Composing, Analyzing and Validating Models to Assess the Performability of Competing Design Candidates

School of Electrical Engineering
and
Computer Science

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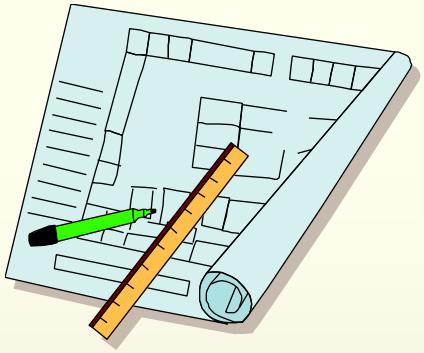
Research Agenda



Goal: *Verification* and *validation* of *systems* and *software*

Modern high-assurance systems

Advantages of a formal approach

How do we get there from here: Modeling Cycle

Safety and reliability analysis:

- Railroad Switching System *including* Design-to-Cost
- Vehicle Braking/Traction/Steering Control System
- Operating System with Dynamic Priority Mechanism

Summary of ongoing work

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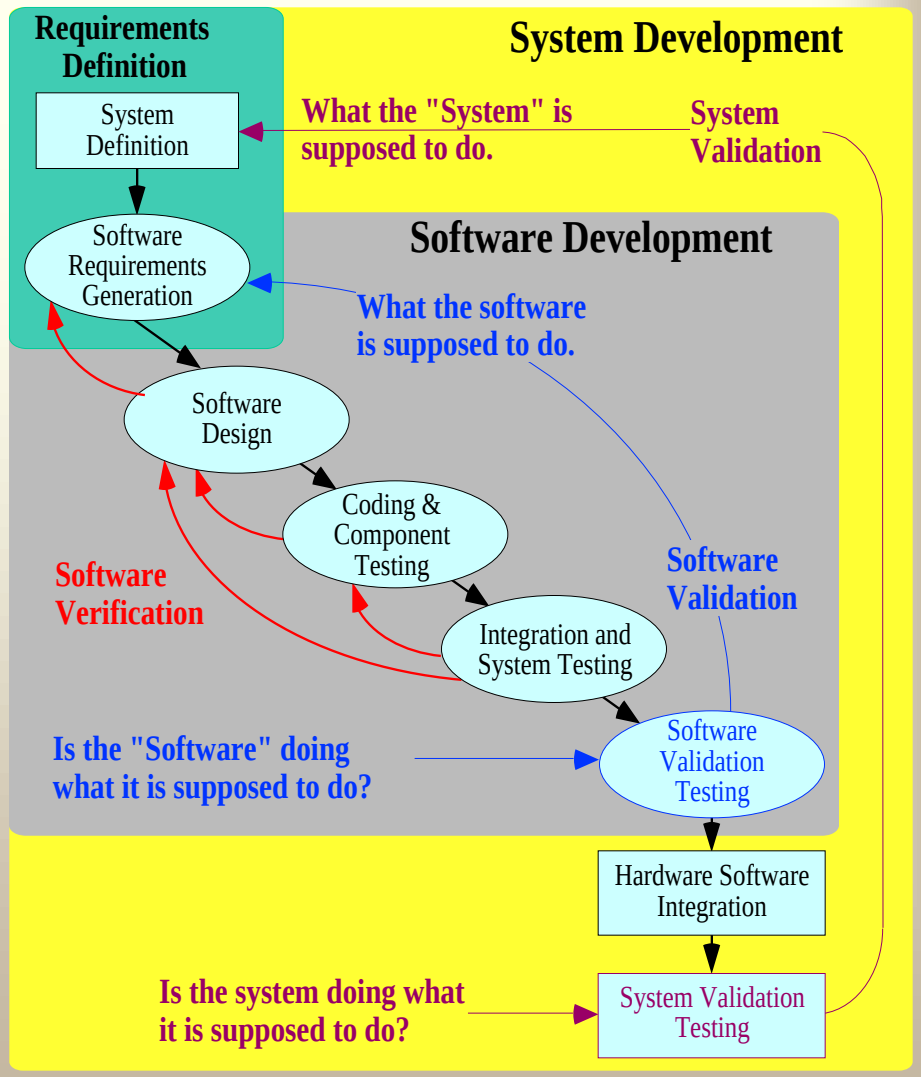
Verification and *Validation*

Verification determines if the products of a given phase of the **SW life cycle** fulfill the **requirements** established during the previous phase.

> Formal proof of **program** correctness
>
> Reviewing, inspecting, **testing,** checking, auditing, or otherwise establishing and documenting whether or not items, **processes,** services, or **documents** conform to specified **requirements** (ANSI/ASQC A3-1978).

Validation checks ***if*** the program, as implemented, meets the expectations of the customer in such a way to ensure compliance with software requirements**.**



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Modern High-Assurance Systems

Share five key attributes:

- **Reliable,** meaning they are correct,
- **Available,** meaning they remain operational,
- **Safe,** meaning they are impervious to catastrophe (fail-safe),
- **Secure,** meaning they will never enter a hazardous state,
- **Timely,** meaning their results will be produced on time and satisfy deadlines (timing correctness).

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Advantages of Formal Specification

Provides insights into the requirements / design

Specifications may be analyzed mathematically

Demonstrate *consistency* and *completeness*

Prove the implementation corresponds to the specification

Help identify appropriate *test cases*

Characterize aspects of the specification more precisely:

- Structural, Functional, and Logical
- Behavioral
  - Dynamic: timing combined with probabilistic nature
- Data oriented.

And, the potential for cost savings….

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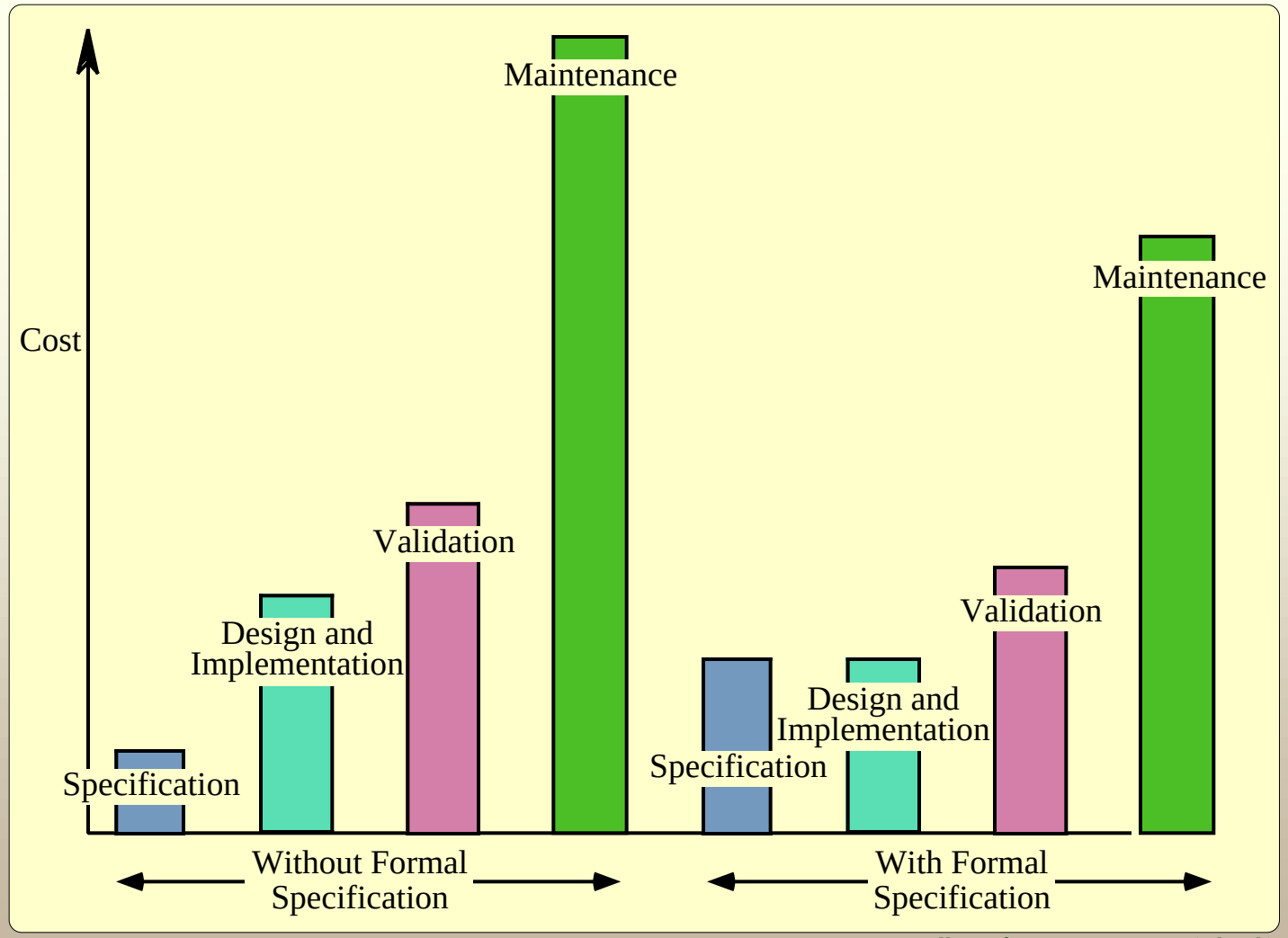
Expenditure Profile Changes



From Ian Sommerville, Software Engineering (5th Ed.)

The Vision

Methods and tools are needed for the creation of safe and correct systems. . .

Reduce the effort of constructing reliable models for . . .

- Application level safety, performance and reliability analysis
- Improved tractability for verifying correctness and for solving large stochastic models
- Reasoning about unambiguous specifications and designs

Need for an integrated environment to provide interoperability among formalisms

- Link stochastic analysis with correctness checking
- Allow various formal methods to be applied independently based on a common representation form.
- Demonstrate on industrial strength problems
- Learn what works and what doesn't

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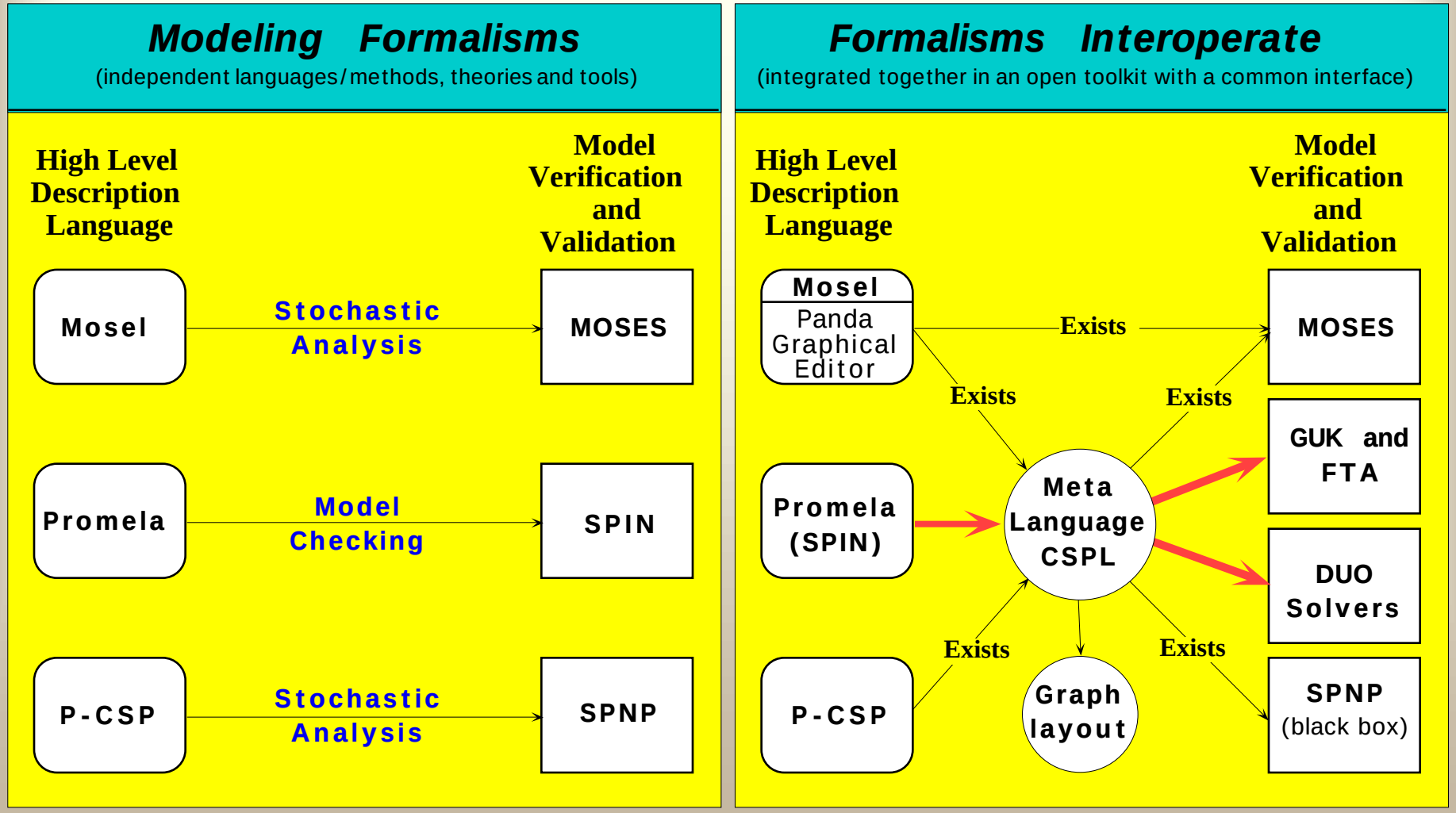
Integrated Environment to Provide Interoperability



