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Softwaretechnik
Jun.-Prof. Dr.-Ing. Steffen Becker

Model Transformations in Non-Functional Analysis

Assistant Prof. Dr.-Ing. Steffen Becker

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Personal Background

- Studied Wirtschaftsinformatik in Darmstadt
  - Meta-Modelling Focus
  - Component Meta-Models and Marketplaces
- Research Assistant in Oldenburg
  - Palladio Component (Meta-)Model
  - Model-Driven Architecture-Based Quality Prediction
- Research Assistant in Karlsruhe
- Department Manager at FZI
- Disputation in Oldenburg to become
  Dr.-Ing. in a performance engineering context
- Since April 2010 Juniorprofessor at U Paderborn

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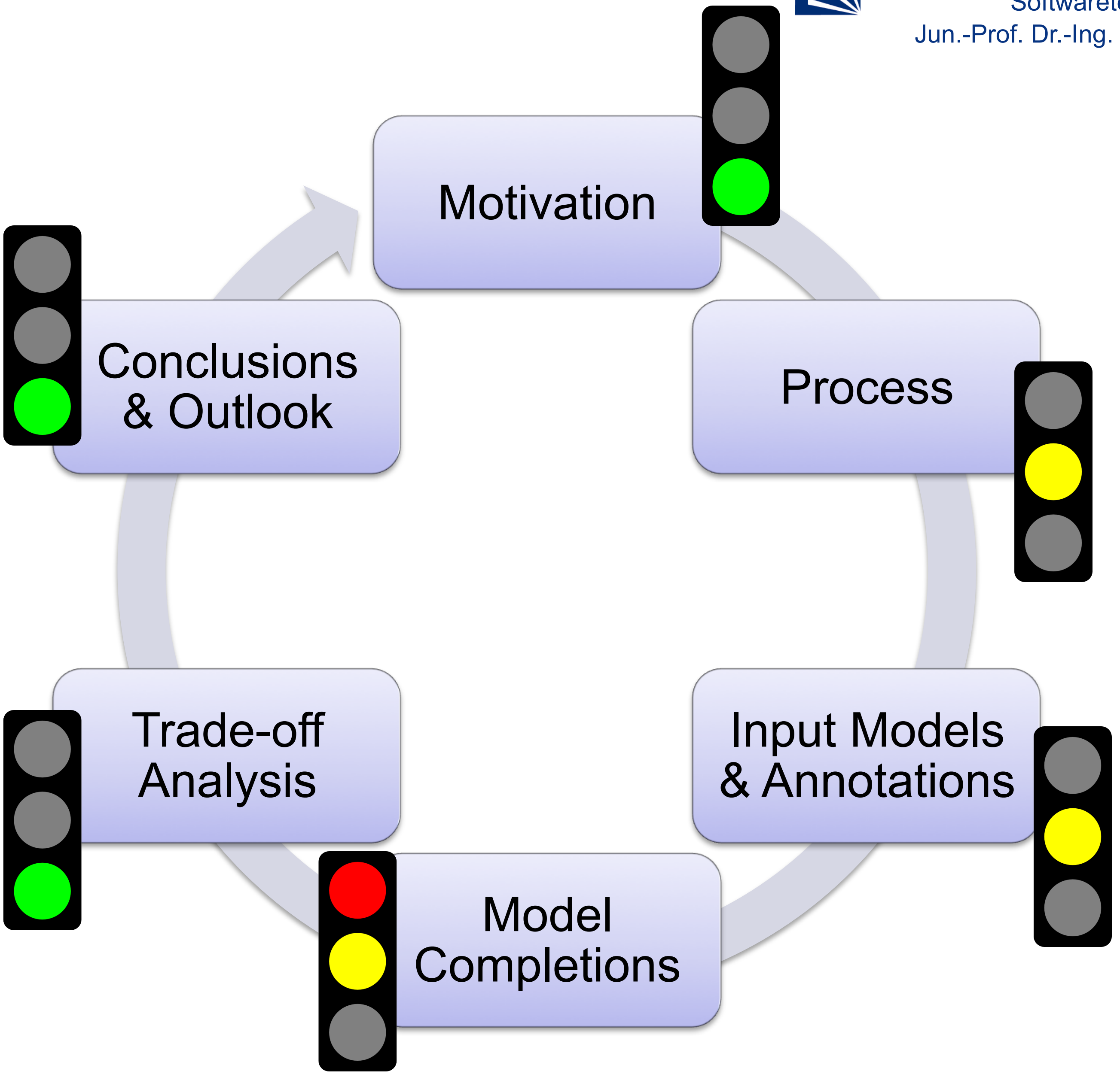
Outline



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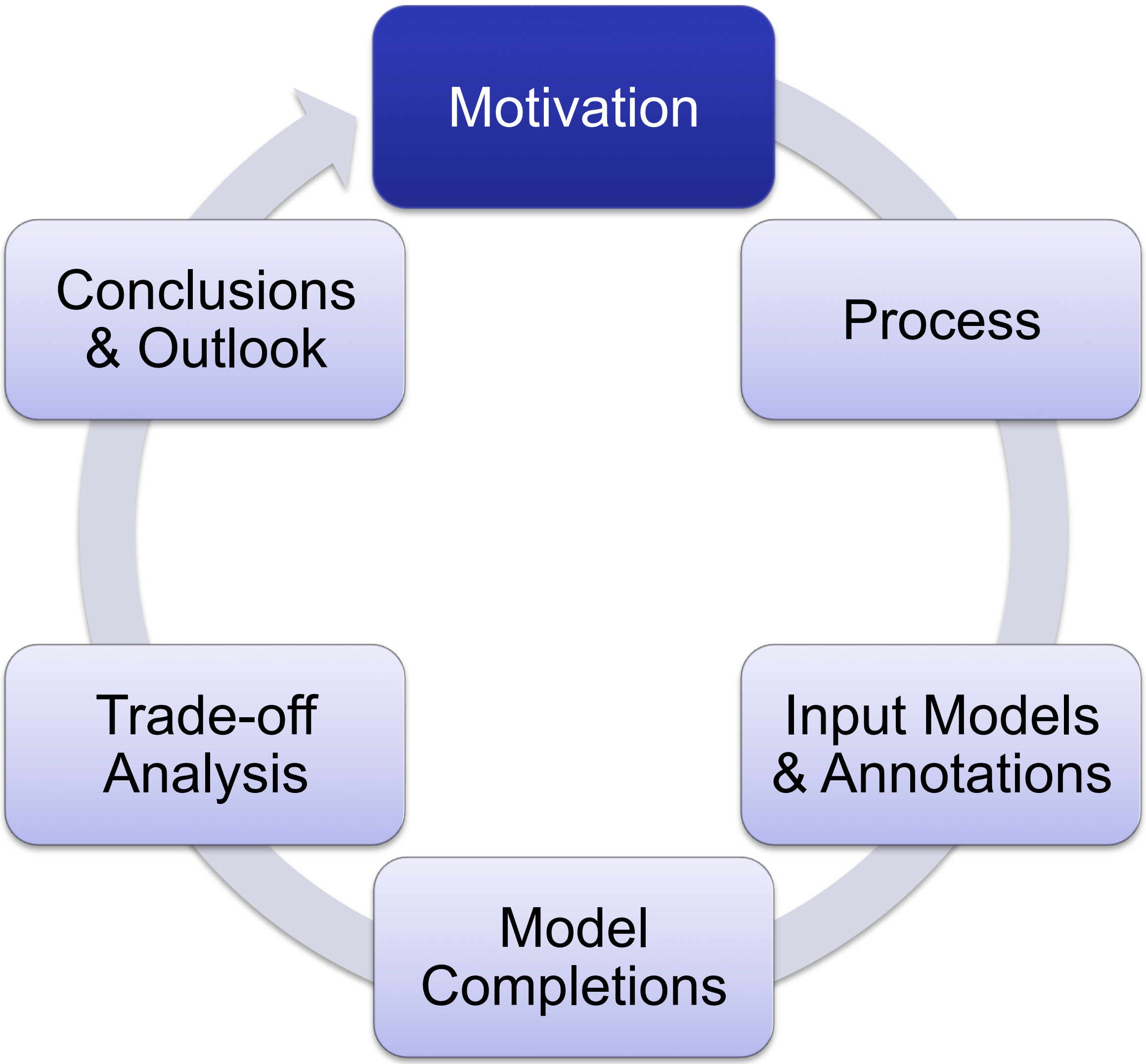

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Example: SAP Business By Desgin

leidet offenbar noch unter Kinderkrankheiten. Die Wirtschaftszeitung *Euro am Sonntag* berichtet in ihrer aktuellen Ausgabe von Performance-Problemen sowie einer drohenden Verschiebung des Starttermins und beruft sich dabei auf Insider. So laufe die Software derzeit noch deutlich langsamer als die Standardanwendung R/3 und verkrafte noch nicht einmal 10 gleichzeitige Nutzer. Von der Zielvorgabe, 1000 parallele Nutzer zu bedienen, sei das Produkt noch "Lichtjahre entfernt". Hauptproblem sei das Design des Systems, das Servern den Zugriff auf brachliegende Kapazitäten anderer Rechner nicht ermögliche. Dem Insider zufolge werde das zu einer Verzögerung führen, das Produkt sei frühestens in einem Jahr marktreif.

- Development costs >300 Mio. €, est. TTM + 1 year (was 3 finally)
- Handles 10 users instead of the planned 1000
- Cite: „Main issue is the *system's design*, which disallows server to access free capacities on other machines…“

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Context?

