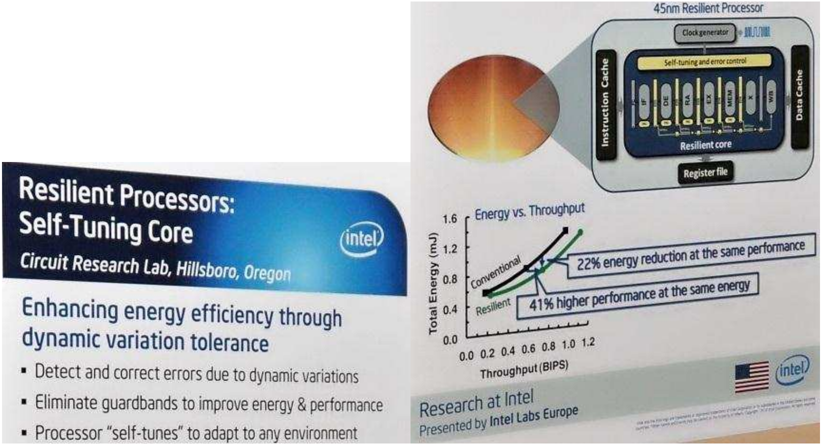
Orientation



Outline

Intel: Palisades



[BTL+10]

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$\Rightarrow$: relation between quality (degree of masking)
and cost.

1. Motivation
2. **Basics**
3. Computation of *LWAV*
4. Lumping
5. Decomposition
6. Status and Outlook

Outline

1. fault tolerance demands redundancy
2. fault tolerance classification
3. the fault masker concept
4. unmasking fault tolerance
5. redundancy classification
6. self-stabilization

Fault Tolerance Demands Redundancy

- to tolerate faults, they must be detected and/or corrected
- detection and correction are functions that require resources
- typically either space (functional or information redundancy) or time (but commonly both)
- sometimes convertible (e.g., TMR)

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Example: **Cyclic Redundancy Checks (CRC)**
requires space (extends the package, information redundancy),
and more space (code for the computation of CRC, functional redundancy),
and time (for the computation, and transmission, temporal redundancy)

Three Kinds of FT.: Focus on Masking and Non-masking

	safe	not safe
live	masking	non-masking
not live	failsafe	intolerant

Table: Fault Tolerance Classes [KA97, Gär99]

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- most desirable

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- intolerant: corrupted packet contained matching checksum
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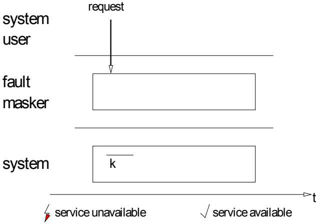

[MDT09]

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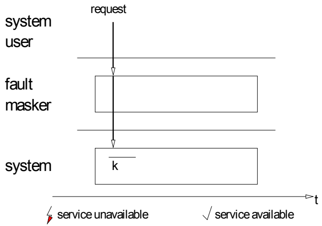

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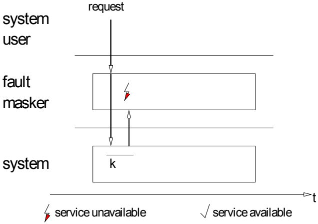

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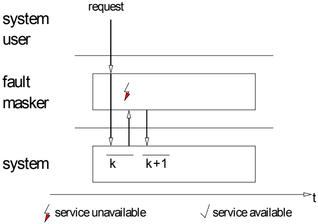

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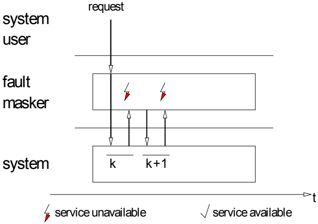

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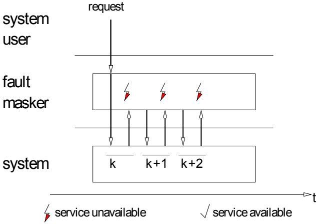

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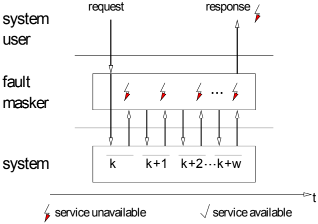

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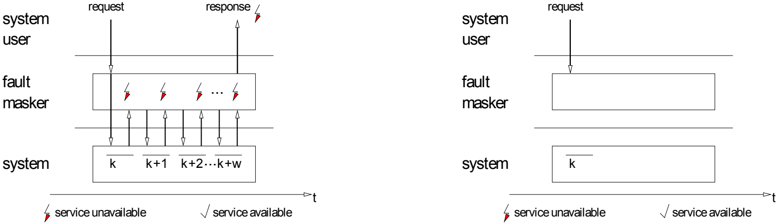

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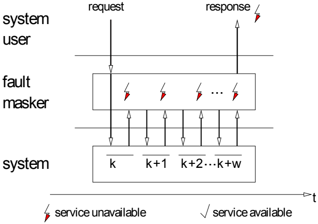