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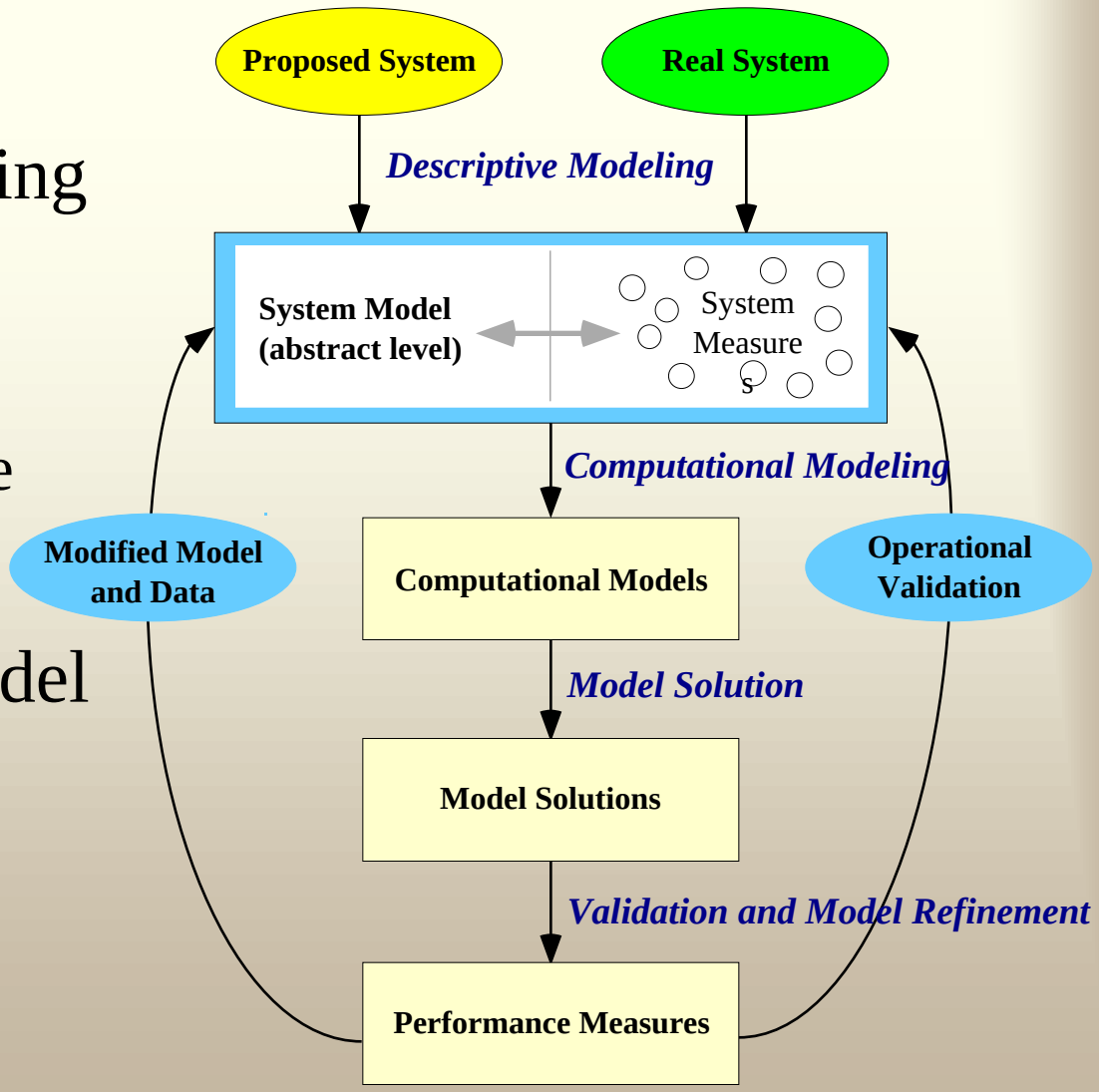
The Modeling Cycle

- Descriptive modeling
- Computational modeling
  - Making it tractable
- Model solution
- Validation and model refinement
  - Operational
  - Proposed



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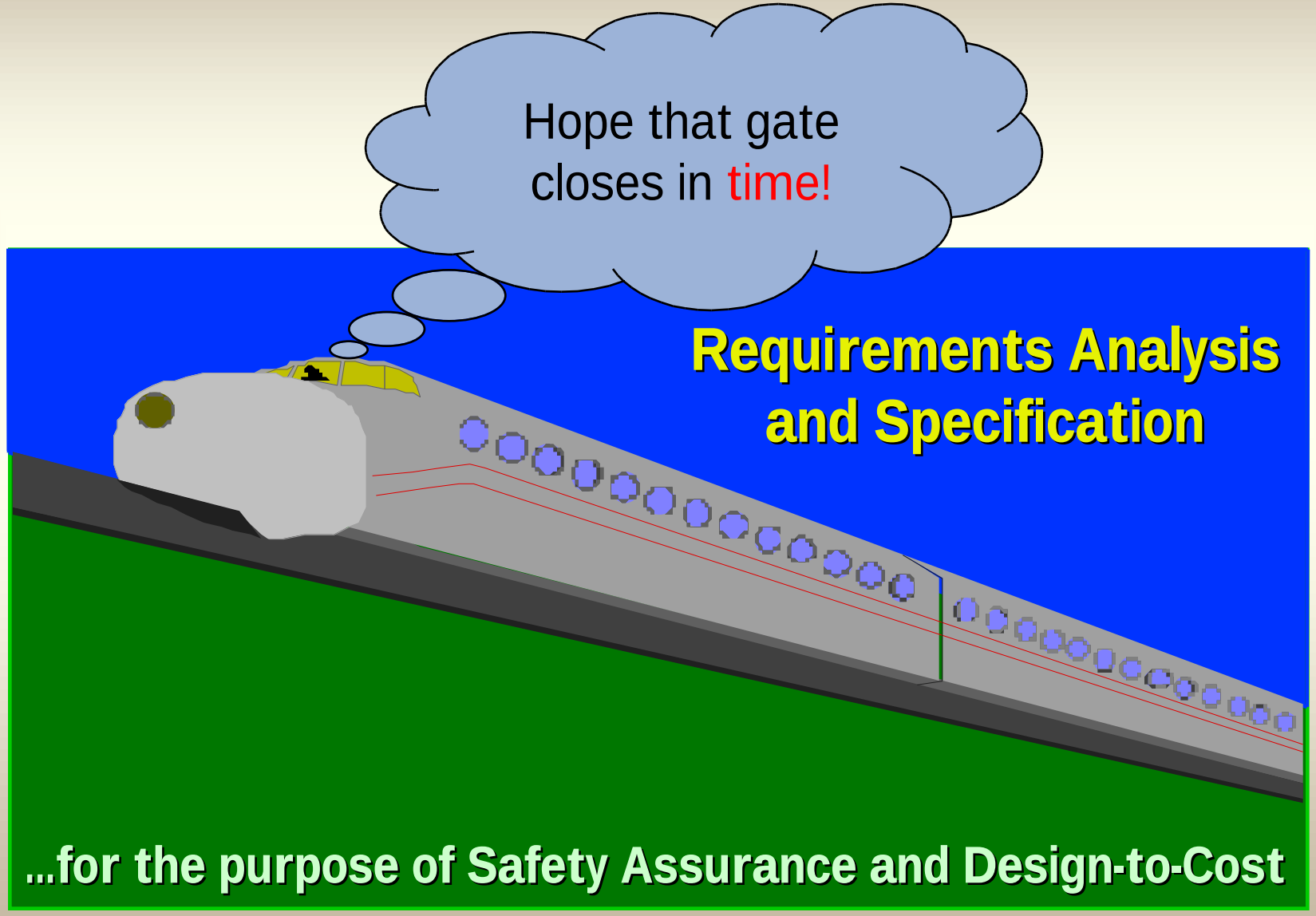
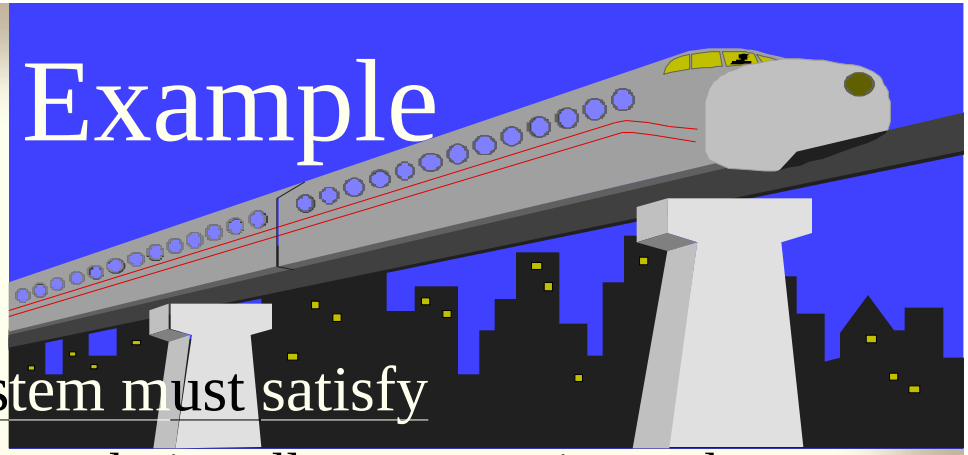
Railway Switching System



Railway Switching Example



Requirements:

Two Basic Properties the system must satisfy

Safety property – the gate is down during all occupancy intervals

Utility property – the gate is open when no train is in the crossing

The Solution in General Terms:

- Two Processes: The TRAIN and the GATE
- TRAIN sends an "arriving" signal to the GATE as it nears the intersection and proceeds towards the intersection.
- GATE, upon receiving the signal, closes the gate and remains closed until the train departs.
- TRAIN sends a "departing" signal after leaving the intersection.
- GATE, upon receiving the signal opens the gate and remains open.
- The two processes repeat continuously.

This model encompasses the environment which includes the train(s) and the gate, as well as the interface between them.

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Compose a Functional Model Using the Process Algebra CSP translated to SPNs

TRAIN =

(IN_TRANSIT);

(GATE ! a → AT_INTERSECTION);

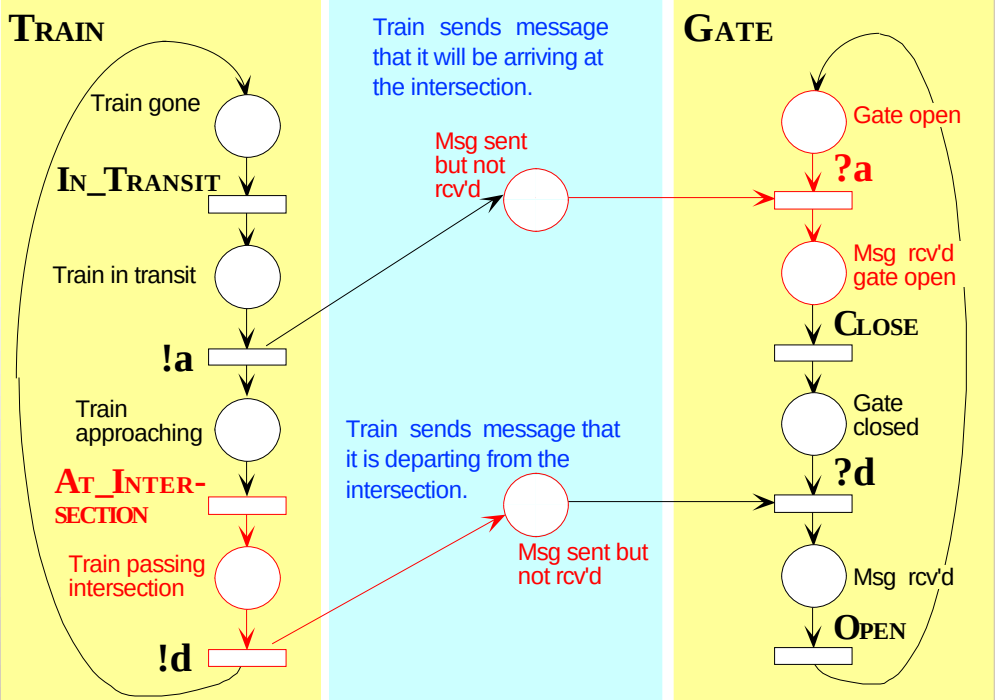
(GATE ! d → TRAIN)

GATE =

(TRAIN ? a → CLOSE);

(TRAIN ? d → OPEN → GATE)

RAIL_ROAD_CROSSING = TRAIN $\|_{\{a,d\}}$ GATE



Several possible failure modes exist: (1) communication failure [t_2, t_4, t_5 and t_7], (2) mechanical failure [t6 and t9], and (3) timing failure [t_3 occurs before t_6] (i.e., train arrives at intersection before the gate has closed).