System Type

- Web-based system
- Three-tier business information system

Characteristics

- Request-Response communication, often blocking
- Open world assumptions, users come whenever they like

Metrics of Interest

- Response time for requests, Utilization, Throughput
- PROFOD
- Costs

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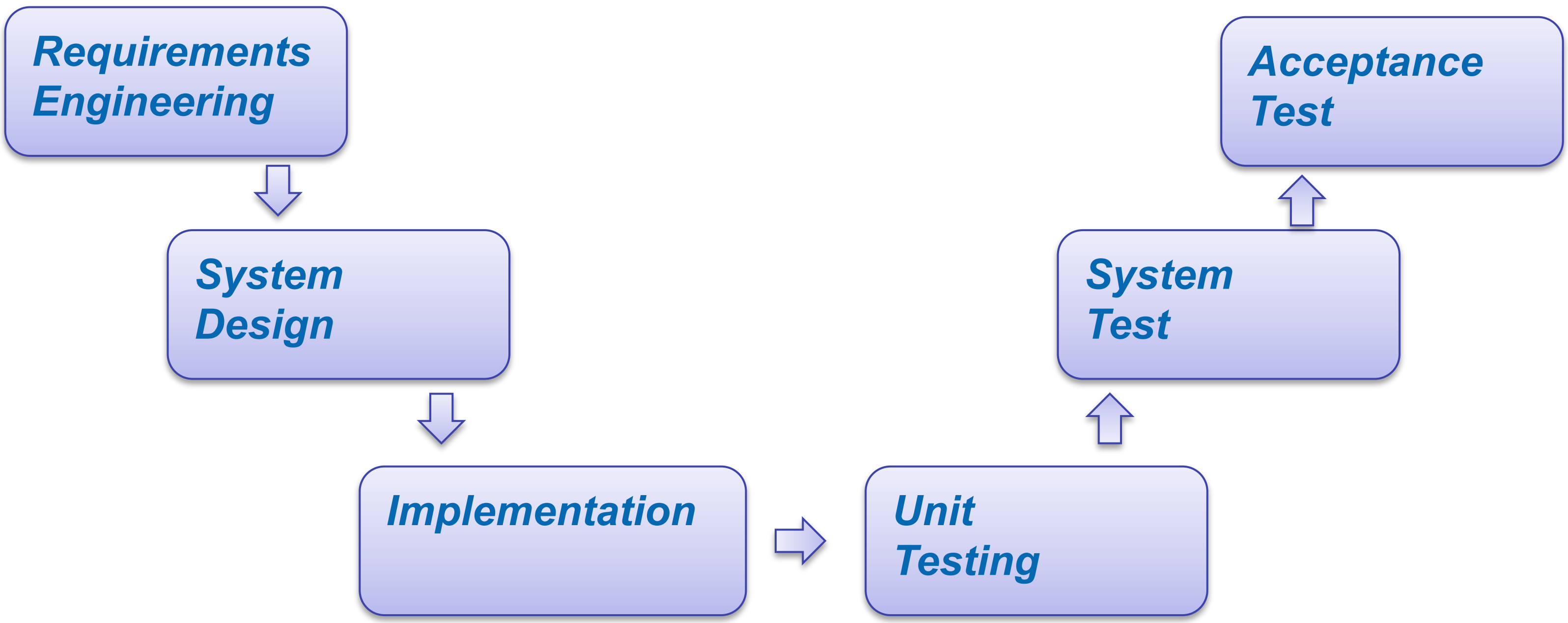
What might have happened?



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What might have happened?

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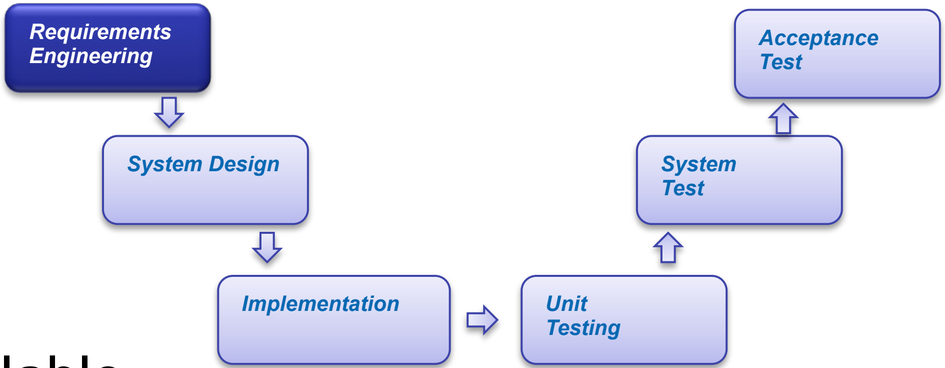
- Capture non-functional properties
- Typical issues
  - Imprecise
    “The system has to be scalable, reliable, performant, … and should not cost anything”
  - Ignore context
    “The system should be unavailable only 3 min / year”
  - Overly strict
    “The system should always react in 1sec”



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Examples: HowTo do it better

- Response time of service bookFlight is 1ms
- Service fails 1h per year in the mean
- Development of the system cost 10.000€
- Average utilisation of server CPU is 80%
- Mean repair time of the server is 1h
- Throughput must at least be 5M transactions per hour

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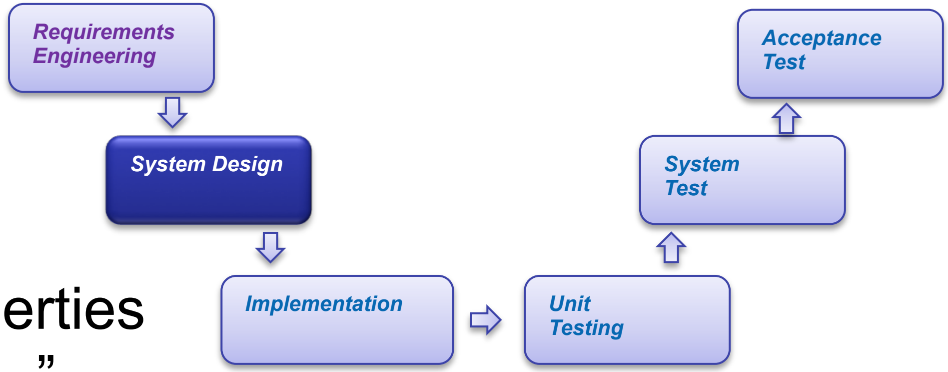
What might have happened?



- Design architecture, classes, components, …
- Typical issues
  - Ignore non-functional properties
    “We can fix anything later…”
  - Reason on them
    Informal (SAAM, ATAM), based on experience
  - Document non-functional rationales for decisions
    Implicit in patterns or class designs
  - No context again
    “A cache in front of a data access is always good…”

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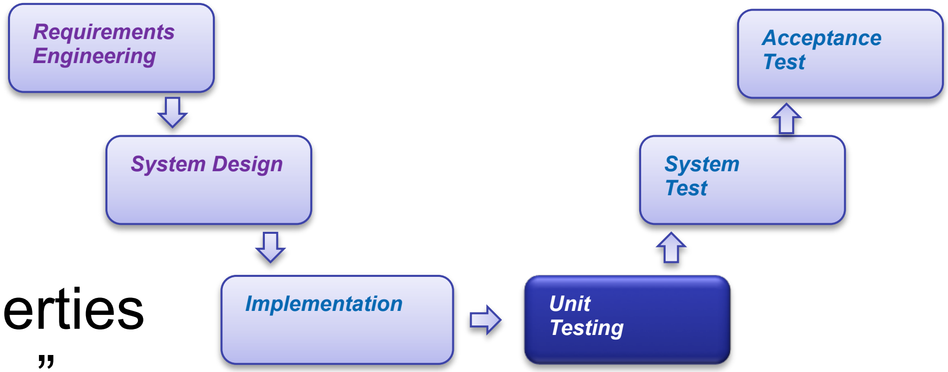
What might have happened?

- Test single entities
- Typical issues
  - Ignore non-functional properties
    "We can fix anything later…"
  - No context
    "I do not know the context of my module, and here it performs fine!"
  - No explicit non-functional tests
    Mainly test of module functionality



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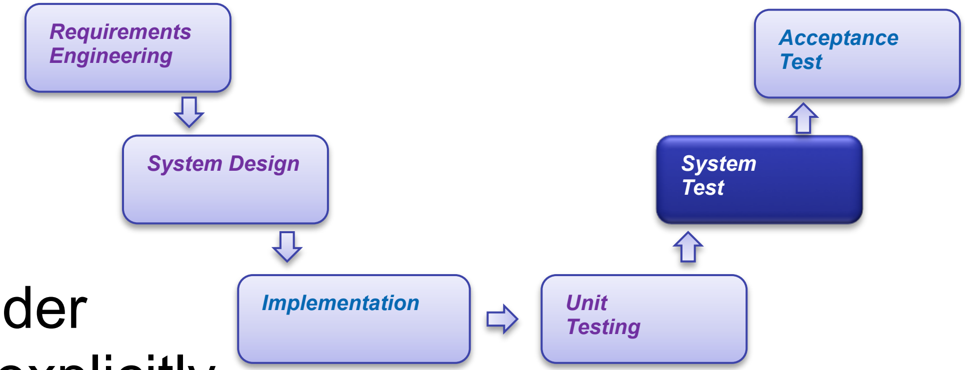
What might have happened?



- Test drive composed system
- Typical issues
  - For the first time we consider non-functional properties explicitly
  - Create context
    “Target is one million users, can we test that in our lab? What will it cost?”
- If issues arise
  - Re-Implement, Re-Design, Re-Negotiate
  - Project failures are likely
  - Most kinds of architecture rework is very costly

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Compared to: What is Engineering?

"[..] creative application of scientific principles to design or develop structures, machines, apparatus, [..] to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property."