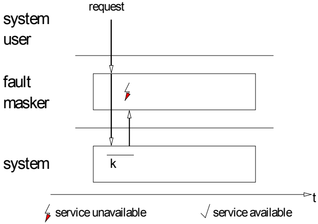

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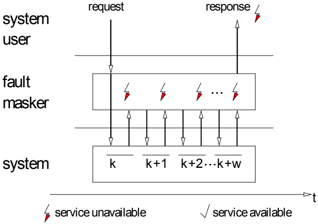

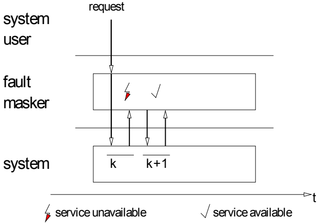

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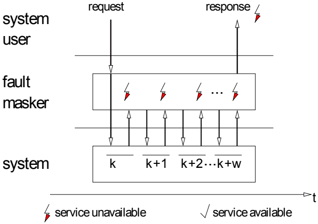

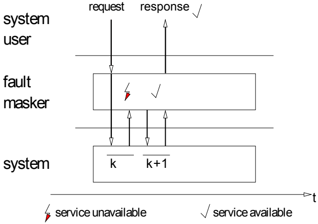

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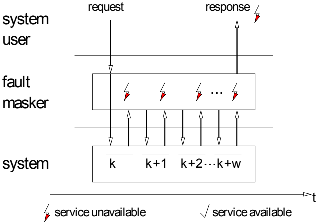

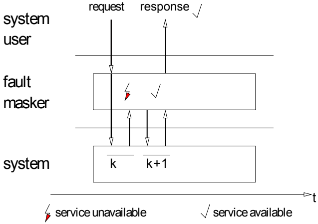

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the fault masker detects all faults

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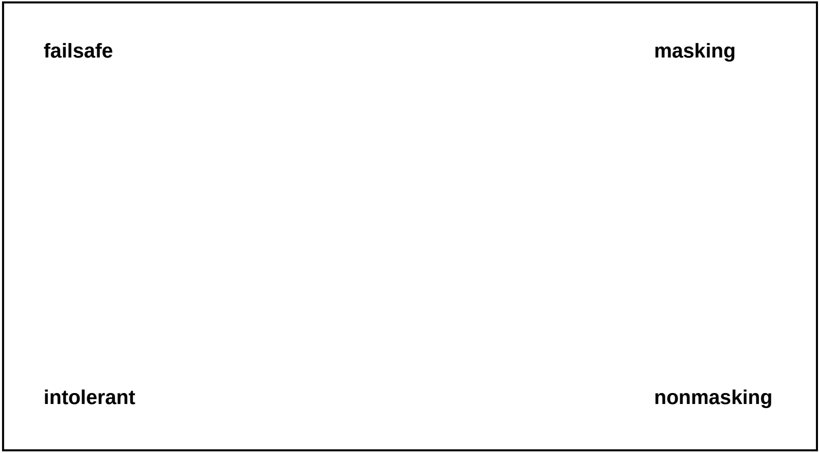

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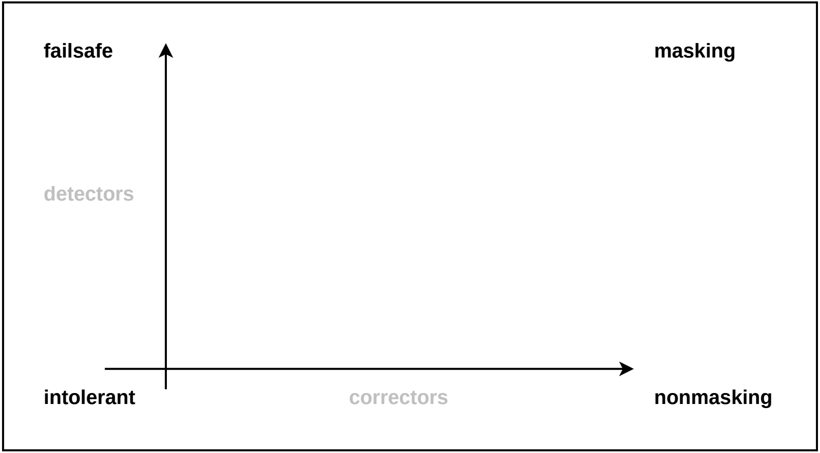