- **Problem:** A hazard exists which becomes *more* evident viewed as a Petri net

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Refined System Model

Hazard Removed

TRAIN =

(IN_TRANSIT);

(GATE ! a → GATE ? ok → AT_INTERSECTION);

(GATE ! d → TRAIN)

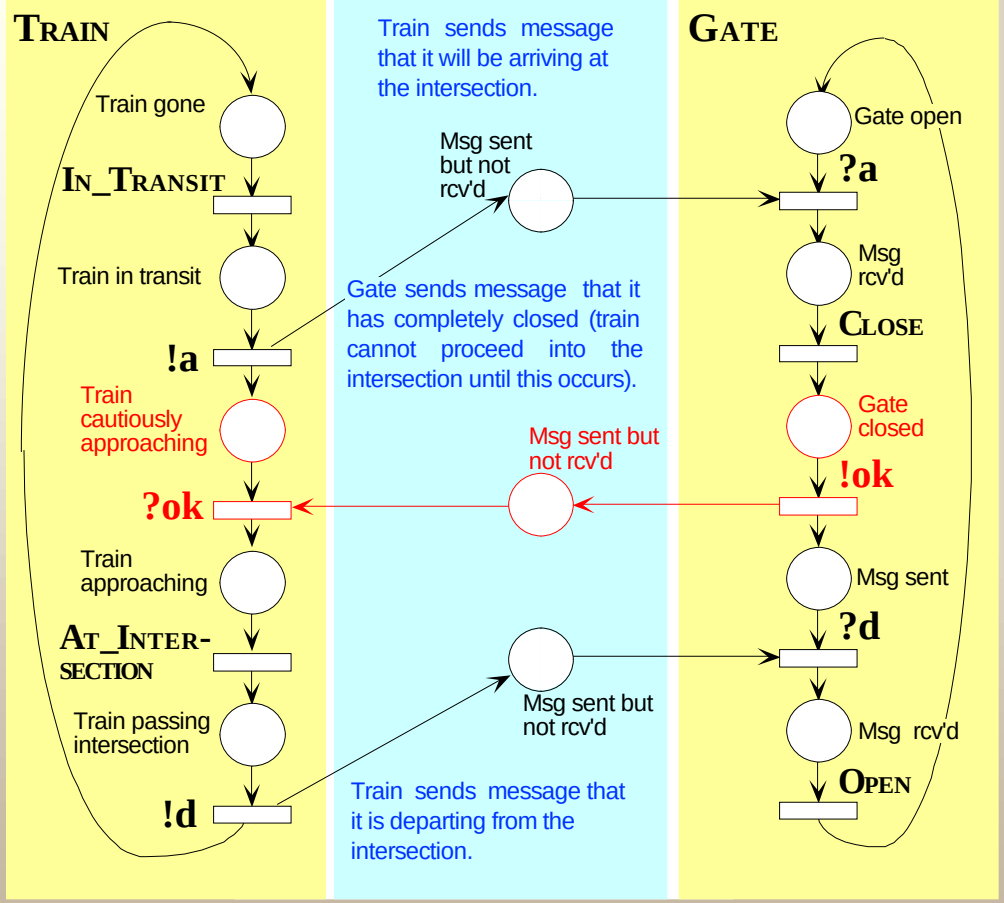
GATE =

(TRAIN ? a → CLOSE → TRAIN ! ok);

(TRAIN ? d → OPEN → GATE)

SAFER_RAIL_ROAD_CROSSING =

TRAIN $\|_{\{a,ok,d\}}$ GATE



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Lower Level Abstraction

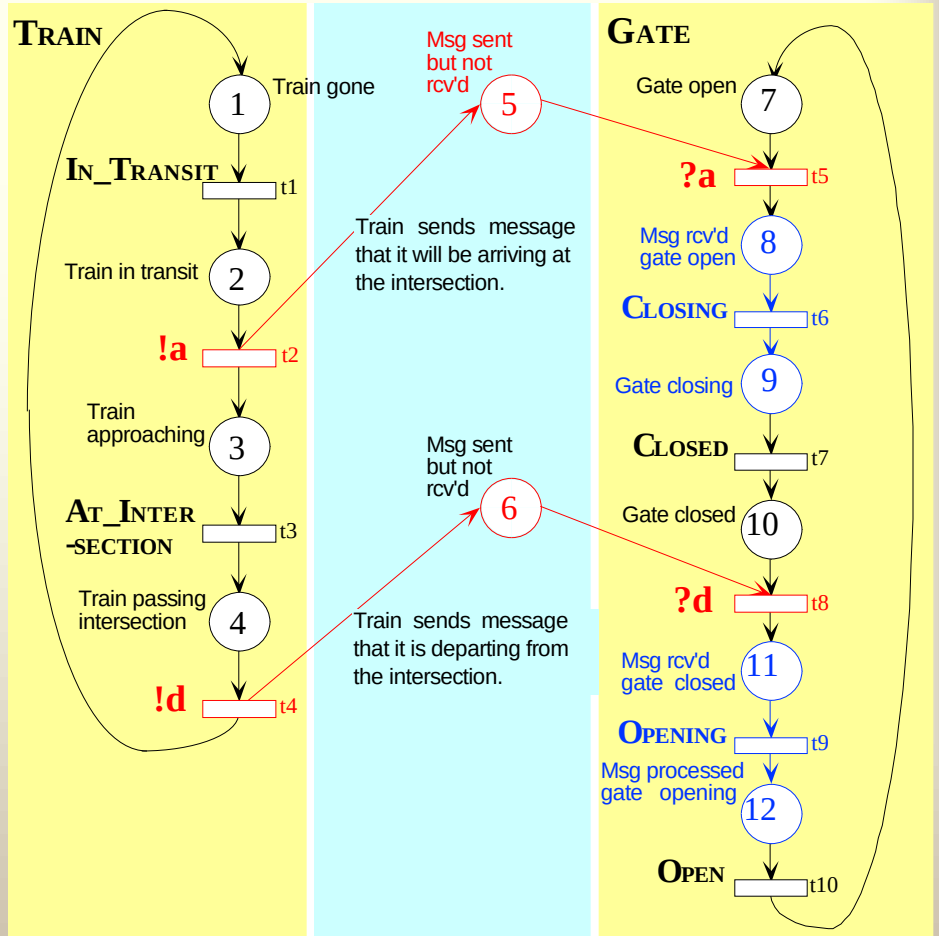
Timing hazard version

Mechanical Failures

- Safety Critical (closing)
- Cost Critical (opening)

Communication Failures

- Safety Critical (arrival message [and OK message])
- Cost Critical (departing message)



Several possible failure modes exist: (1) communication failure [t_2, t_4, t_5 and t_8], (2) mechanical failure [t6 and t9], and (3) timing failure [t_3 occurs before t_7] (i.e., train arrives at intersection before the gate has completely closed).

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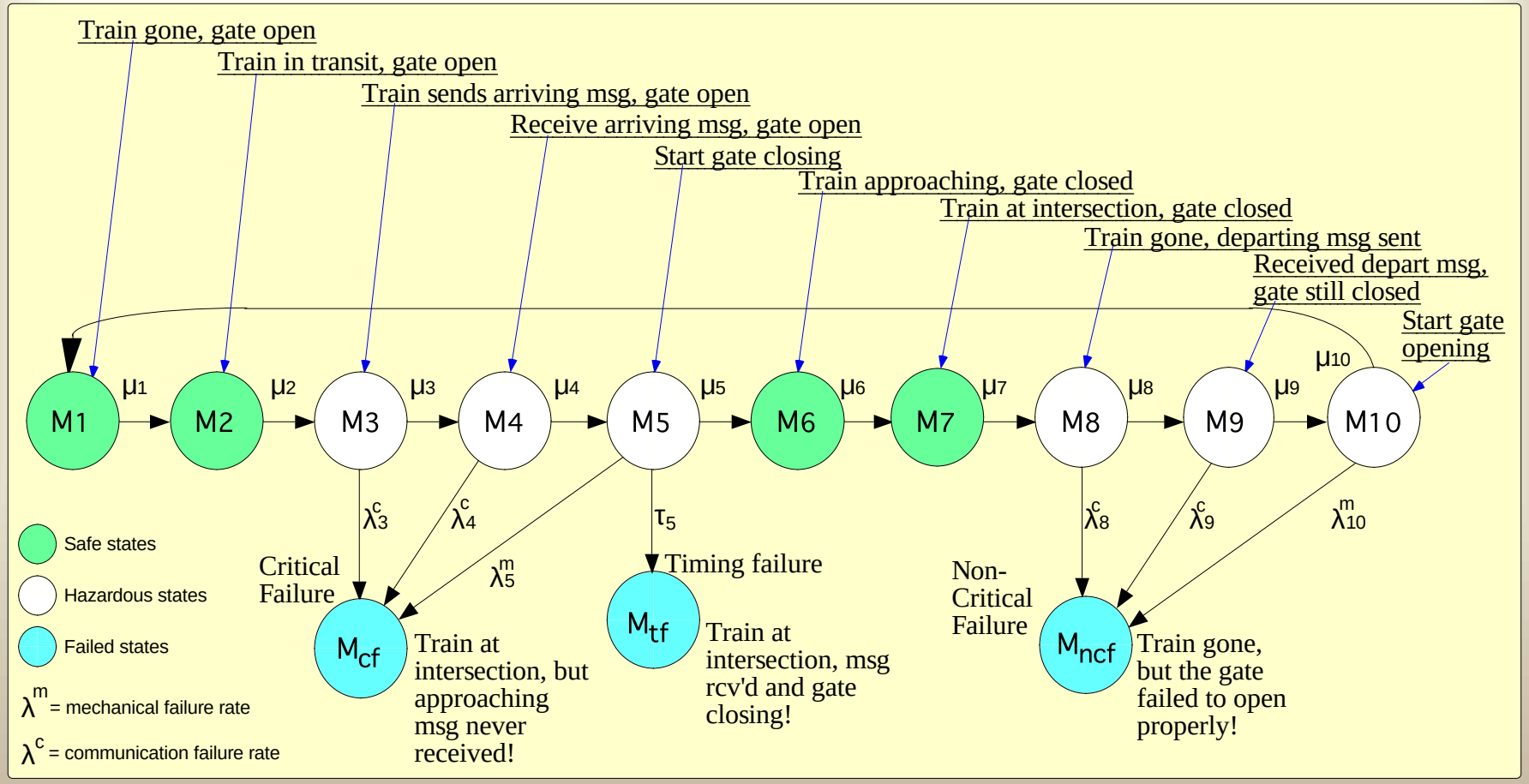
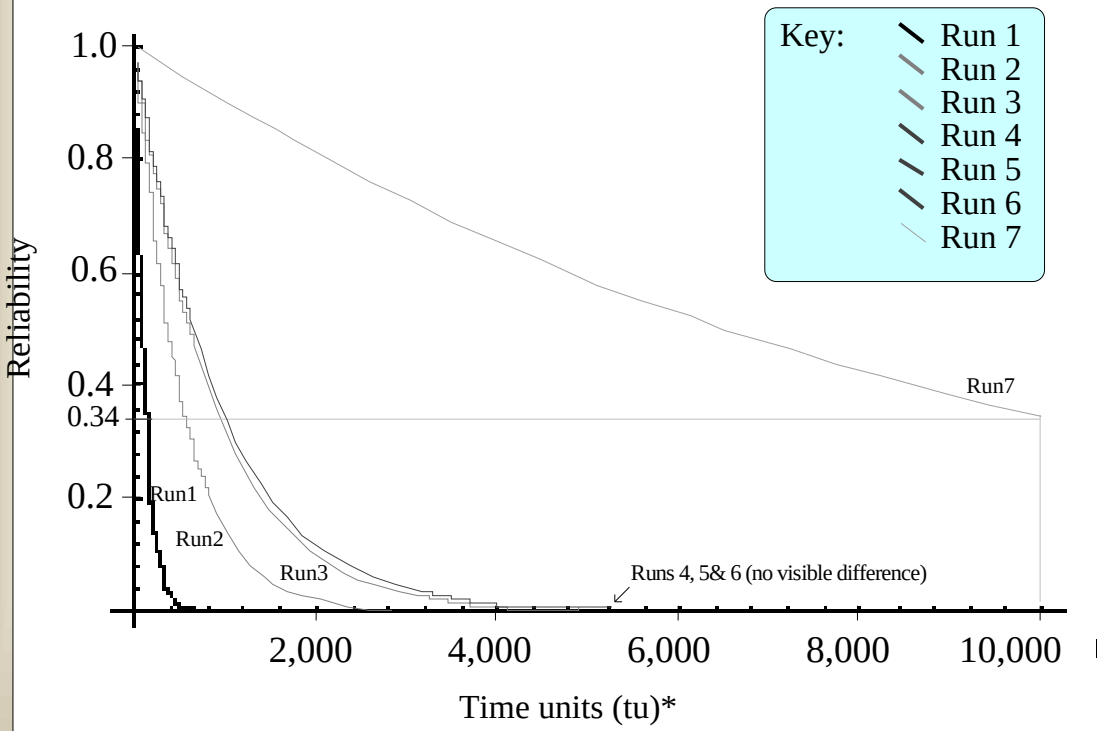
Generate the ERG/RG → Markov