Systematic design of system	System model
	Environment model
	Requirements model
Forecast of quality aspects	Requirement fulfilment
	Economic operation
	Safety properties

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Engineering history

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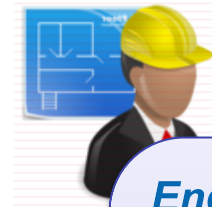
Craftsmanship

- Customer and developer often identical
- Talent and experience guide development

Industrial production

- Work division
- Specialised education
- Tools developed by third-parties



Engineering

Optimized Quality of products and processes

requires

- Scientific foundations / theory
- Guidelines to apply methods to real world problems

based on [Shaw&Garlan95]

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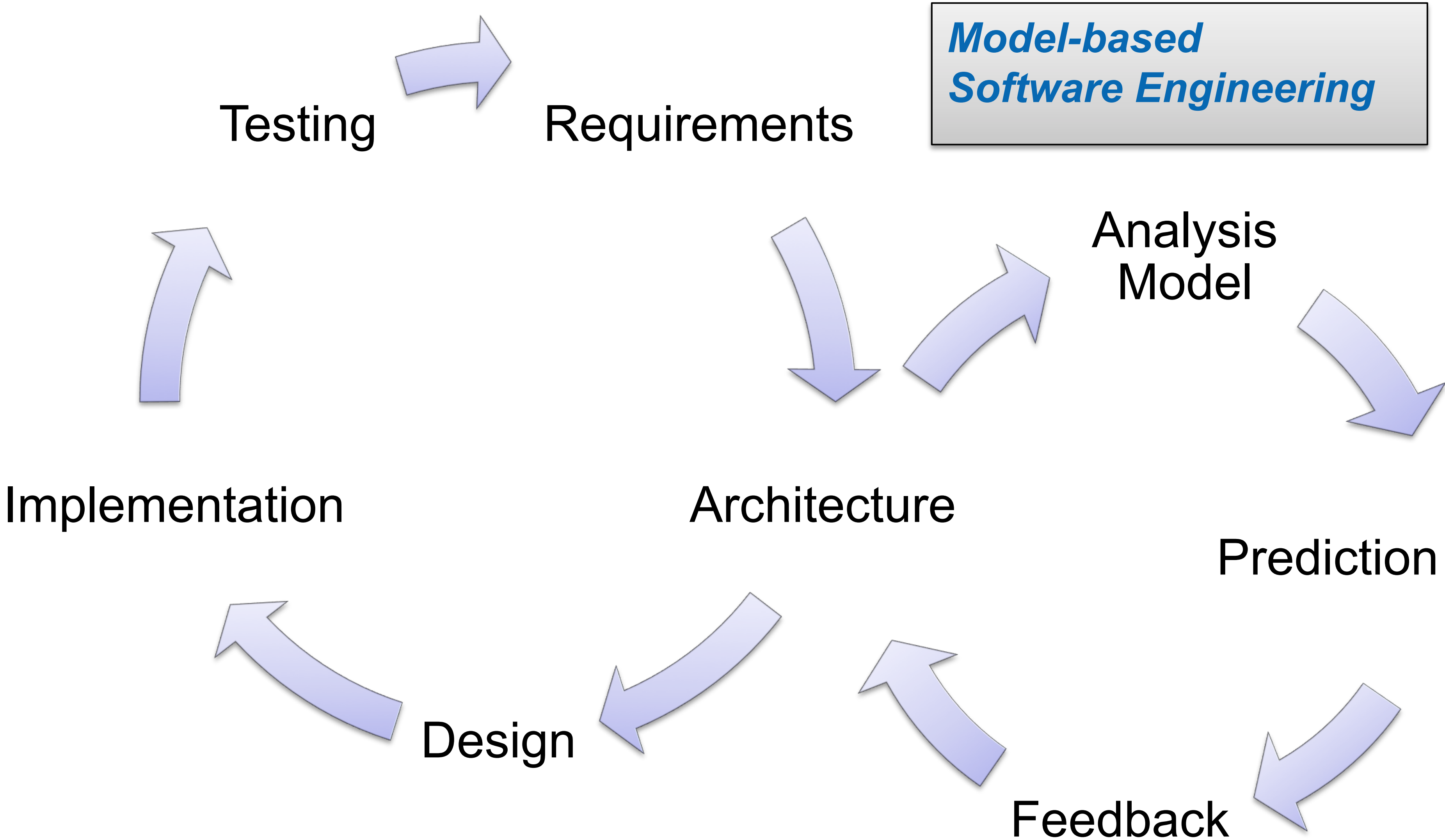
Development Cycles

Model-based Software Engineering



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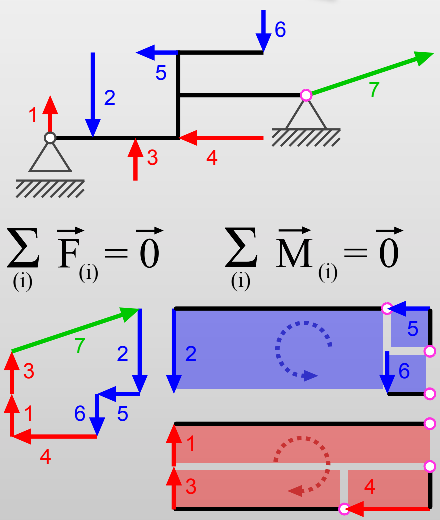
Civil Engineering Analogy

Model

Theory



$$\sum_{(i)} \vec{F}_{(i)} = \vec{0} \qquad \sum_{(i)} \vec{M}_{(i)} = \vec{0}$$

[http://de.wikipedia.org/wiki/Statik_%28Physik%29]

Analysis Results

3.7 Spannungsnachweis

$I_p = 0{,}25$

$\mu = 0{,}80$

$\eta = 2{,}0$

$Q_{zul.} = 0{,}7178\ \text{MN} \cdot 0{,}8 \cdot 0{,}5$

$= 0{,}287\ \text{MN}$

$= 287\ \text{kN}$

$N = 79{,}7 + 1{,}30^2 \cdot 1{,}30 \cdot 25$

$= 134{,}6\ \text{kN}$

$$\boxed{V_{max} = N = 134{,}6\ \text{kN} < Q_{zul.} = 287\ \text{kN}}$$

Die vertikale Tragfähigkeit ist gewährleistet

[http://de.wikipedia.org/wiki/Baustatik]

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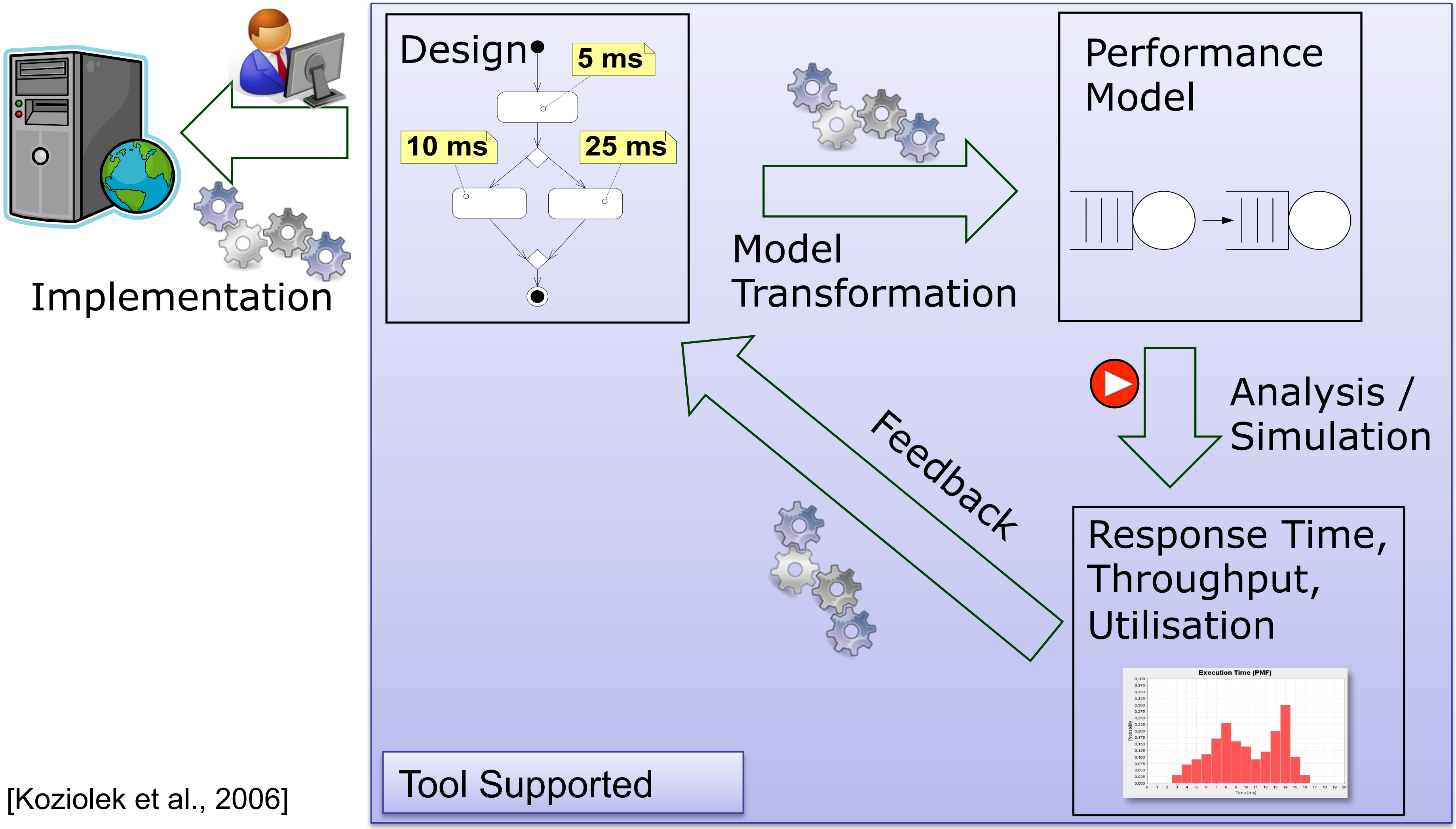
An Instance is Model-Driven Performance Engineering



[Koziolek et al., 2006]