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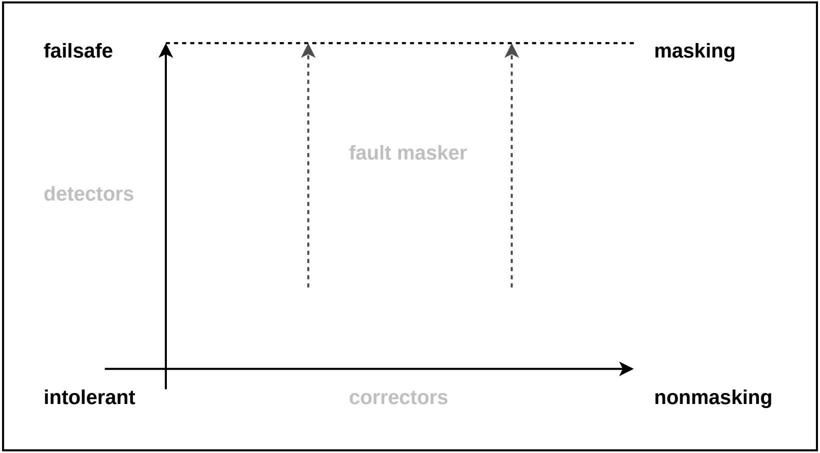

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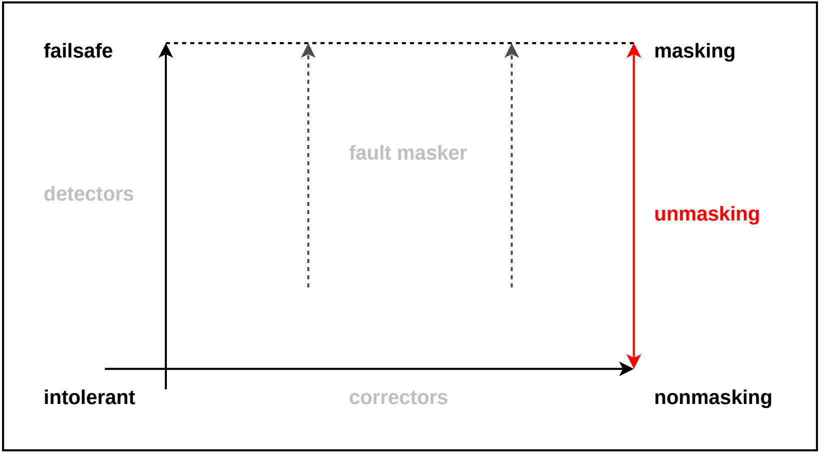

Redundancy Establishes Detection and Correction

- information redundancy
  - error correcting or detecting codes
  - N-Modular Redundancy
- temporal Redundancy
  - self-stabilization
  - re-requests
  - N-Modular Redundancy

Focus: Correction Based on Temporal Redundancy (e.g., Self-Stabilization)

information redundancy: thoroughly discussed

- we can compute the quality of spatial redundancy (i.e., number and severity of faults covered, either in a masking or non-masking fashion)
- spatial redundancy commonly used to ensure data integrity

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temporal redundancy (assuming detection as given):

- commonly used for system integrity
- how good can time heal/cure the system from faults?
- what is a proper metric?
- how can we calculate this metric?

Self-Stabilization

Definition (Self-Stabilization [Dol00, Dij74])

A system is self-stabilizing wrt. a safety predicate $\mathcal{P}$ iff:

1. *Starting from any state, it is guaranteed that the system will eventually reach a state that satisfies the safety predicate $\mathcal{P}$ (**convergence** property), provided that no fault happens.*
2. *Given that the system satisfies the safety predicate, it is guaranteed to stay in a state that satisfies the safety predicate $\mathcal{P}$ (**closure** property), provided that no fault happens.*

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A Suitable Metric 1/2

Definition (Limiting Window Availability (*LWA*))

Assume that at time $t = 0$, an initial system state distribution holds that corresponds to the steady state distribution of a system. Then, Limiting Window Availability of window size w (of this system), denoted by LWA_w, $w \geq 0$, is the probability that the system has at least once reached a state satisfying $\mathcal{P}$ within the following w time steps:

$$LWA_w = prob\{\exists k, 0 \leq k \leq w : c_k \models \mathcal{P}\}$$

w is called window size.

A Suitable Metric 2/2

Definition (Limiting Window Availability Vector (*LWAV*))

The limiting window availability vector of size i (of a system), denoted by $LWAV_i$, is an i-dimensional vector of probabilities. The element in the i^{th} position is the limiting window availability of window size $i-1$ of that system: $LWAV_i := \langle LWA_0, LWA_1, \ldots, LWA_{i-1} \rangle$.

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Definition (Limiting Window Availability Vector Gradient (*LWAVG*))

The limiting window availability vector gradient of size i (of a system), denoted by $LWAVG_i$, is an i-dimensional vector of probabilities. The element in the i^{th} position is the limiting window availability of window size i minus the limiting window availability of window size $i-1$ of that system:

$$LWAVG_i := \langle LWA_1 - LWA_0, LWA_2 - LWA_1, \ldots, LWA_i - LWA_{i-1} \rangle.$$

Test Set-Up: Algorithm and Topology

const **id** $:= 0$,
var **reg**,
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Figure: Broadcast Sub-Algorithm for the Root Process

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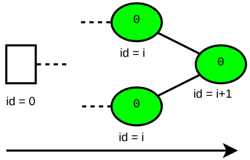