Reliability Prediction



Results:

Run1....Rel[10,000]=*4.58042 x10-40*	Mttf=*1.09934 x105tus*
Run2....Rel[10,000]=*4.58554 x10-9*	Mttf=*5.20472 x105tus*
Run3....Rel[10,000]=*1.07427 x10-5*	Mttf=*8.73755 x105tus*
Run4....Rel[10,000]=*2.34974 x10-5*	Mttf=*9.37937 x105tus*
Run5....Rel[10,000]=*2.56342 x10-5*	Mttf=*9.45662 x105tus*
Run6....Rel[10,000]=*2.58888 x10-5*	Mttf=*9.46547 x105tus*
Run7....Rel[10,000]=*3.44604 x10-1*	Mttf=*6.15169 x106tus*

Input Parameters:**

1. τ5=*0.00908*	λ3, 4, 8, 9=*1.0 x10-7*	λ5, 10=*1.0 x10-4*
2. τ5=*0.000908*	λ3, 4, 8, 9=*1.0 x10-7*	λ5, 10=*1.0 x10-4*
3. τ5=*0.0000908*	λ3, 4, 8, 9=*1.0 x10-7*	λ5, 10=*1.0 x10-4*
4. τ5=*0.00000908*	λ3, 4, 8, 9=*1.0 x10-7*	λ5, 10=*1.0 x10-4*
5. τ5=*0.0*	λ3, 4, 8, 9=*1.0 x10-7*	λ5, 10=*1.0 x10-4*
6. τ5=*0.0*	λ3, 4, 8, 9=*0.0*	λ5, 10=*1.0 x10-4*
7. τ5=*0.0*	λ3, 4, 8, 9=*0.0*	λ5, 10=*1.0 x10-5*

*Time units: each x-axis tick is 1000tus. If 1 tu = second, then ~16mins/tick, or 10,000 ticks ~2778hrs (full range of data).

**Constants: μ1= 0.0001, μ2-4, 7, 8= 1.0, μ9, 10= 1.0, while μ5 and μ6 = were held set at 0.1 and 0.01 respectively.

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Design-to-Cost

Evaluate (judiciously) the costs (and benefits) for providing fault-avoidance and/or fault-tolerance using a cost function to optimize design parameters.

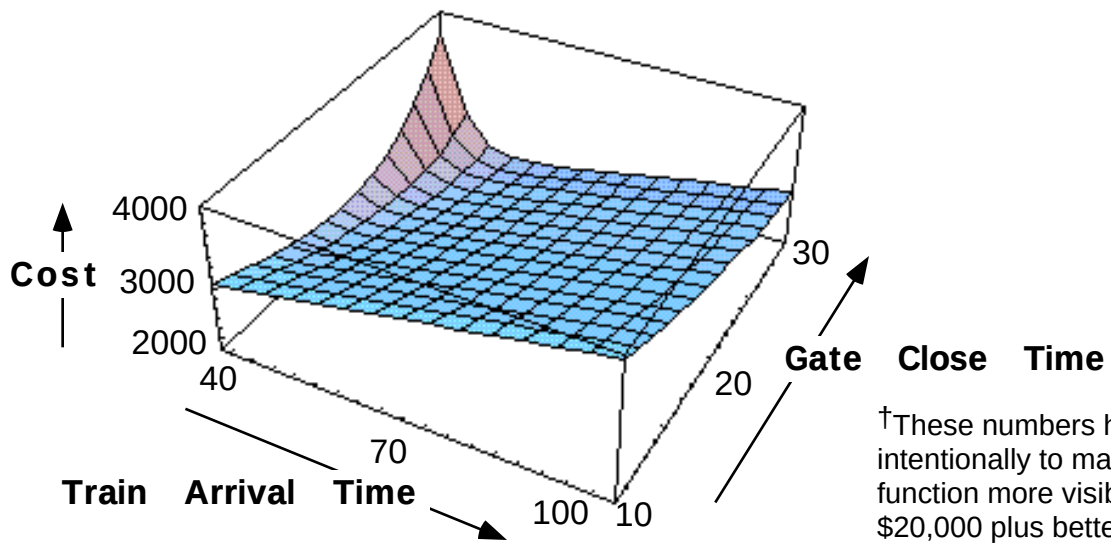
$$Q = \omega p\left(failure\right) + \varphi \int_0^\infty \theta\, p_\theta(\theta)\, d\theta + \nu$$

....where w = cost of failure, f = cost of delay/time units, n = cost of the gate/train passing and the <u>average</u> train travel time is

$$= \int_0^\infty \theta p_\theta(\theta) d\theta$$

$$\nu\,(gmpt) = \frac{\left(40 - gmpt\right)^4 + 20{,}000}{100}$$

....is the gate cost per run as a function of the gmpt (gate most probable closing time).



†These numbers have been exaggerated intentionally to make the variations of the cost function more visible. Otherwise, a gate that cost $20,000 plus better operate more than just 100 times!

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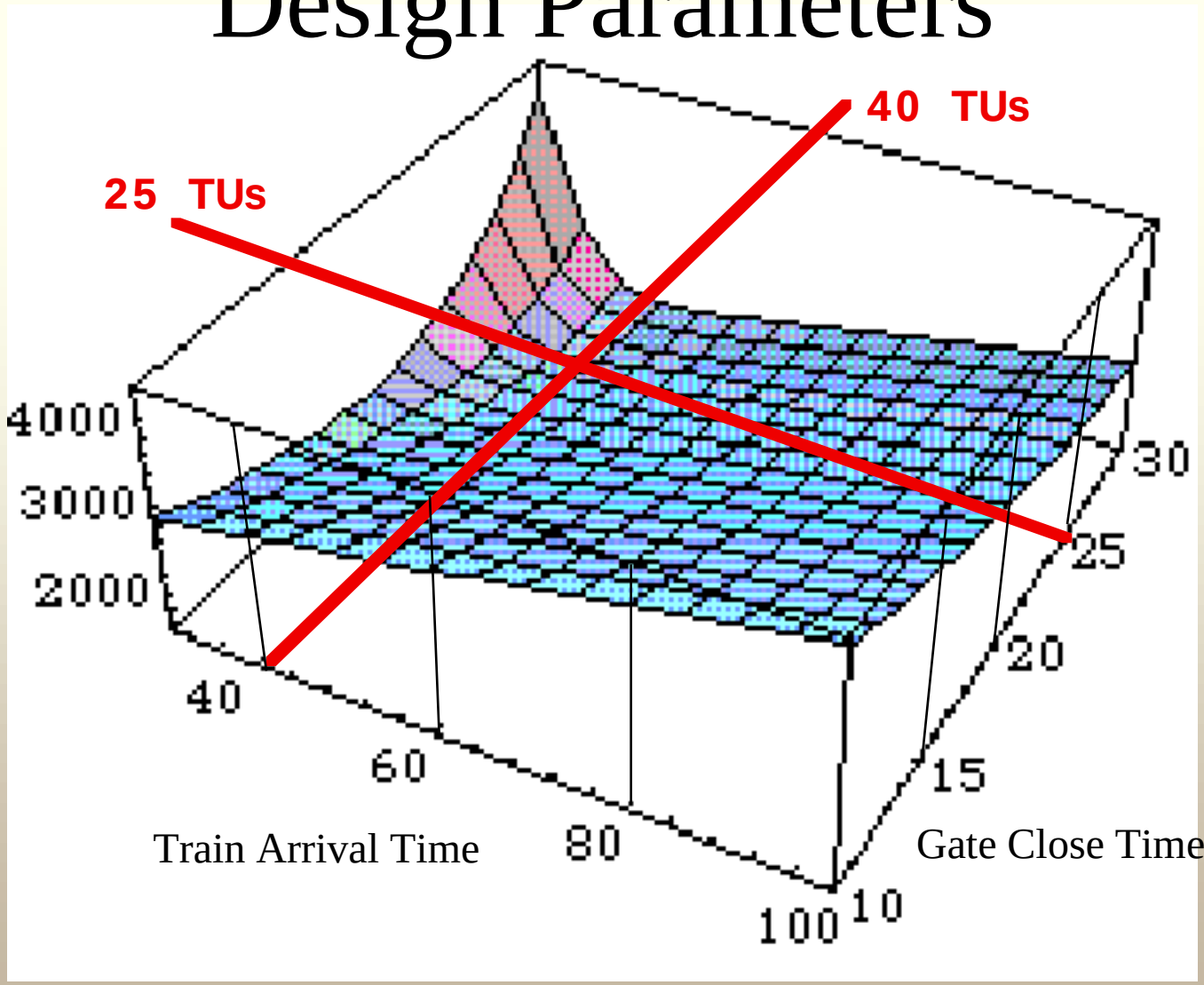
Costs May Be Correlated to Design Parameters



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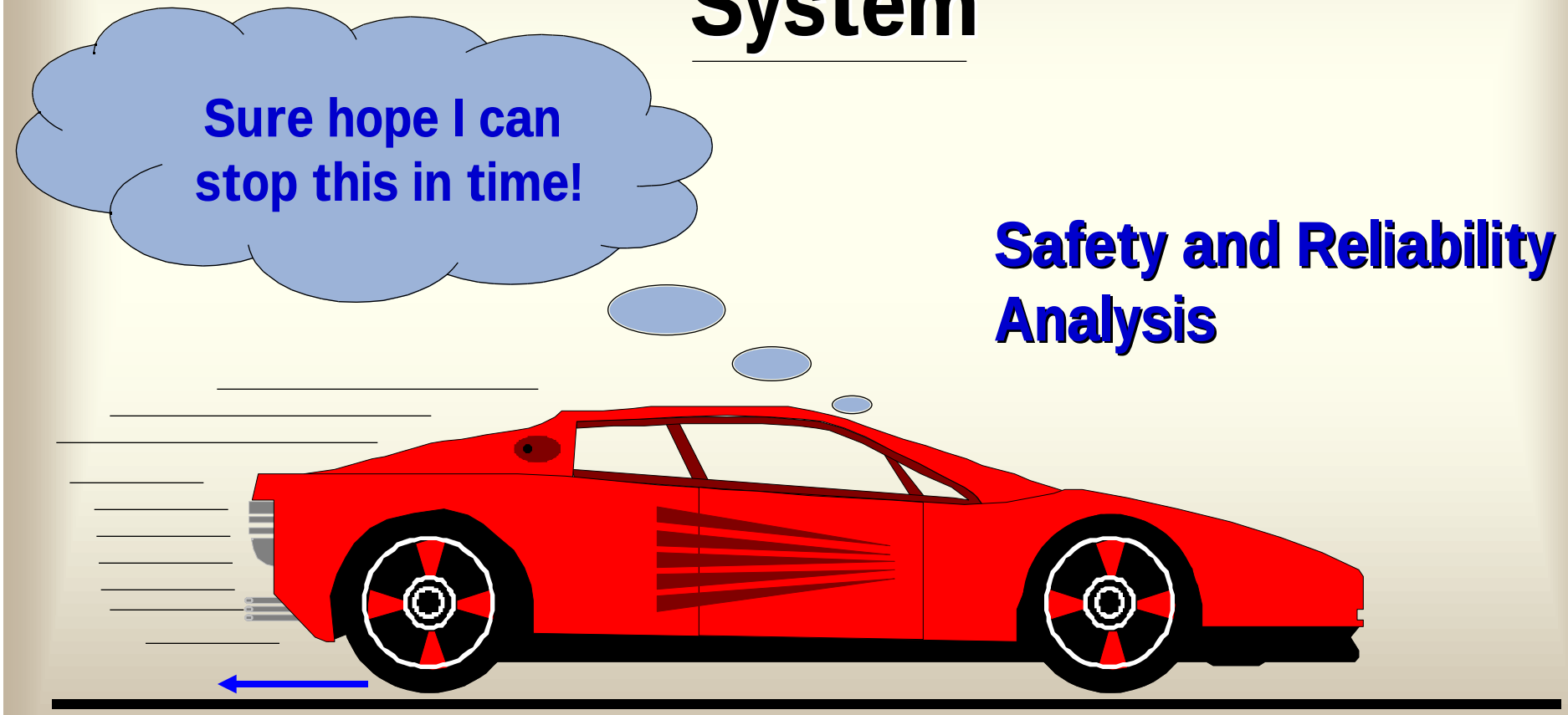
Braking / Traction / Steering Control System