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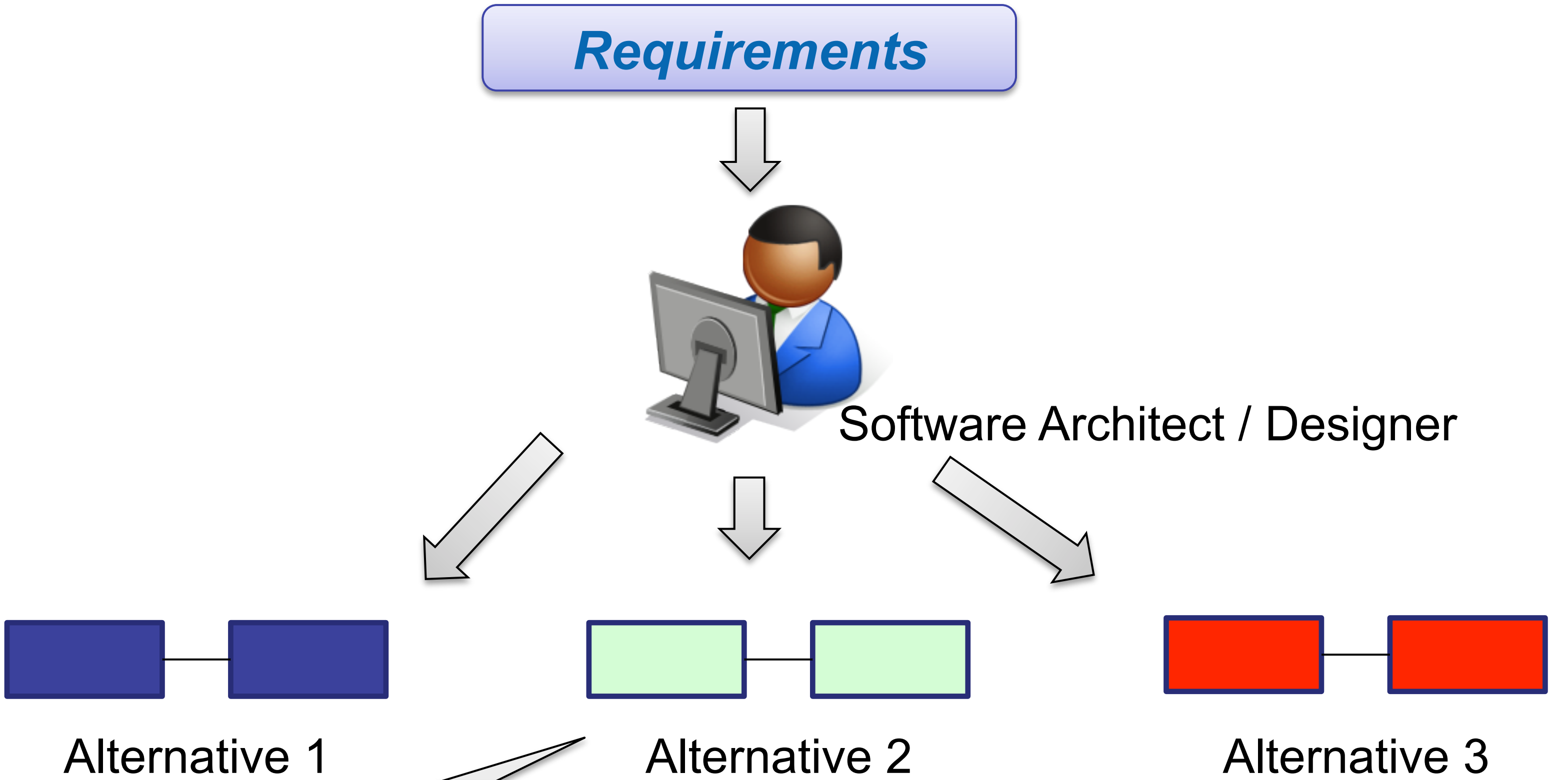
Different alternative designs...



Assume: Same functionality, different QoS

Which alternative do we implement?

[SWA09]

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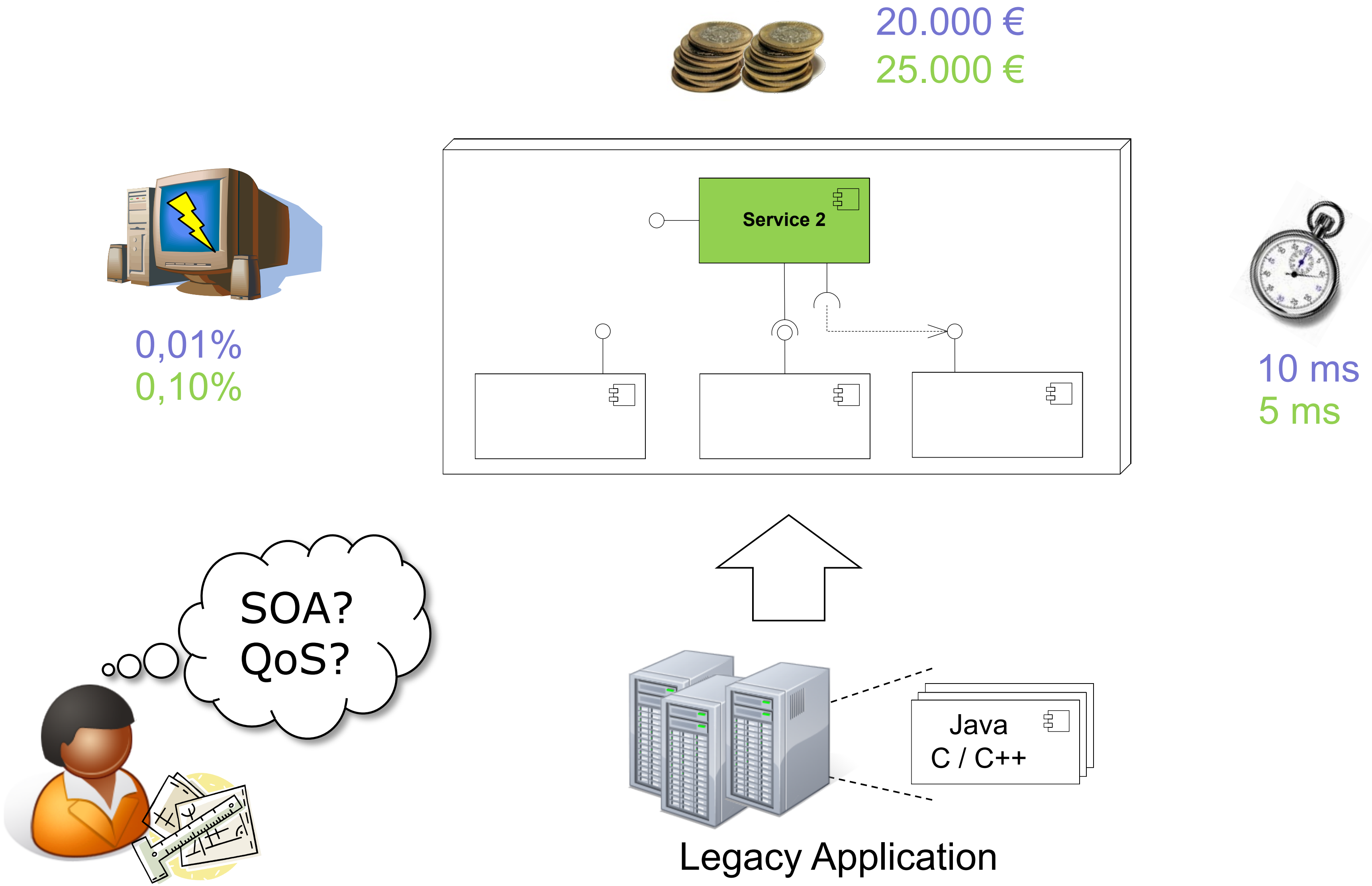
Example…



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What is evaluated?

Examples

- Encryption component: Length of the key
  - Security vs. performance
- Message formats: priority of message processing
  - Expressiveness / transmission security vs. performance (of the whole system)
- After such design alternatives are identified, they can be evaluated:
  - Detailed design
  - Application of analysis methods
  - Prototyping

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Further examples?

- On site assignment:
  - Collect some alternative design or architectural patterns
  - List their variants?
  - What is their expected impact wrt. quality properties?

- Examples
  - MVC vs. its variants?
  - MVC vs PAC?
  - Cache
  - Pooling
  - ...