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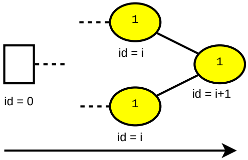

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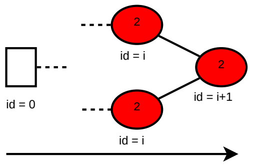

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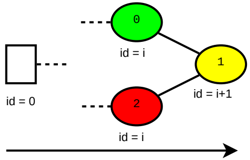

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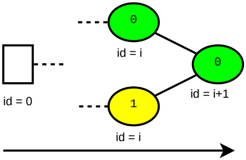

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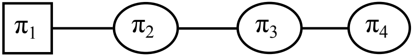

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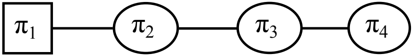
Figure: Broadcast Sub-Algorithm for the Root Process



$$c_t \models \mathcal{P} : \text{reg}_1 = 0 \wedge \text{reg}_2 = 0 \wedge \text{reg}_3 = 0 \wedge \text{reg}_4 = 0$$

<u>const</u> **neighbors** $:= \{\pi_i, \ldots\}$,
<u>const</u> **id** $:= \min\{\mathbf{id}(\pi_i), \ldots\} + 1$,
<u>var</u> **reg**,
<u>var</u> **set** $:= \{\mathbf{reg}_i, \pi(\mathbf{reg}_i) \in \mathbf{neighbors} | \forall i : \text{id}(\pi_i) = \text{id} - 1\}$
repeat$\{$
$\neg((\exists \mathbf{reg}_i : \pi(\mathbf{reg}_i) \in \mathbf{set} \wedge \mathbf{reg}_i = 2)$
$xor(\exists \mathbf{reg}_i : \pi(\mathbf{reg}_i) \in \mathbf{set} \wedge \mathbf{reg}_i = 0))$
  $\rightarrow \mathbf{reg} := 1$
$\Box \exists \mathbf{reg}_i : \pi(\mathbf{reg}_i) \in \mathbf{set} \wedge \mathbf{reg}_i = 0$
  $\rightarrow \mathbf{reg} := 0$
$\Box \exists \mathbf{reg}_i : \pi(\mathbf{reg}_i) \in \mathbf{set} \wedge \mathbf{reg}_i = 2$
  $\rightarrow \mathbf{reg} := 2\}$

Figure: Broadcast Sub-Algorithm for Non-Root Processes

The Resulting Markov Chain

$\downarrow$from/to$\rightarrow$	$\langle 0,0,0,0\rangle$	$\langle 0,0,0,2\rangle$	$\langle 0,0,2,0\rangle$	$\langle 0,2,0,0\rangle$	$\langle 2,0,0,0\rangle$
$\langle 0,0,0,0\rangle$	$p(e_1+e_2+e_3+e_4)$	qe_4	qe_3	qe_2	qe_1
$\langle 0,0,0,2\rangle$	pe_4	$p(e_1+e_2+e_3)+qe_4$			
$\langle 0,0,2,0\rangle$	pe_3		$p(e_1+e_2)+qe_3$		
$\langle 0,2,0,0\rangle$	pe_2			$p(e_1+e_4)+qe_2$	
$\langle 2,0,0,0\rangle$	pe_1				$p(e_3+e_4)+qe_1$
$\langle 0,0,2,2\rangle$		pe_3			
$\langle 0,2,0,2\rangle$		pe_2		pe_4	
$\langle 0,2,2,0\rangle$			pe_2		
$\langle 2,0,0,2\rangle$		pe_1			pe_4
$\langle 2,0,2,0\rangle$			pe_1		pe_3
$\langle 2,2,0,0\rangle$				pe_1	

Table: Transitions Grouped by Number of Operational Processes

e_i: probability, that π_i is elected for execution

q: probability, that a fault occurs

$p = 1 - q$

$e_1 = e_2 = e_3 = e_4 = 0.25,\ q = 0.01$

Compound	State	Steady State Probability
$\mathbb{0}$	$\langle 0,0,0,0 \rangle$	0.936254913358677
$\mathbb{1}$	$\langle 0,0,0,2 \rangle$	0.020767040703947
$\mathbb{1}$	$\langle 0,0,2,0 \rangle$	0.006443085000445
$\mathbb{1}$	$\langle 0,2,0,0 \rangle$	0.005896554367512
$\mathbb{1}$	$\langle 2,0,0,0 \rangle$	0.004721801275921
$\mathbb{2}$	$\langle 0,0,2,2 \rangle$	0.011734460936930
$\mathbb{2}$	$\langle 0,2,0,2 \rangle$	0.000103249069863
$\mathbb{2}$	$\langle 0,2,2,0 \rangle$	0.003596242185866
$\mathbb{2}$	$\langle 2,0,0,2 \rangle$	0.000101514623954
$\mathbb{2}$	$\langle 2,0,2,0 \rangle$	0.000028052478081
$\mathbb{2}$	$\langle 2,2,0,0 \rangle$	0.002411422793886
$\mathbb{3}$	$\langle 0,2,2,2 \rangle$	0.005204454376759
$\mathbb{3}$	$\langle 2,0,2,2 \rangle$	0.000049131622044
$\mathbb{3}$	$\langle 2,2,0,2 \rangle$	0.000042503806239
$\mathbb{3}$	$\langle 2,2,2,0 \rangle$	0.001243938539611
$\mathbb{4}$	$\langle 2,2,2,2 \rangle$	0.001401634860264