Safety and Reliability Analysis

TC/ABS Functional Description

(Traction Control / Antilock Brake System)

ABS maintains steer-ability and driving stability under skidding conditions

Anti-Slip control maintains adhesion to the road and driving stability

Electronic Stability program maintains limits among yaw-rate, steering-angle, and lateral velocity preventing under/over-steer

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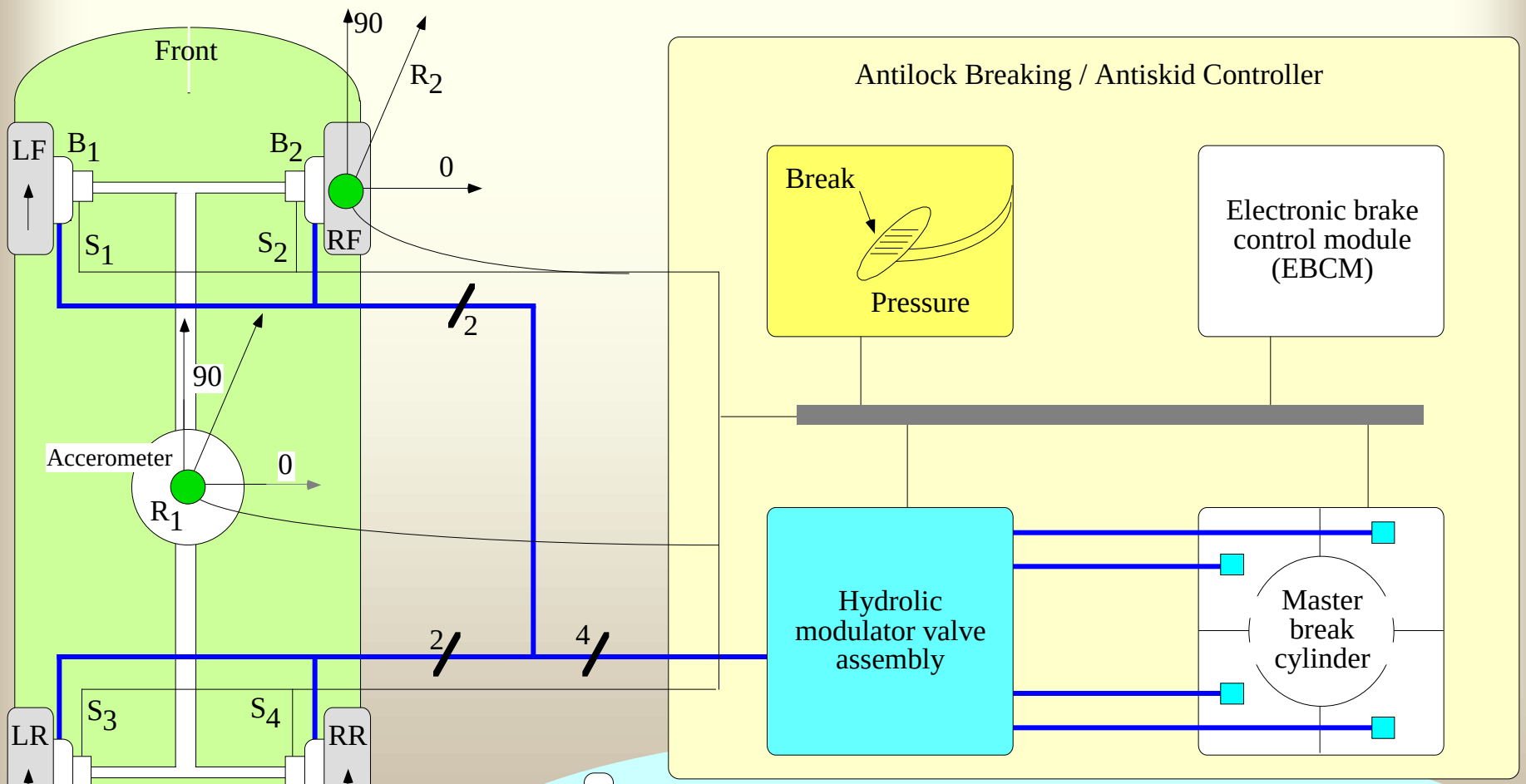
TC/ABS Schematic



Disc break (4 indpt)

Wheel speed sensor (4 indpt)

$B_{1\text{-}4}$ = Brakes (LF, RF, LR, RR)

$S_{1\text{-}4}$ = Speed sensors (LF, RF, LR, RR)

$R_{1\text{-}2}$ Turing angles (of the vehicle and the tires respectively)

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Skid+Steering Control System

If Any-Wheel-Locks **then** Pulsate-Locked-Wheel

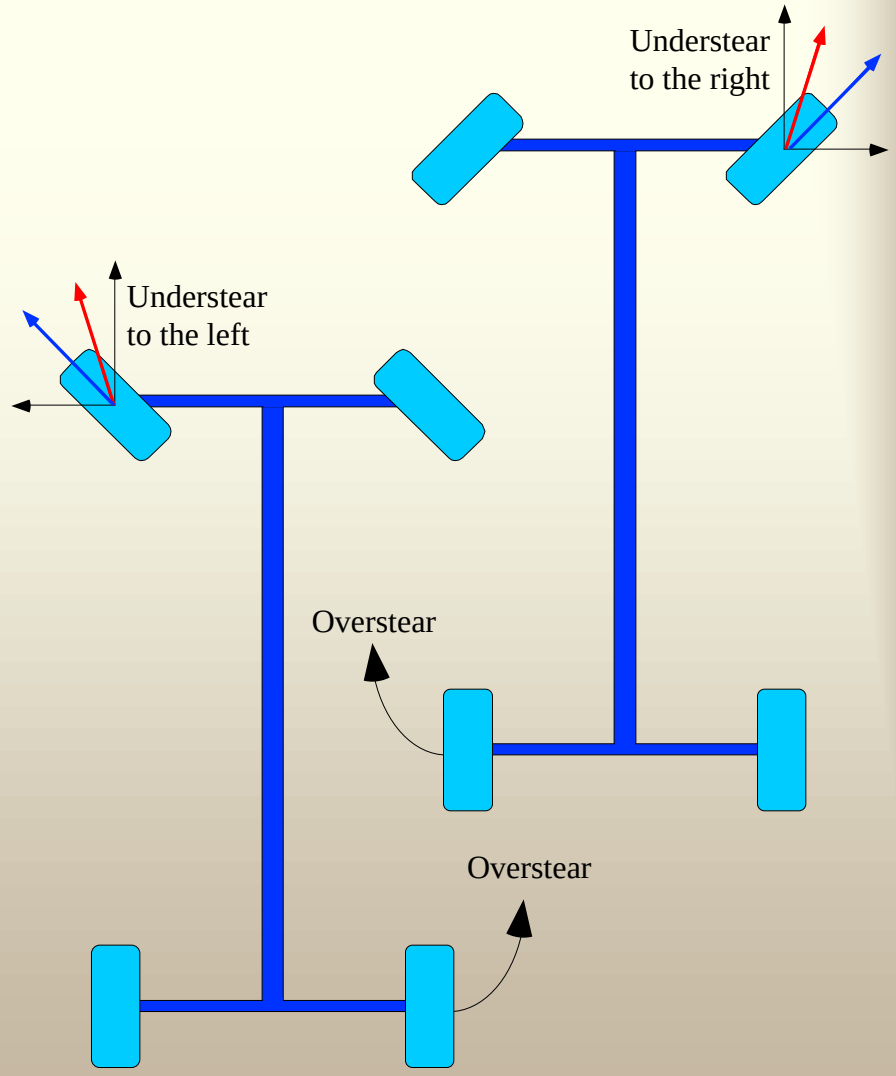
If Either-Rear-Wheel-Slips **then** Brake-Slipping-Wheel

If Under-Steer-Left **then** Brake(Left-Front, Left-Rear)

If Under-Steer-Right **then** Brake(Right-Front, Right-Rear)

If Over-Steer-Left **then** Brake(Right-Rear, Right-Front)

If Over-Steer-Right **then** Brake(Left-Rear, Left-Front)



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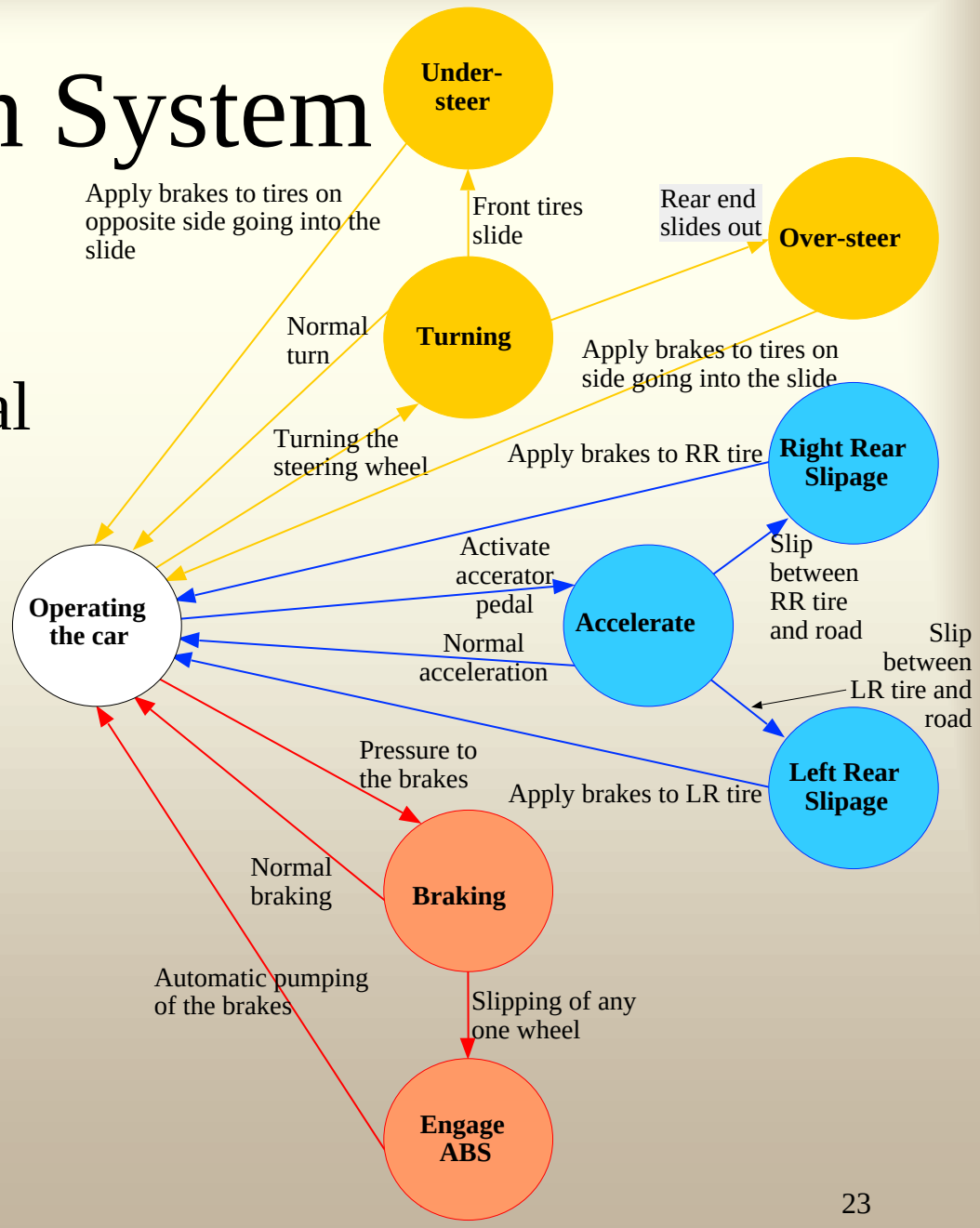
State Transition System

- Deciding how the faults affect nominal and off nominal operation
- Failure modes
  - Loss of vehicle
  - Loss of stability
  - Degraded function
  - Over/Under-steer