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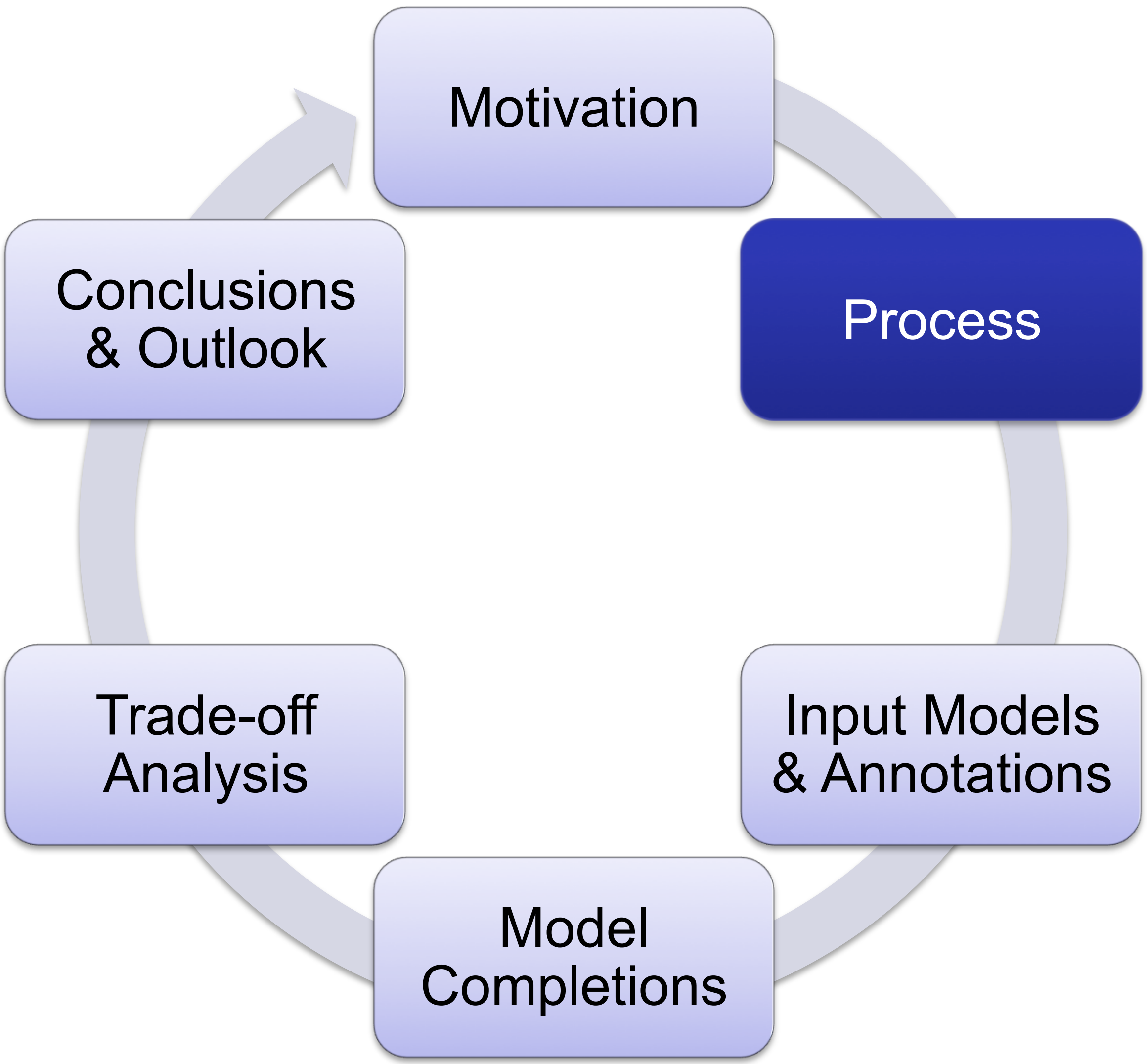
Outline



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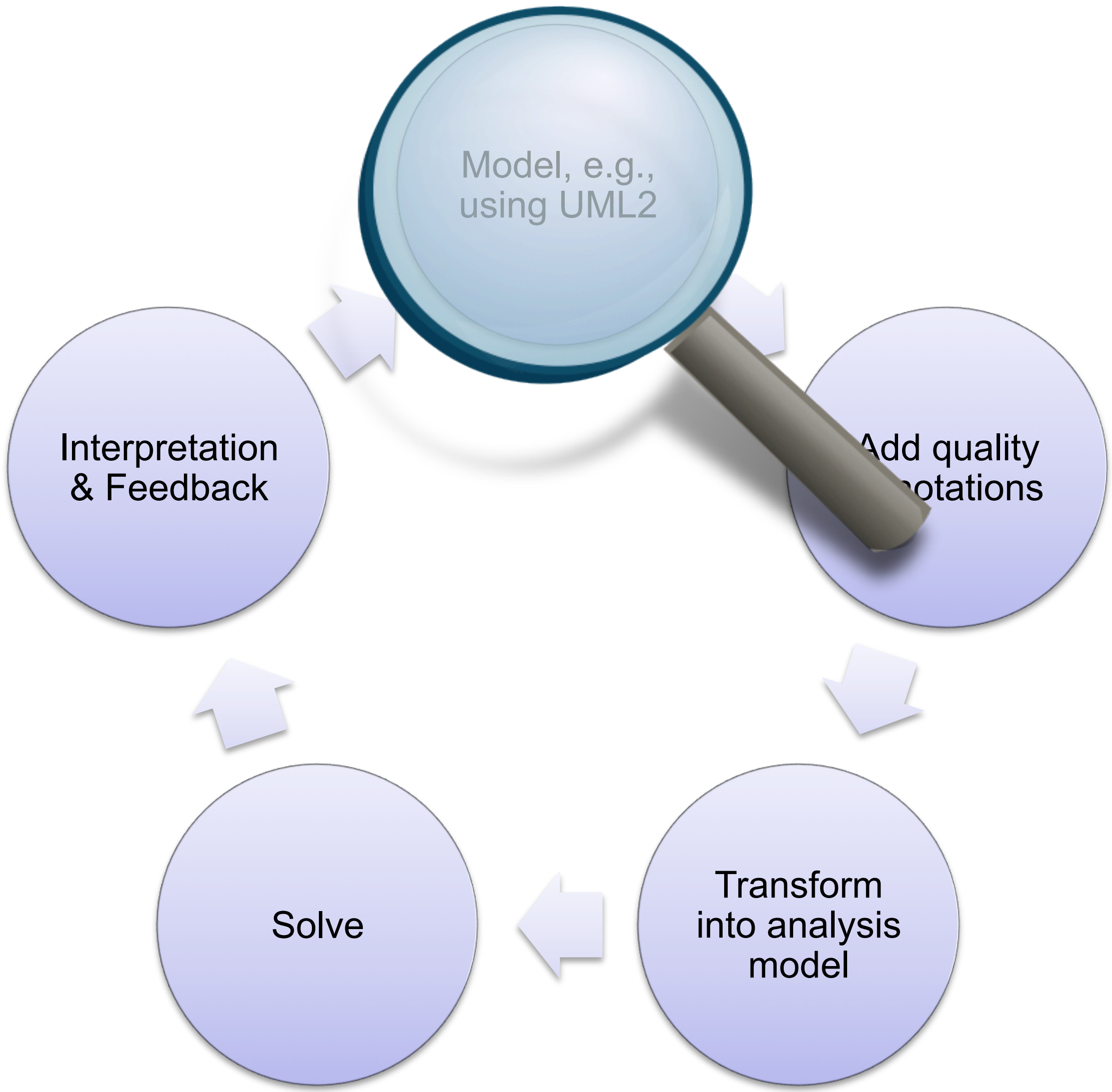
Process



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Model

Software Architects create a model of the SuS

- SW Models primarily focus on software & hardware – not QoS issues
- Software architects create and maintain models
  - Can they do this?
  - A question for empirical Software Engineering

Many languages exist, e.g.,

- UML2 + MARTE
- PalladioCM
- PUMA
- ProgressCM

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Annotations

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Models need QoS annotations, e.g.,

- Resource demands
- Failure rates

Requirements?

- Easy to specify
- Tool support to prevent mistakes
- Easy access from model transformations

State of the Art?

- MARTE
  - Extensive & complex standard
  - Parsers not well standardized
- Specialised languages
  - Commonly have precise syntax & semantics
  - Some accessible by model-transformations

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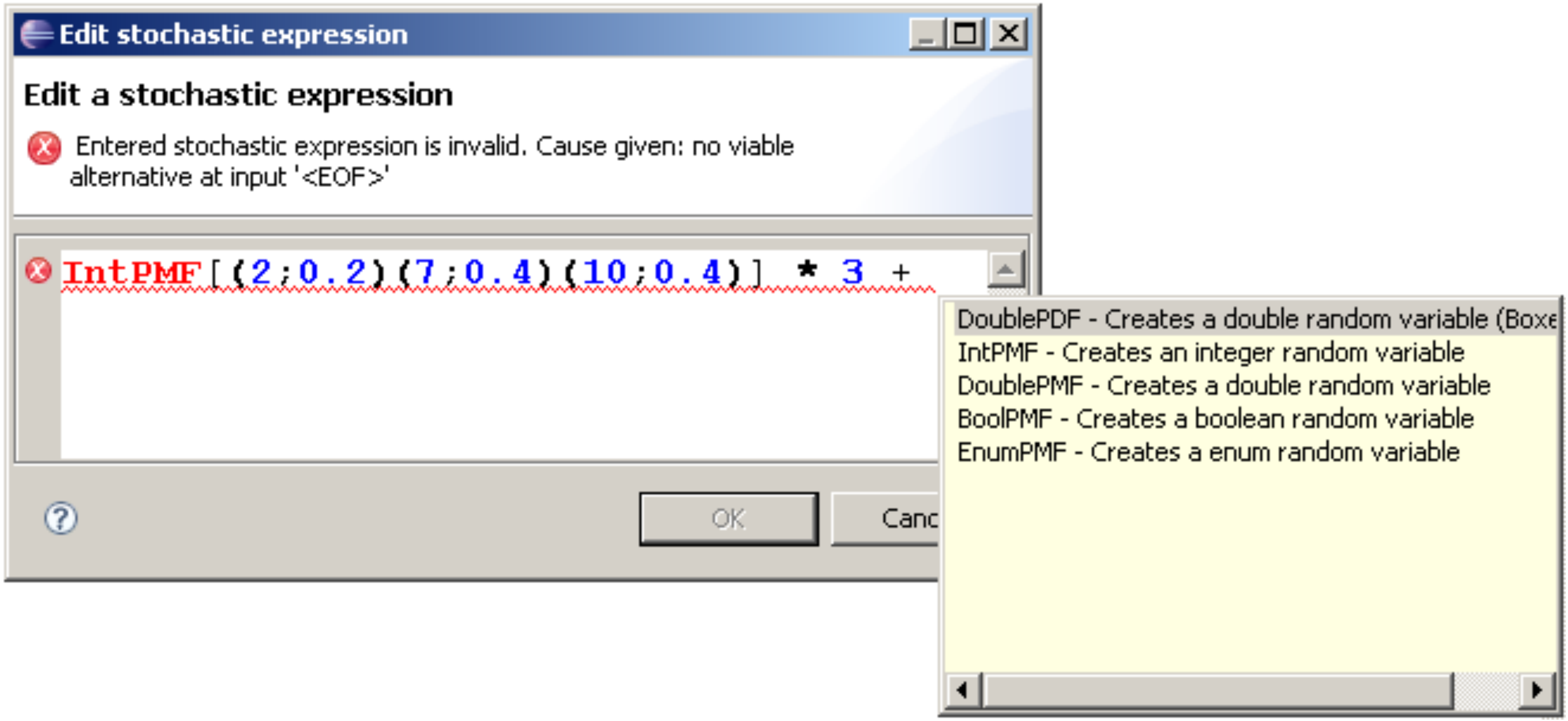
Screenshot
PCM StoEx language



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Transform

Generates analysis model

- (L)QN
- Markov Chain

Requirements?