Table: Steady State Probability Distribution

How to Get There: State Space Analysis

1. compute transition probabilities between each pair of states
   - ⇒ (ergodic) Markov chain
2. compute steady state probability distribution
3. use steady state distribution as initial probability distribution for modified chain
4. transform set of legal states into sink
5. probability mass in set of legal states after i computation steps is LWA_i

The Markov Chain Yielding the *LWA*

↓from/to→	$\langle 0,0,0,0\rangle$	$\langle 0,0,0,2\rangle$	$\langle 0,0,2,0\rangle$	$\langle 0,2,0,0\rangle$	$\langle 2,0,0,0\rangle$
$\cancel{\langle 0,0,0,0\rangle}$	$\cancel{p(e_1+e_2+e_3+e_4)}$	$\cancel{qe_4}$	$\cancel{qe_3}$	$\cancel{qe_2}$	$\cancel{qe_1}$
$\langle 0,0,0,0\rangle$	1	0	0	0	0
$\langle 0,0,0,2\rangle$	pe_4	$p(e_1+e_2+e_3)+qe_4$			
$\langle 0,0,2,0\rangle$	pe_3		$p(e_1+e_2)+qe_3$		
$\langle 0,2,0,0\rangle$	pe_2			$p(e_1+e_4)+qe_2$	
$\langle 2,0,0,0\rangle$	pe_1				$p(e_3+e_4)+qe_1$
$\langle 0,0,2,2\rangle$		pe_3			
$\langle 0,2,0,2\rangle$		pe_2		pe_4	
$\langle 0,2,2,0\rangle$			pe_2		
$\langle 2,0,0,2\rangle$		pe_1			pe_4
$\langle 2,0,2,0\rangle$			pe_1		pe_3
$\langle 2,2,0,0\rangle$				pe_1	

Table: Transitions Grouped by Number of Operational Processes

Limitations

- computation works for example
- but what about larger systems?
  - state space explosion is obvious
- solution: two ways
  - lumping
  - decomposition

Markov Chain Abstraction (Lumping)

- goal: smaller Markov chains

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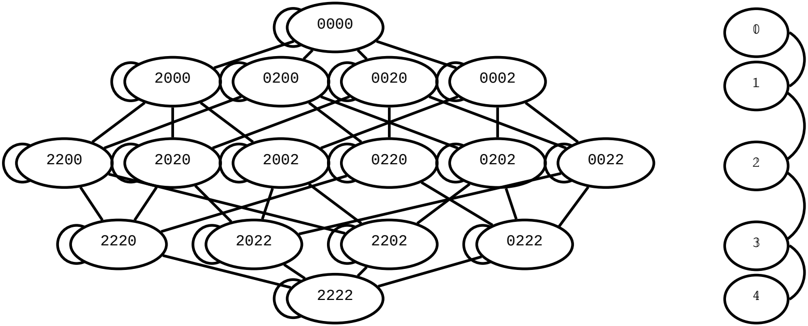
- question: what states (and transitions) can be lumped still being the *LWAV*?

Markov Chain Abstraction (Lumping)

- goal: smaller Markov chains
- lumping aggregates states and transitions
- question: what states (and transitions) can be lumped still being the *LWAV*?
- answer (for this example): all states that have the same amount of incorrect processes

Lumping Example 1/3



Lumping Example 2/3

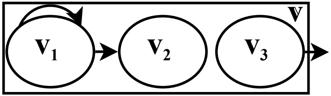
Lumping aggregates states and transitions.

Lumping Example 2/3

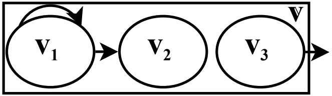
Lumping aggregates states and transitions.

$$prob(\overrightarrow{\mathbb{v},\mathbb{w}}) = \frac{\sum_{i=0}^{n}\sum_{j=0}^{m} p(\overrightarrow{v_i, w_j}) \cdot p(v_i)}{\sum_{i=0}^{n} p(v_i)}$$