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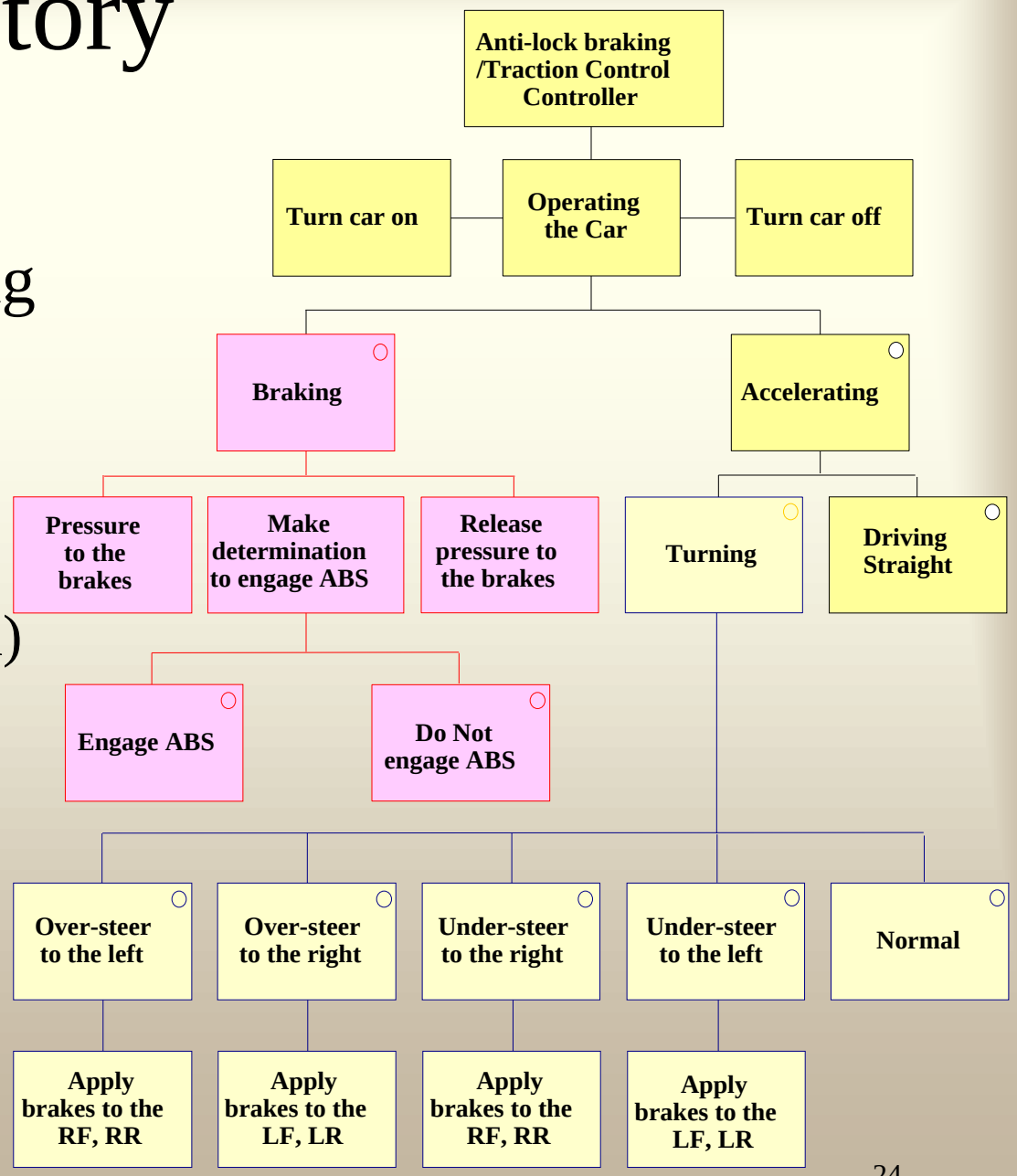
Entity Life History Diagram

- Descriptive Modeling
- View of the system
  - Braking
  - Steering
  - Skidding (not shown)
- Structure Chart
  - Invocation structure
  - Choices (pathways)
  - Flow



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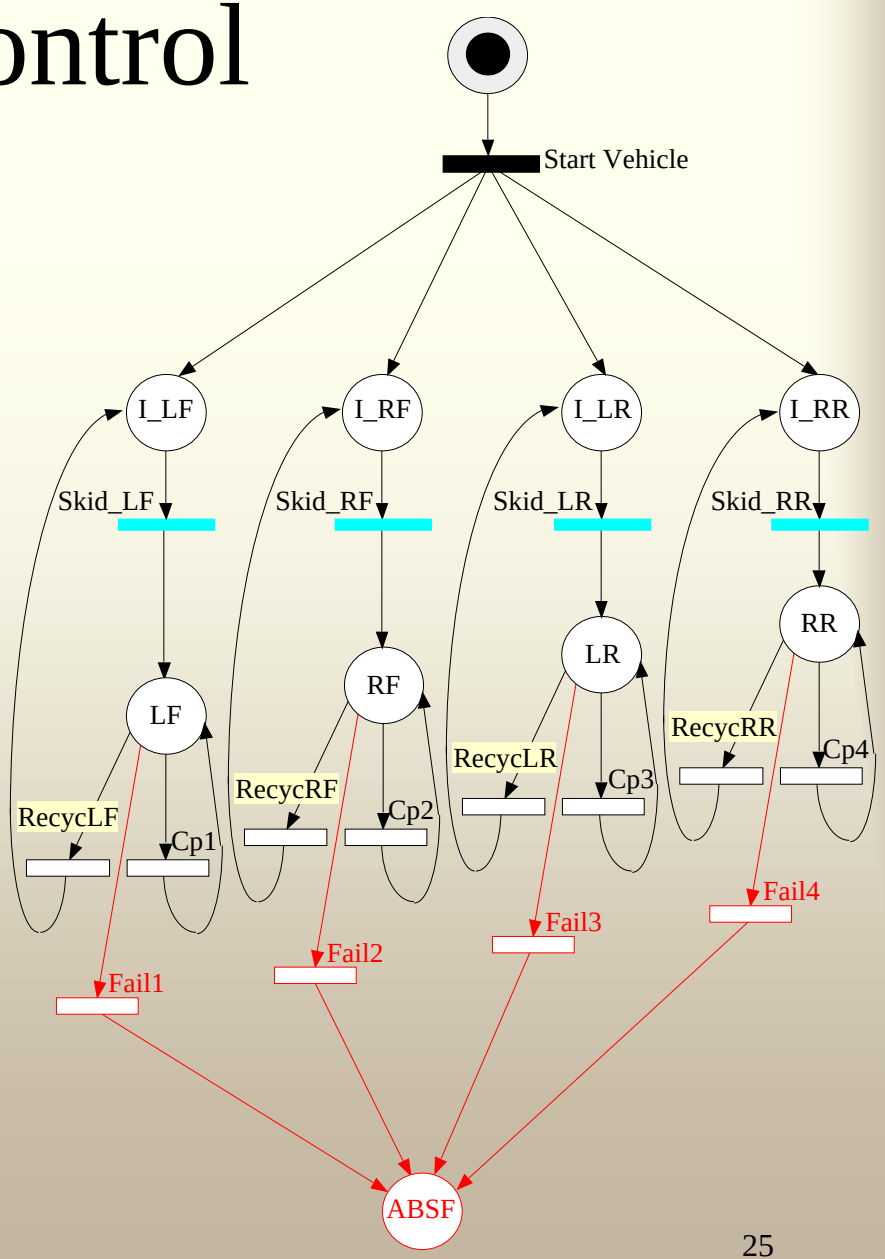
ABS Skidding Control

Computational Modeling

Skidding of any tire may be detected

- Compensation mechanism cycles (loop counter-clock-wise) until skidding ceases
- Fault may occur activating a failure mode causing:
  - Loss of vehicle
  - Loss of stability
  - Degraded function
  - Over/Under-steer



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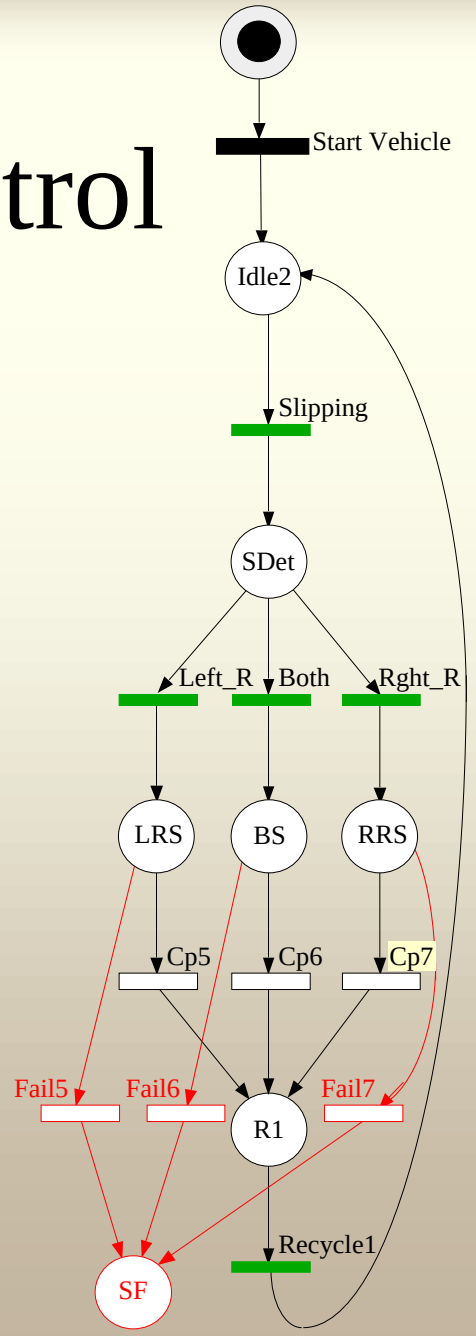
Slipping/Traction Control

Rear wheels lose traction

- Compensation mechanism is one shot process
- Fault may occur activating a failure mode causing:
  - Loss of stability
  - Degraded function



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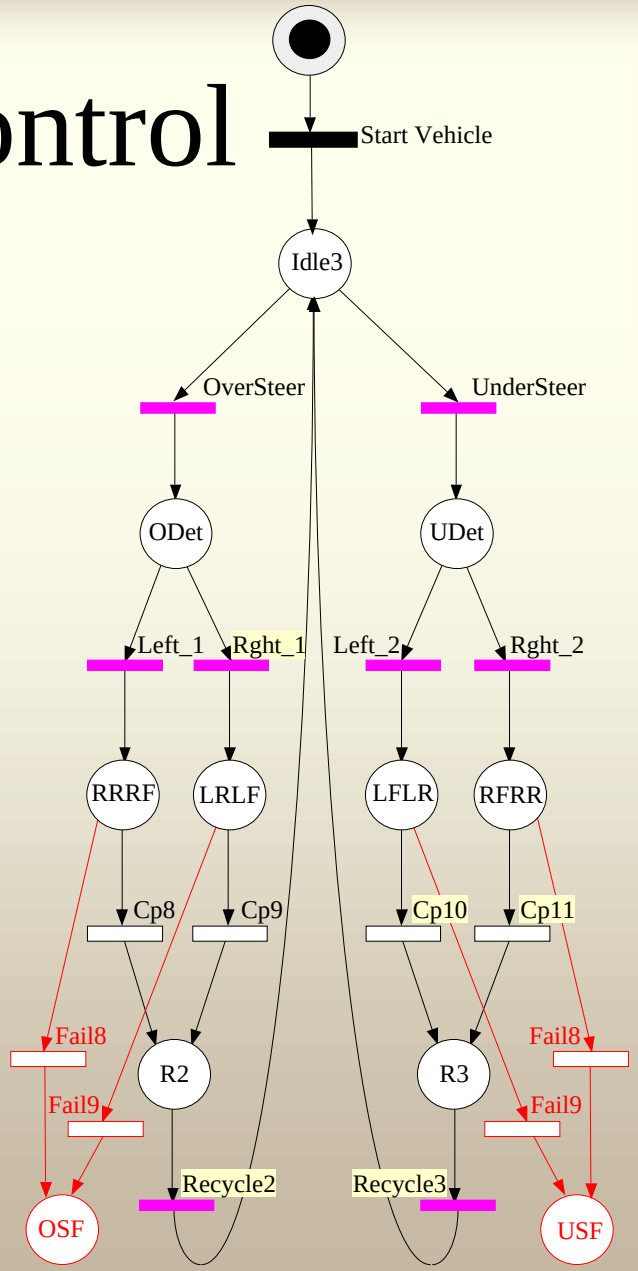
Over/Under-Steer Control

When over/under-steer threshold is detected

- Compensation mechanism is a one shot process
- Fault may occur activating a failure mode causing:
  - Loss of stability
  - Degraded function
  - Over/Under-steer