- Should be fully automated and easily accessible by software architects
  - Again, a question for empirical software engineering
  - In practice experiments not done often enough!
- Full automation implies all information is in the model

Development?

- Needs expert both for software models and analysis theory
- Additionally, expertise in MDD technologies required

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Solve

Automated step to generate analysis results

- Throughput
- PROFOD

Usually done by running external solvers like

- PRISM
- Java Modelling Tools (QN tool)
- SimQPN (Petri Net based)
- CSP Checker (Process algebra)
- …

Issues?

- Typical issue: Models and tools do not scale for arbitrary inputs
- → Transformations often need to abstract!

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PCM:
Example transformations & solvers…

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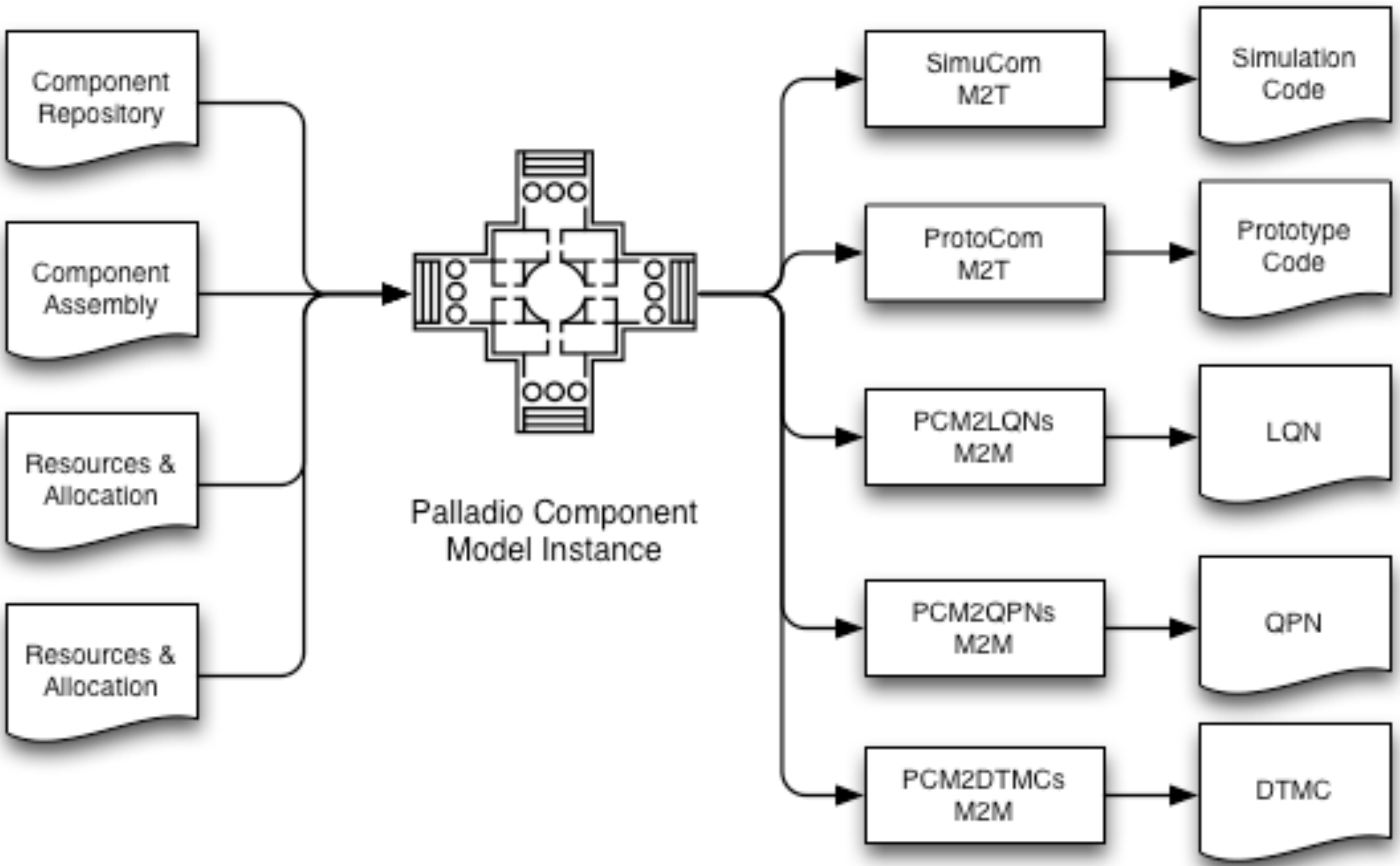

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Why so many solvers…?

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Disclaimer: This is joint work

- Presentation of the results of a series of experiments
- Performed over 1 year duration
- Submitted to Transactions of Software Engineering (TSE), currently under review
- Results of joint work
  - Karlsruhe Institute of Technology
  - University of Zurich
  - University of Paderborn
  - Gameforge

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Experiment Design: Research Questions

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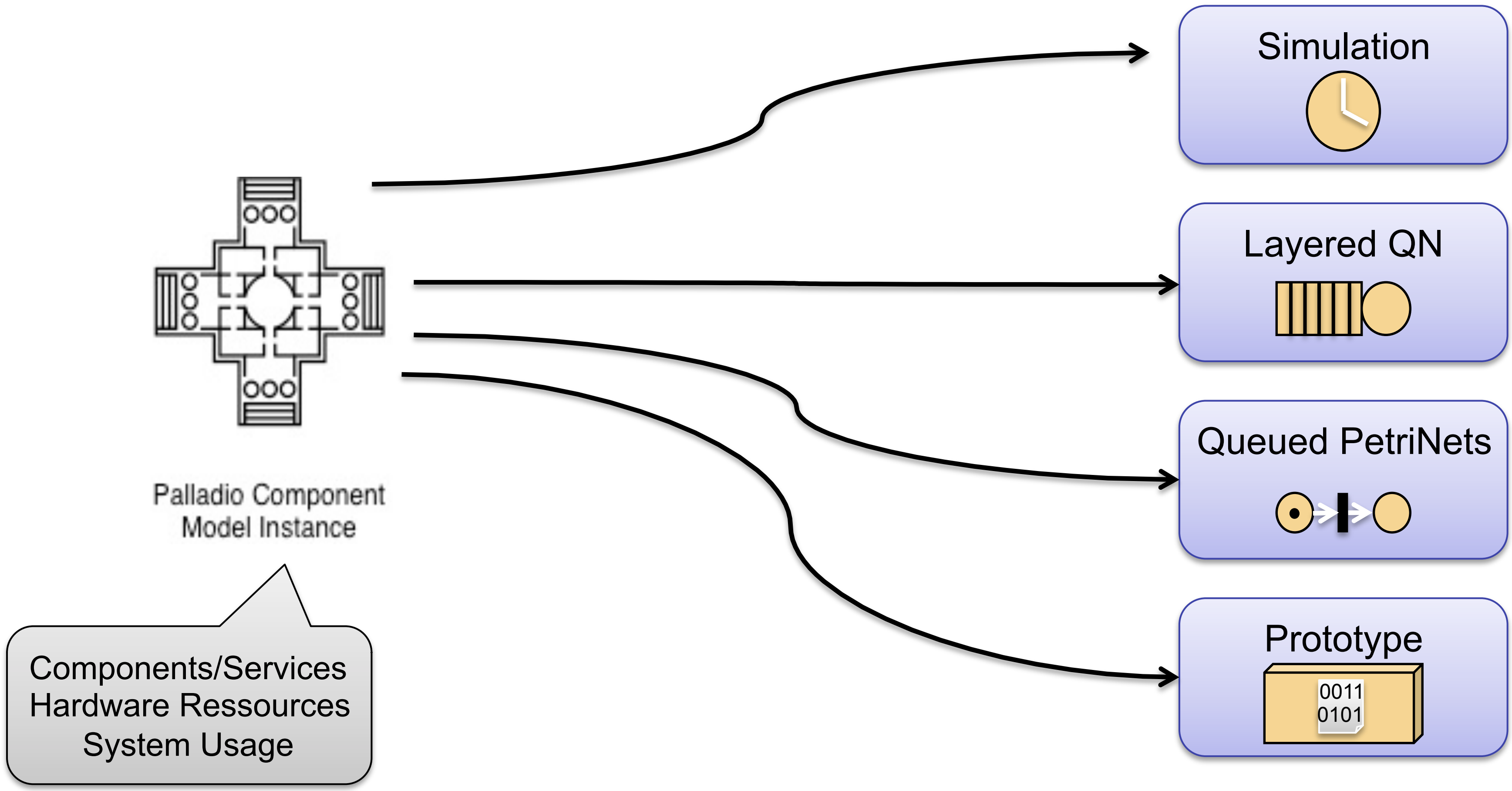
R2: What is the runtime of each solver?