Lumping Example 3/3

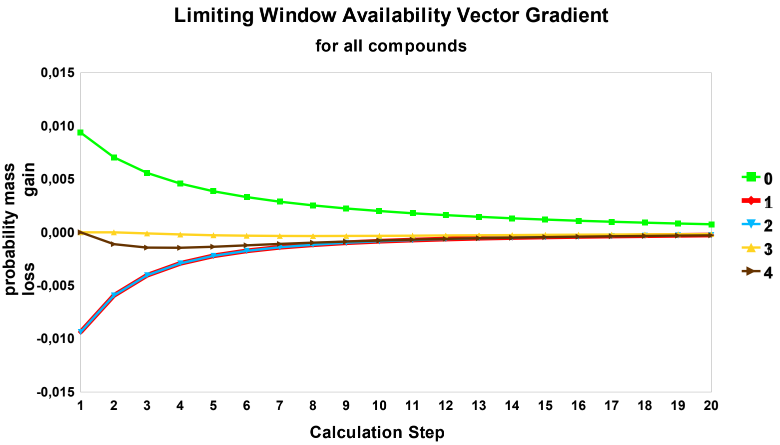


Lumping Example 3/3

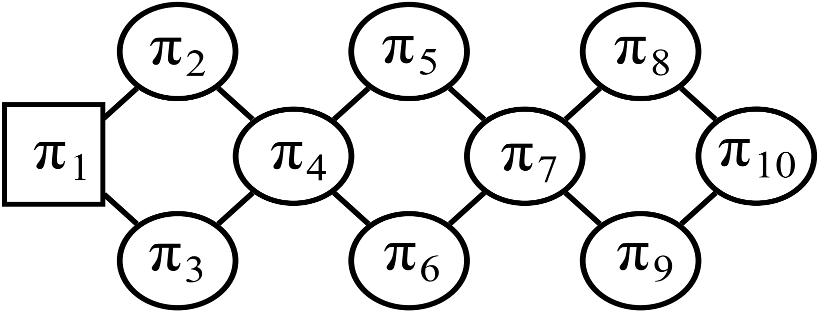


$$p(\overrightarrow{\mathbb{V}, \mathbb{V}}) = \frac{p(\overrightarrow{v1, v1}) \cdot p(v1) + p(\overrightarrow{v1, v2}) \cdot p(v1)}{p(v1) + p(v2) + p(v3)}$$

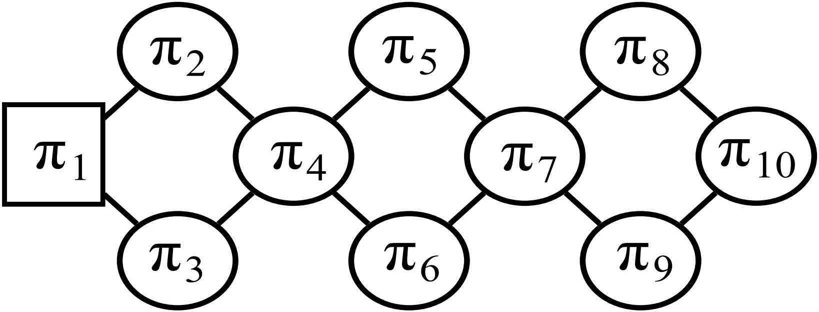
Small Example: Result



LWA at Large



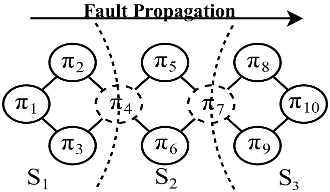
LWA at Large

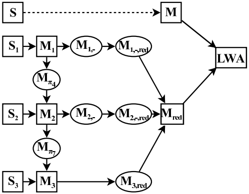


17496 state Markov chain

Decomposing and Lumping

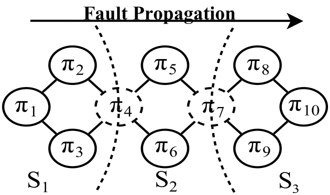
- lumping aggregates states that have something in common

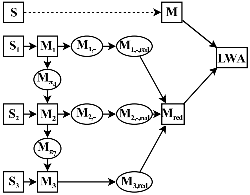




Decomposing and Lumping

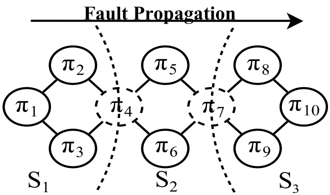
- lumping aggregates states that have something in common
- here: lumping of states that have the same amount of defective processes in common

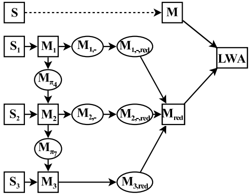




Decomposing and Lumping

- lumping aggregates states that have something in common
- here: lumping of states that have the same amount of defective processes in common
- decomposition allows the construction of (much) smaller sub-Markov chains

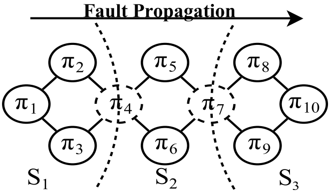


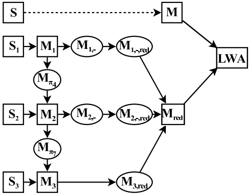


Decomposing and Lumping

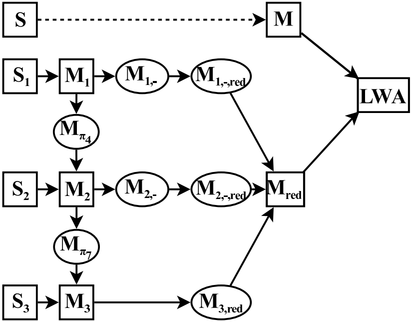
- lumping aggregates states that have something in common
- here: lumping of states that have the same amount of defective processes in common