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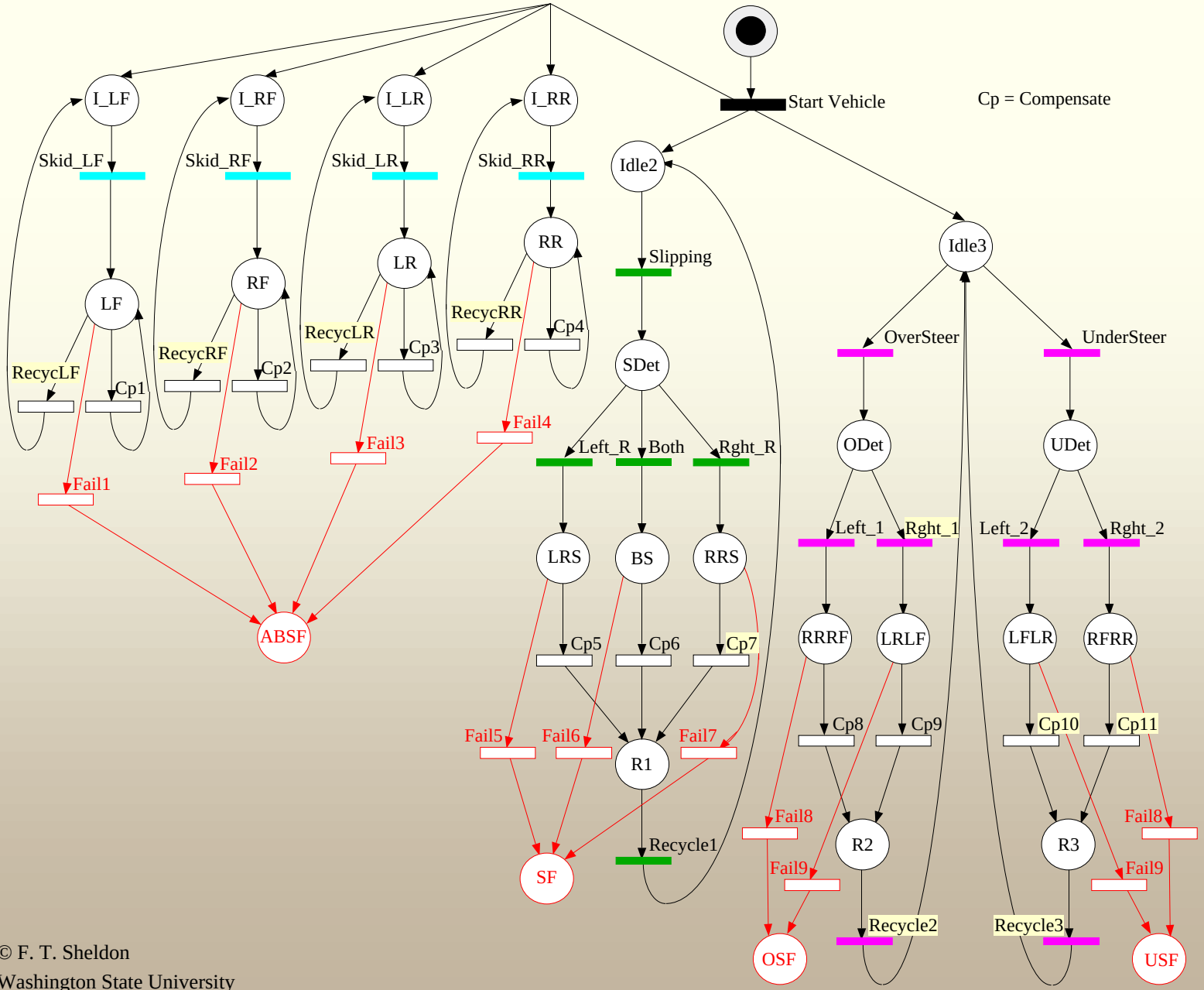
TC/ABS Combined



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Derive Failure Rate Mappings

- Determine causality
  - Fault
  - Symptom
  - Suspect component
- Calculate cumulative failure rates
  - Assign to failure transitions in SPN

Fault >	One Wheel (PL)	One Wheel (LB)	One Axle (PL)	One Axle (LB)	Both Axles (PL)	Both Axles (LB)
Symptom >	Degraded Function	Over/Under-Steer of the Car	Loss of Vehicle	Loss of Stability	Loss of Vehicle	Loss of Stability
Component						
Wheel Speed Sensor	2.00E-10	2.00E-10				
Pressure Sensor			1.50E-10	1.50E-10	1.50E-10	1.50E-10
Main Brake Cylinder			1.00E-10		1.00E-10	
Pressure Limiting Valve			6.00E-12	6.00E-12		
Inlet Valve			6.00E-12	6.00E-12		
Drain Valve			6.00E-12	6.00E-12		
Toggle Switching Valve	6.00E-12	6.00E-12				
Hydraulic Pump			6.80E-10		6.80E-10	
Pressure Tank					2.00E-11	
Controller	6.00E-11	6.00E-11	6.00E-10	6.00E-11	6.00E-11	6.00E-11
Steering Angle Sensor						
Lateral Accel Sensor						
Yaw Rate Sensor						
Tubing	3.00E-11		3.00E-11		3.00E-11	
Piping	4.00E-11		4.00E-11		4.00E-11	
Cumulative Failure Rate	3.36E-10	2.66E-10	1.62E-09	2.28E-10	1.08E-09	2.10E-10

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Modeling an Operating System with Stochastic Petri Nets

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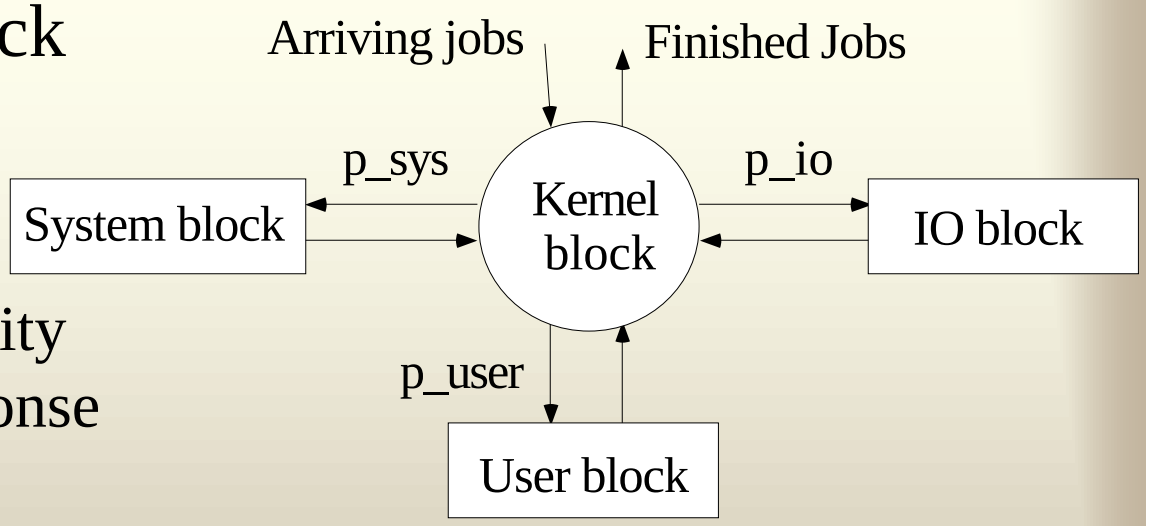
Dynamic Priority OS
Functional Level Abstraction

Each elementary block

- Analytic Sub-model

Dynamic Priorities

- Guarantee high priority jobs get shorter response times



- Goal: Evaluate dynamic increasing/decreasing priority assignments.

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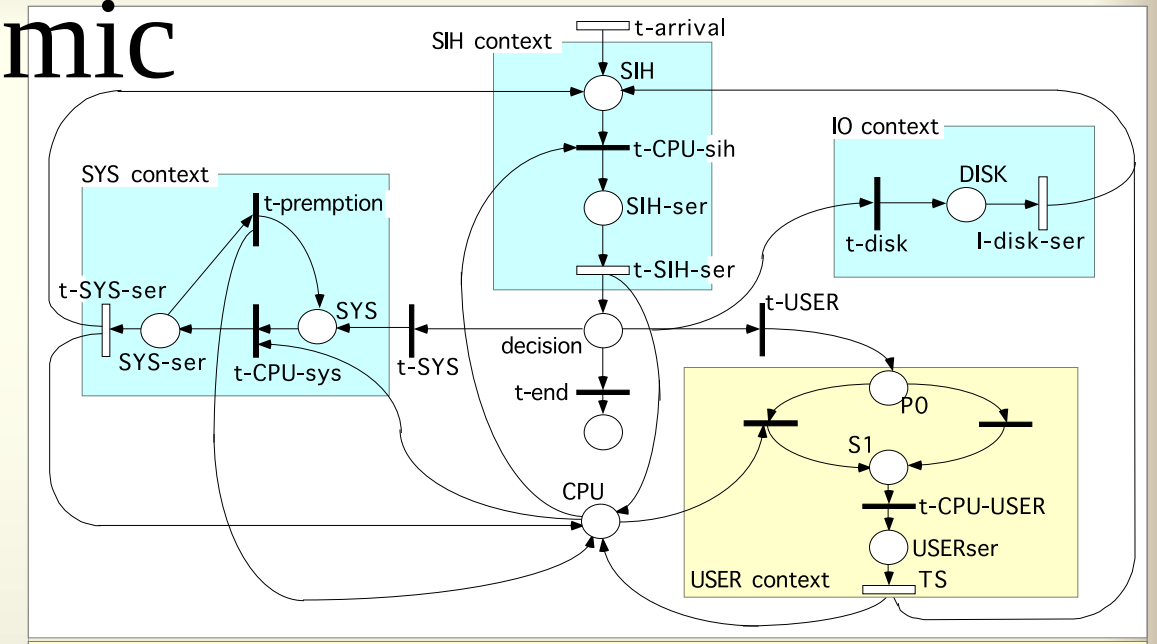
SPN of Dynamic Priority OS

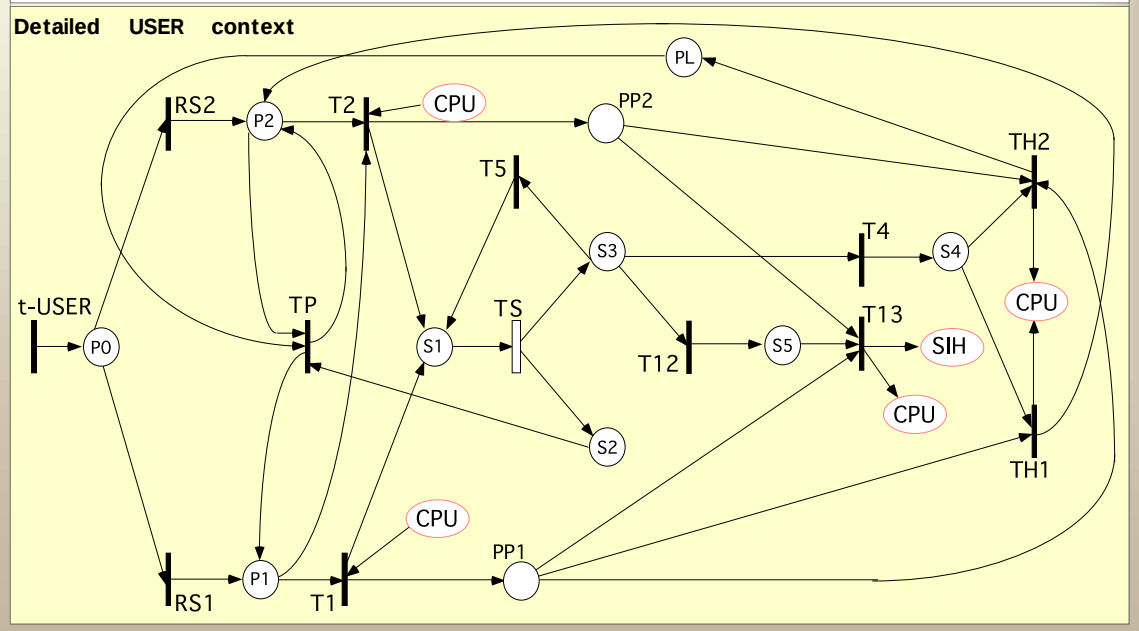
Top: complete system contexts

- Kernel (SIH)
- System (SYS)
- IO
- User

Bottom:

- Detailed User Context





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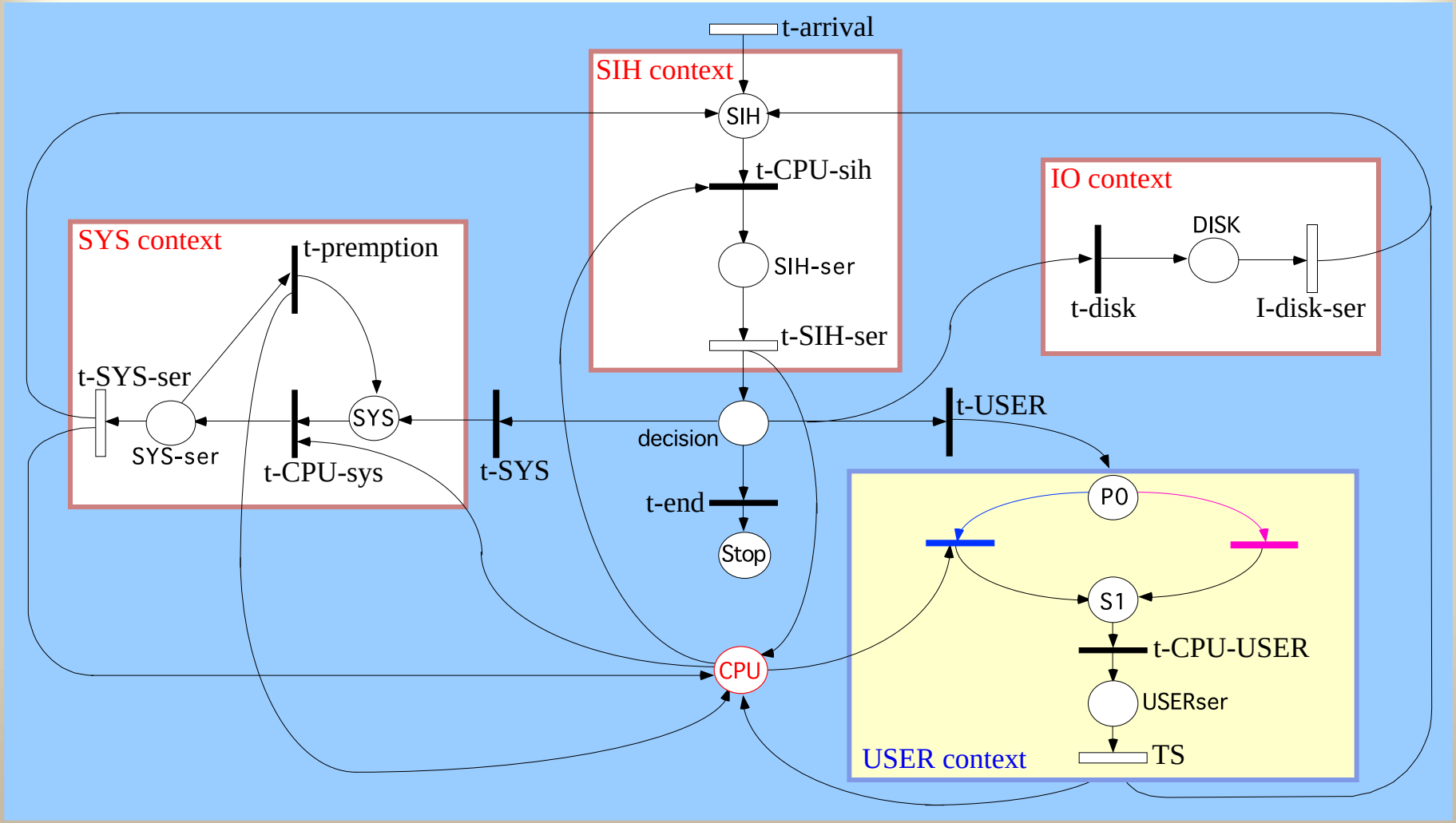
Complete System SPN



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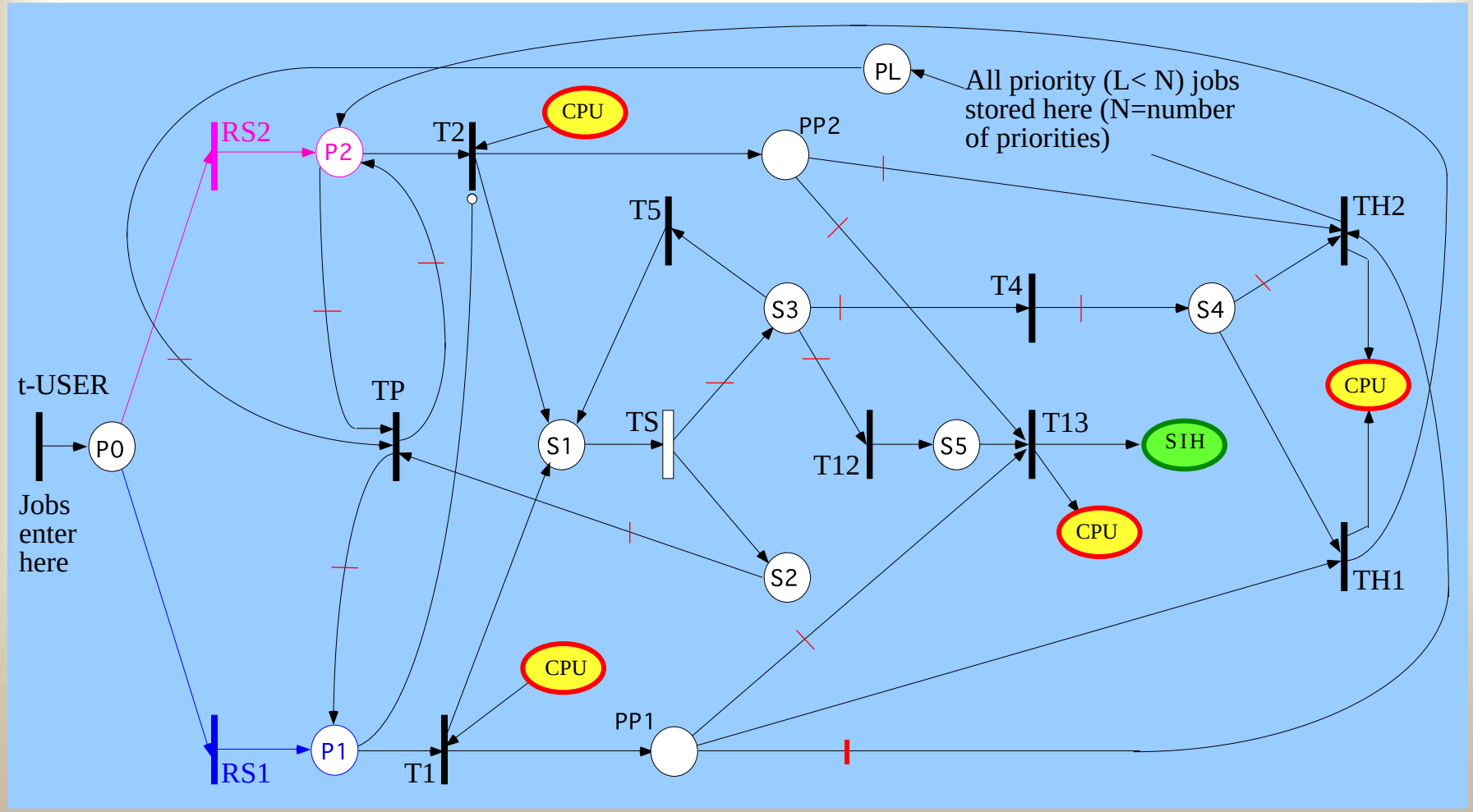
Detailed User Context



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User Context: Basic Characteristics

Lower priority than other contexts

- Gets CPU when there are no jobs to be processed in other contexts.
- Lower priority is assigned to transitions T_i ... than to transitions t_CPU_sys and t_CPU_sih.
- Transitions T_i... enabled when no other jobs are being served ⇒ number of tokens in places PP_i =0.

When transition T_i... fires a token in the CPU place is removed.

- Jobs are processed in priority order.
- Inhibitor arc from P1 (P_i) to T2 (T_{i+1}) guarantees a priority class i job is processed before class i+1.
- Token in S1 the CPU is processing a USER context job of priority i (by token in PP_i).

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System Parameters

System Parameters (job arrival rate $\lambda_{arrival}$ = 0.005)		
Component Definition	**Transition Probability**	**Service Time**
I/O Subsystem Context	p_io = 0.05	s_io = 20
System Context	p_sys = 0.40	s_sys = 1.0
User Subsystem Context	p_user = 0.54	s_user =1.0
Kernel Subsystem Context	p_end = 0.01	s_sih = 0.5

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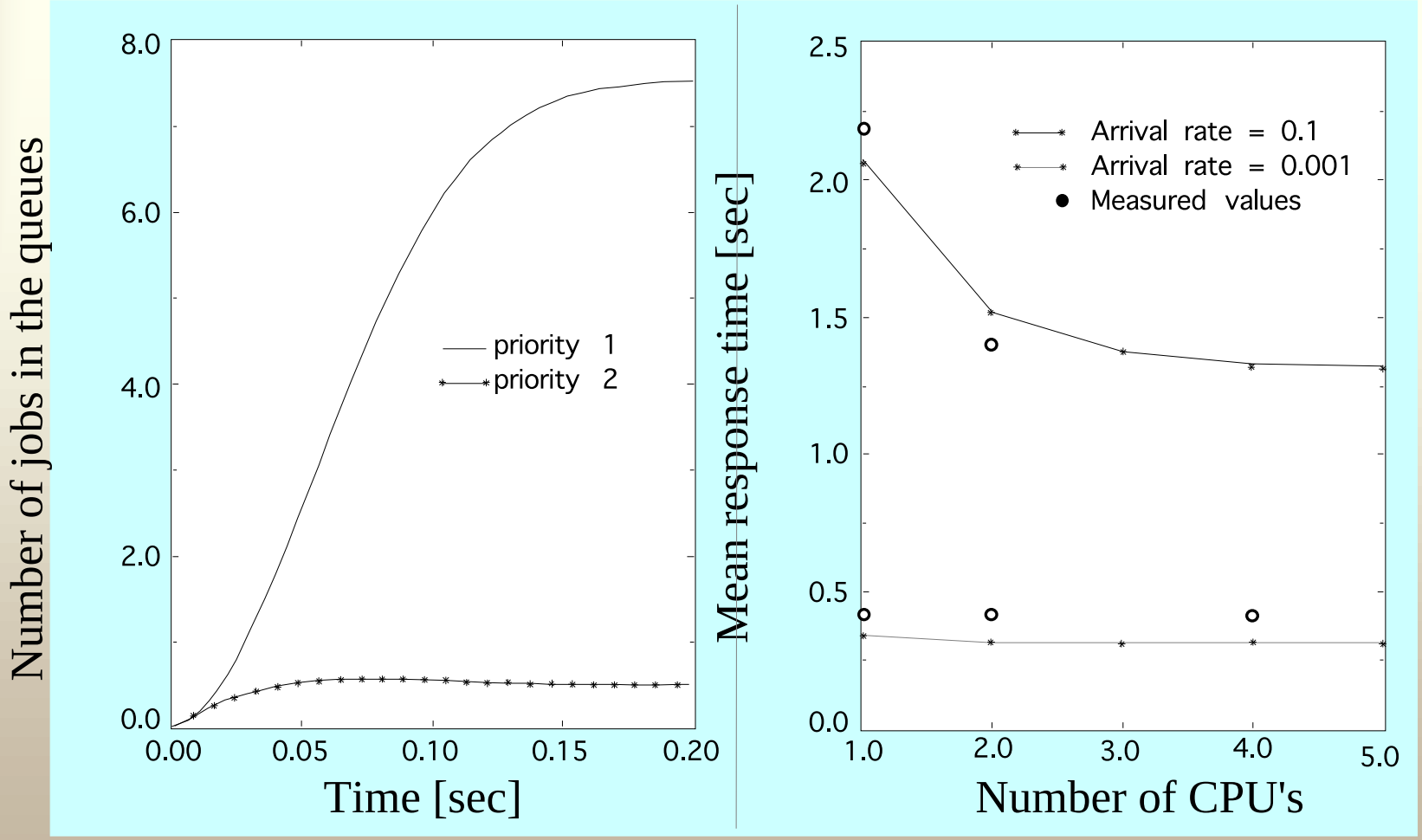
Predicted vs. Measured Results

Transient + Steady State Analysis



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Summary of Ongoing Work

Ongoing

Extending the CSPN language

GUI with SPN Editor ← → CSPL

Promela-based models → SPNs (i.e., CSPL)

CSPL → ERG → RG → Q-matrix → Solved analytically

Fault-tree analysis (Erlangen)

Implementation of solution methods (Erlangen)

Exploring the concept of

Relate stochastic results back (mechanically) → original model as a process of refinement in light of prior runs (sensitivity analysis)

CGI Web-based access to CSPN (and other components)

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The end… time to shut down!

Questions?

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