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Experiment: Test Models

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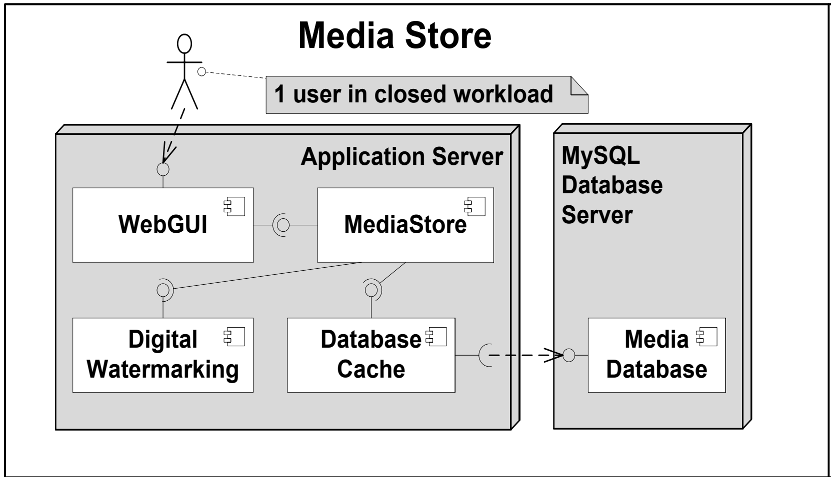

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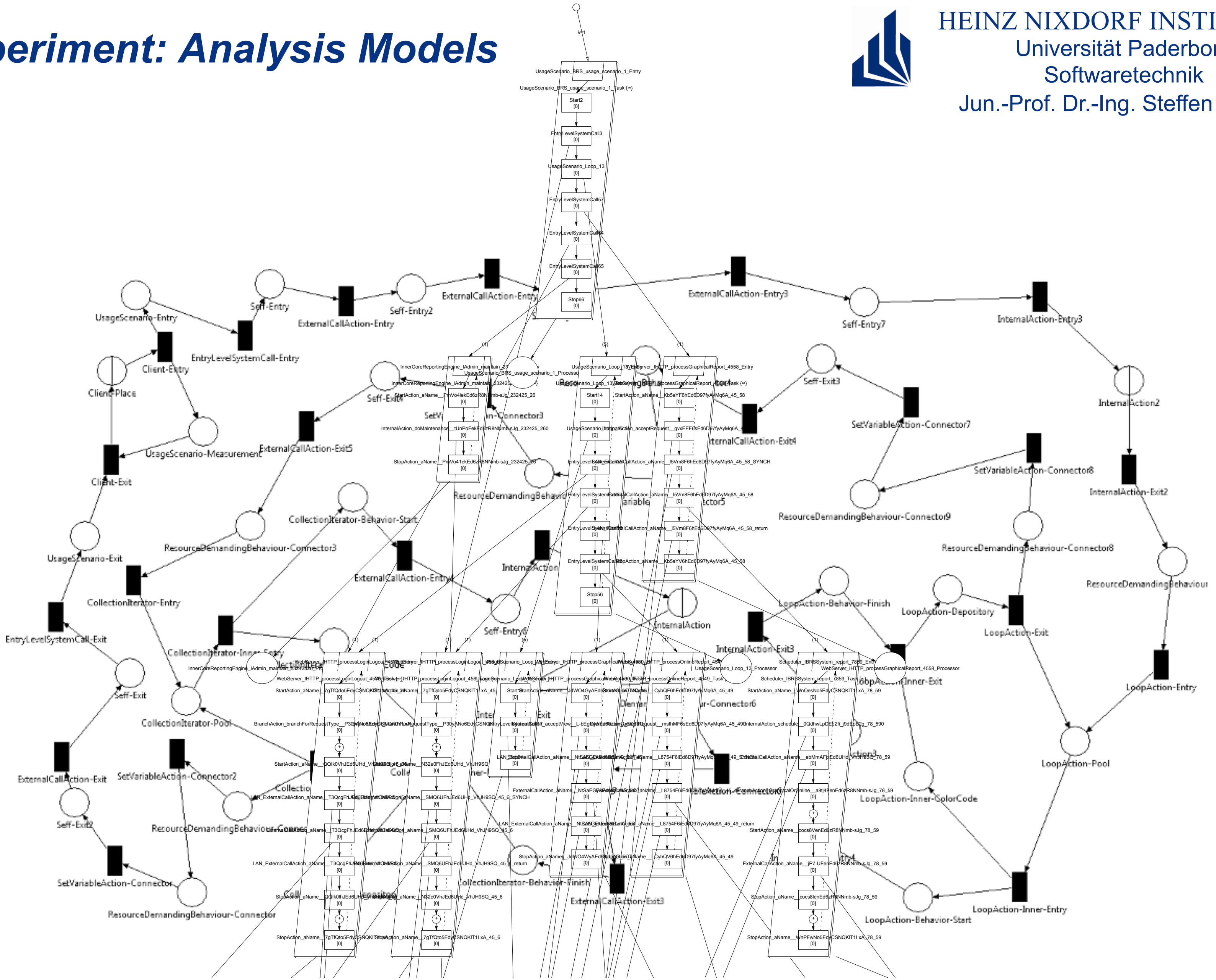
Experiment: Analysis Models



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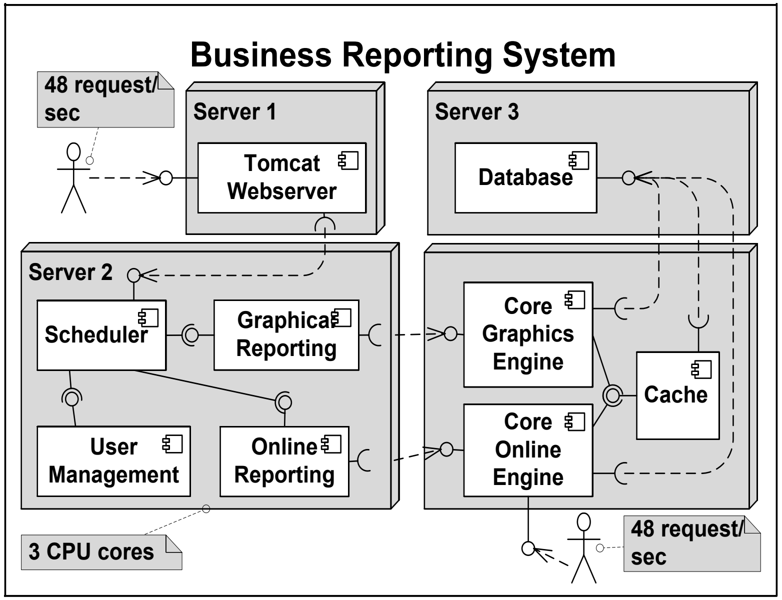
Experiment: Results excerpt



Solver	Mean RT pred.	Diff in %	Solver RT
Simulation	5,22 s	N/A	591,5 s
SimQPN	5,92 s	13,3%	74,5 s
LQN	7,39 s	41,5%	4,0 s
Prototype	6,53 s	25,0%	972,9 s

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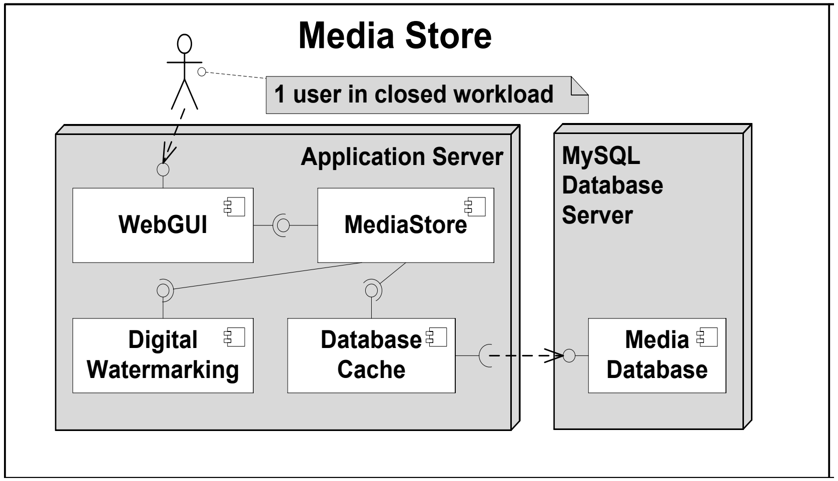
Experiment: Results excerpt



Solver	Mean RT pred.	Diff in %	Solver RT
Simulation	1,33 s	N/A	31,4 s
SimQPN	1,33 s	0%	6,4 s
LQN	1,28 s	-3,3%	1,3 s
Prototype	1,02 s	-22,8%	1034,7 s

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Interpretation

Performing role: Skilled analysts, …

- Take analysis model results
- Translate them into statements about the SuS
- Suggest improved designs

Example:

- Analysis model: Service failure probability > 10%
- Software model: Analyse single failure probabilities
- Countermeasures
  - Introduce redundancy
  - Replication
  - Voting algorithms
  - …