- decomposition allows the construction of (much) smaller sub-Markov chains
- recomposition of smaller lumped Markov chains yields the exact result (80 instead of 17496 states)



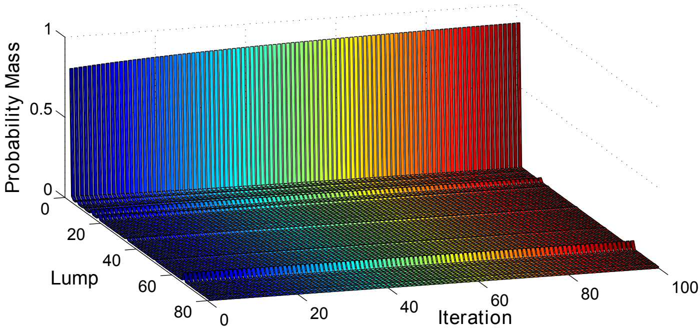


Decomposition Scheme

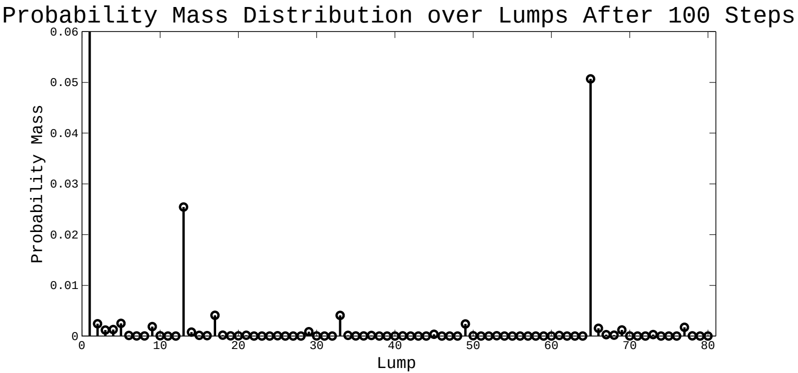


M	comprises 17496 states	$M_{1,-}$	comprises 8 states
M_1	comprises 24 states	$M_{2,-}$	comprises 27 states
M_2	comprises 81 states	$M_{1,-,red}$	comprises 3 states
M_3	comprises 81 states	$M_{2,-,red}$	comprises 3 states
M_{π_4}	comprises 3 states	$M_{3,red}$	comprises 4 states
M_{π_7}	comprises 3 states	M_{red}	comprises 80 states

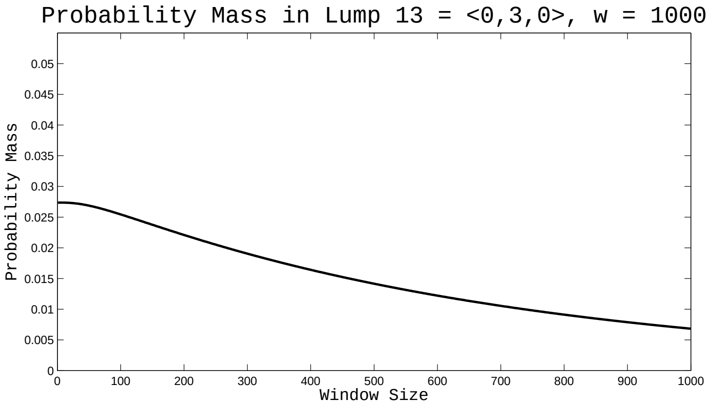
LWAV Over lumps



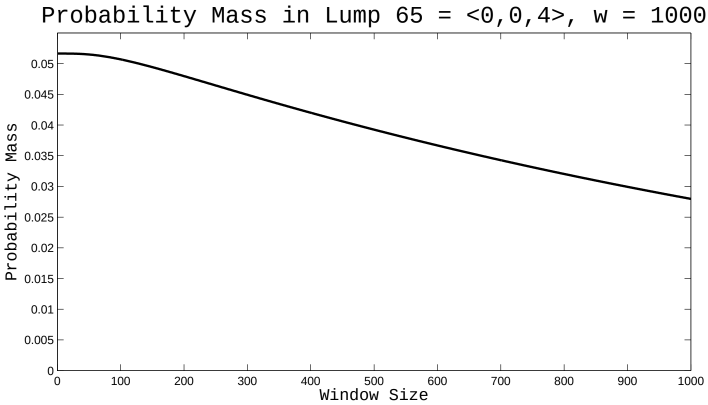
LWAV Over lumps



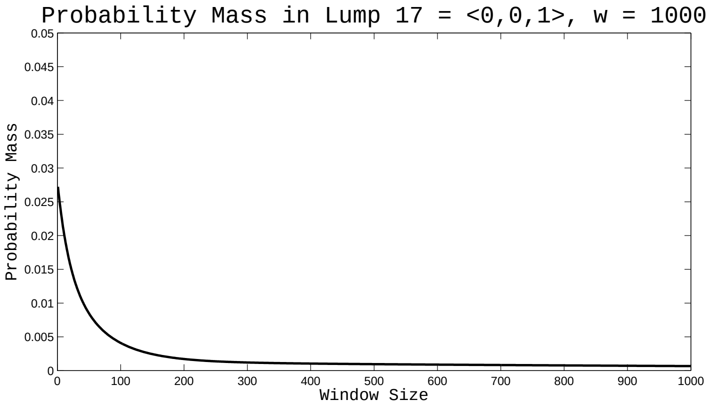
LWAV Over lumps



LWAV Over lumps



LWAV Over lumps



Hierarchical Towards Heterarchical Systems 1/2

- fault propagation unidirectional

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- decomposition easy: no cyclic dependencies

Hierarchical Towards Heterarchical Systems 1/2

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- decomposition easy: no cyclic dependencies
- what about any-way propagation

Hierarchical Towards Heterarchical Systems 2/2

- hierarchical self-stabilizing systems demand a hierarchy (order) among the processes. Fault propagation strictly occurs from root towards leafs.

Hierarchical Towards Heterarchical Systems 2/2

- hierarchical self-stabilizing systems demand a hierarchy (order) among the processes. Fault propagation strictly occurs from root towards leafs.

- semi-hierarchical self-stabilizing systems possess the ability to dynamically reassign the role of the root. Switching the root is called an epoch. Fault propagation during an epoch is unidirectional.

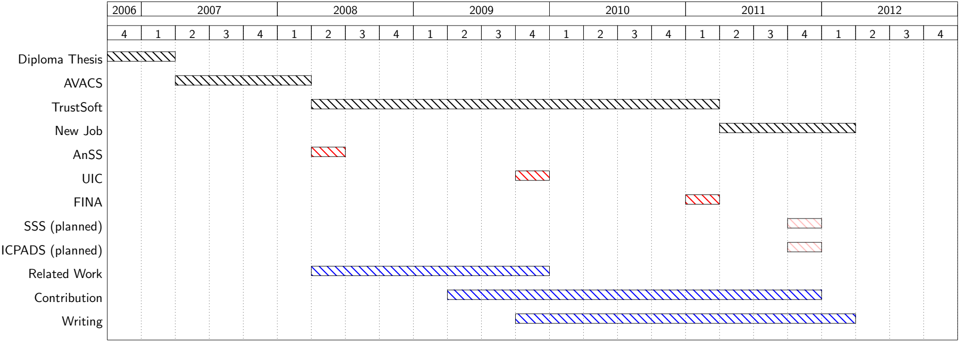
Hierarchical Towards Heterarchical Systems 2/2

- hierarchical self-stabilizing systems demand a hierarchy (order) among the processes. Fault propagation strictly occurs from root towards leafs.

- semi-hierarchical self-stabilizing systems possess the ability to dynamically reassign the role of the root. Switching the root is called an epoch. Fault propagation during an epoch is unidirectional.

- heterarchical self-stabilizing systems achieve their goal in the absence of any order among the processes. Fault propagation can occur in any direction at any time.

Timeline


2006
2007
2008
2009
2010
2011
2012
4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Diploma Thesis
AVACS
TrustSoft
New Job
AnSS
UIC
FINA
SSS (planned)
ICPADS (planned)
Related Work
Contribution
Writing

Current Focus

- FINA - 22.-25. March
  - *LWA*, *LWAV*, and *LWAVG*
  - the computation thereof,
  - basics of lumping
    ⇒ will be presented next month at 7^{th} Int'l Symposium on Frontiers of Systems and Network Applications
- SSS - 22. April: system decomposition of hierarchical self-stabilizing systems
- ICPADS - 24. June: system decomposition of heterarchical self-stabilizing systems
  either by iterations, or maybe flow equations...
- writing it up

Unmasking Fault Tolerance

goal: determination of the sweet spot

- be as masking as possible
- with as little effort as possible

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- be as masking as possible = maximize degree of masking fault tolerance
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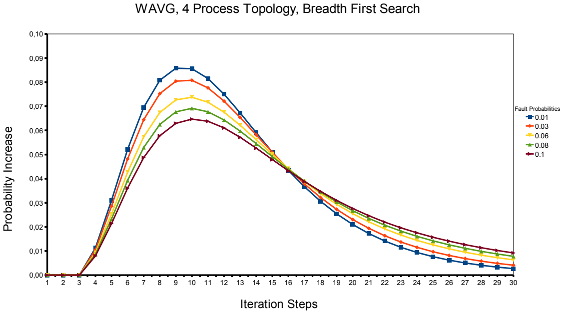

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Unmasking Fault Tolerance: Masking vs. Non-masking Fault-tolerant Systems

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