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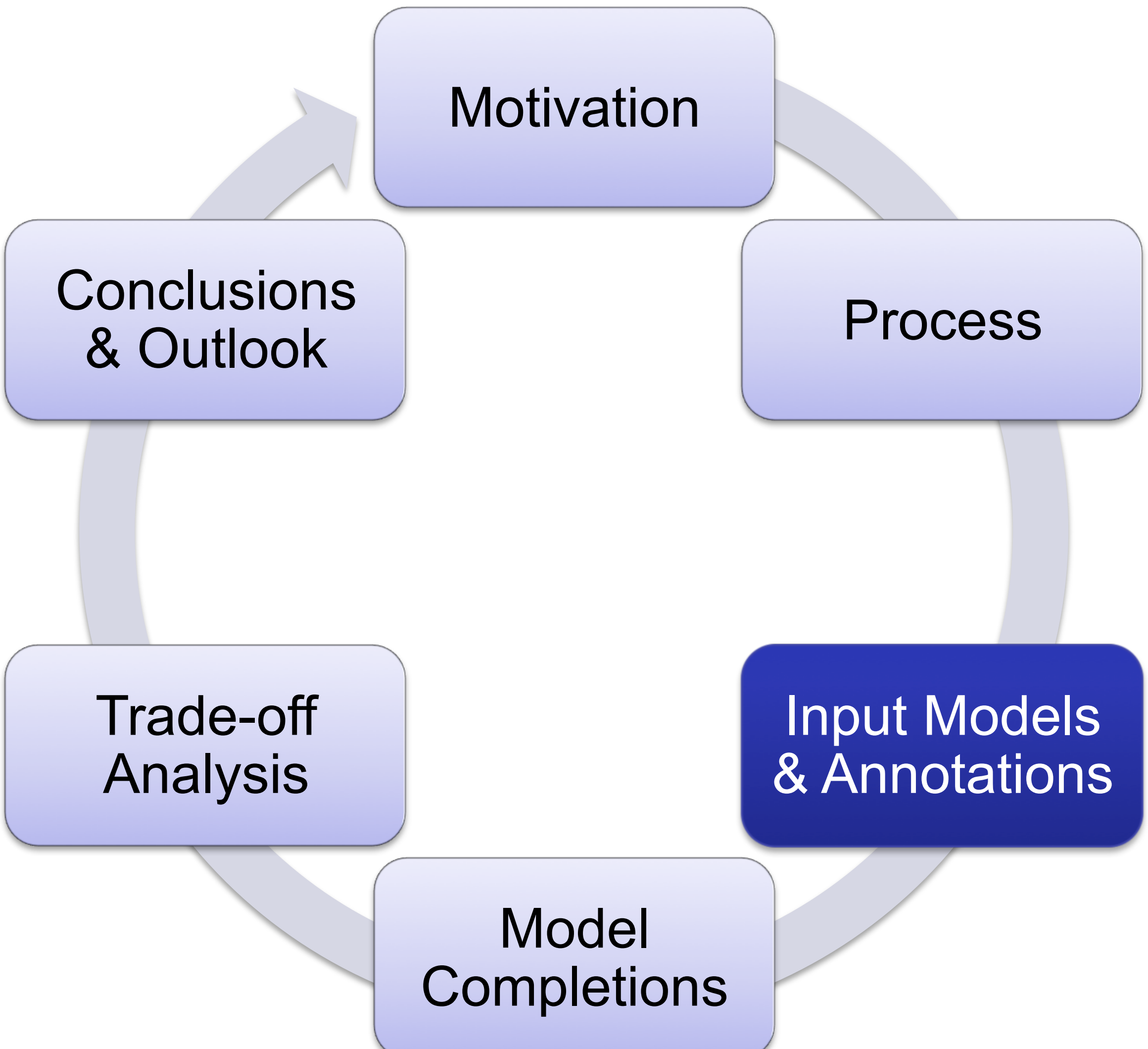

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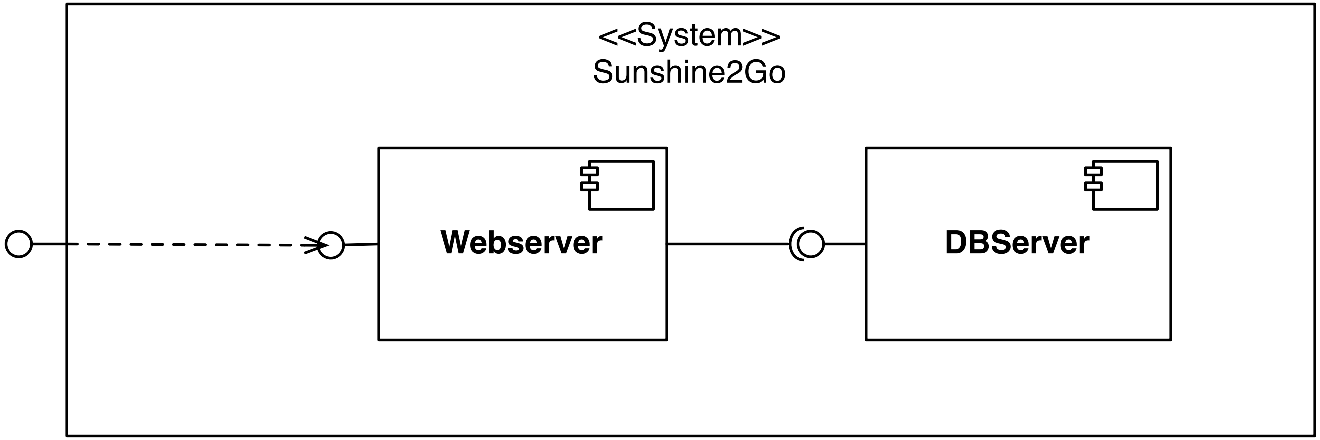
- Dynamic web server example
  - Dynamic web service for querying the weather forecast of the next 7 days “Sunshine2Go”
  - Reports weather conditions of next 7 days for given location in the world



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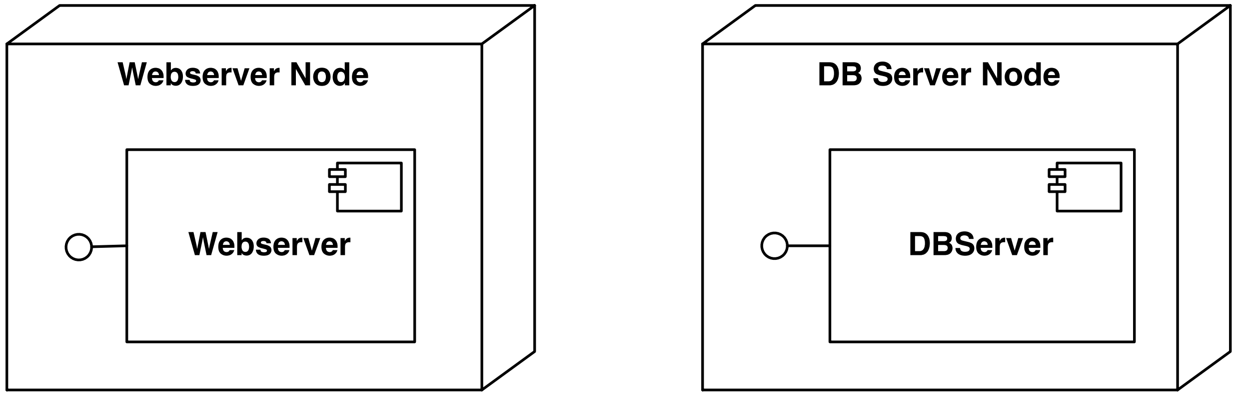
Allocation of “Sunshine2Go”

- Deployment is on local servers per component
- Web server runs the web server component, e.g., Apache
- Database server runs the DB, e.g., MySQL



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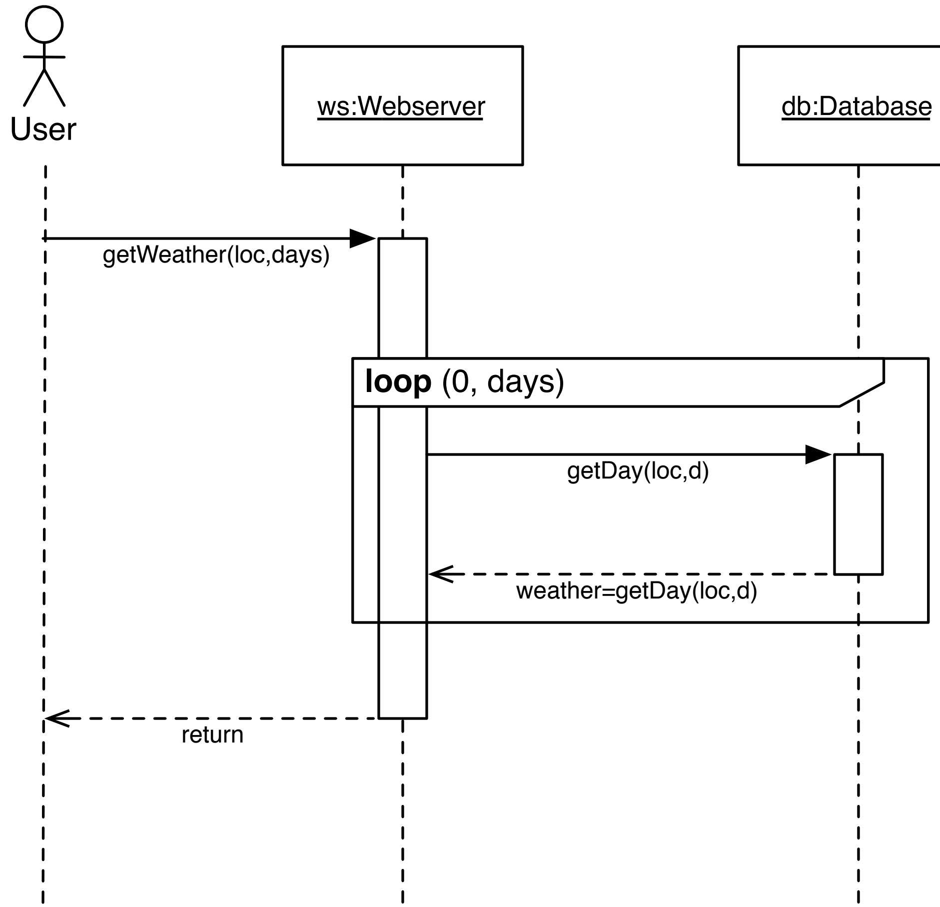
Main usage scenario

- Users query for the weather of a certain location and the amount of days in the future



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Requirements

- Initial use case
  - At the main business hours, users arrive with an mean interarrival time of 3 sec and exponential distribution (Poisson arrival process)
  - The mean response time of each call should not exceed 1sec
  - The utilisation of all resources should be below 80%
- Additional use cases are interesting, but skipped here for time reasons

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Measurements…

- Service time at webserver CPU is exponentially distributed with mean of 1WU
- At the database for each request the CPU has to perform 2WU and the HDD has to execute 1Read
- 1WU of Webserver CPU = 0.01 sec
- 1WU of DB Server CPU = 0.01 sec
- 1WU of DB HDD = 0.03 sec
- All CPU act approx. with processor sharing
- All HDDs approx. with FCFS scheduling
- Measurements indicate each step can fail with a probability of failure of 0.001

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Enhancing the model using UML MARTE

Using UML MARTE

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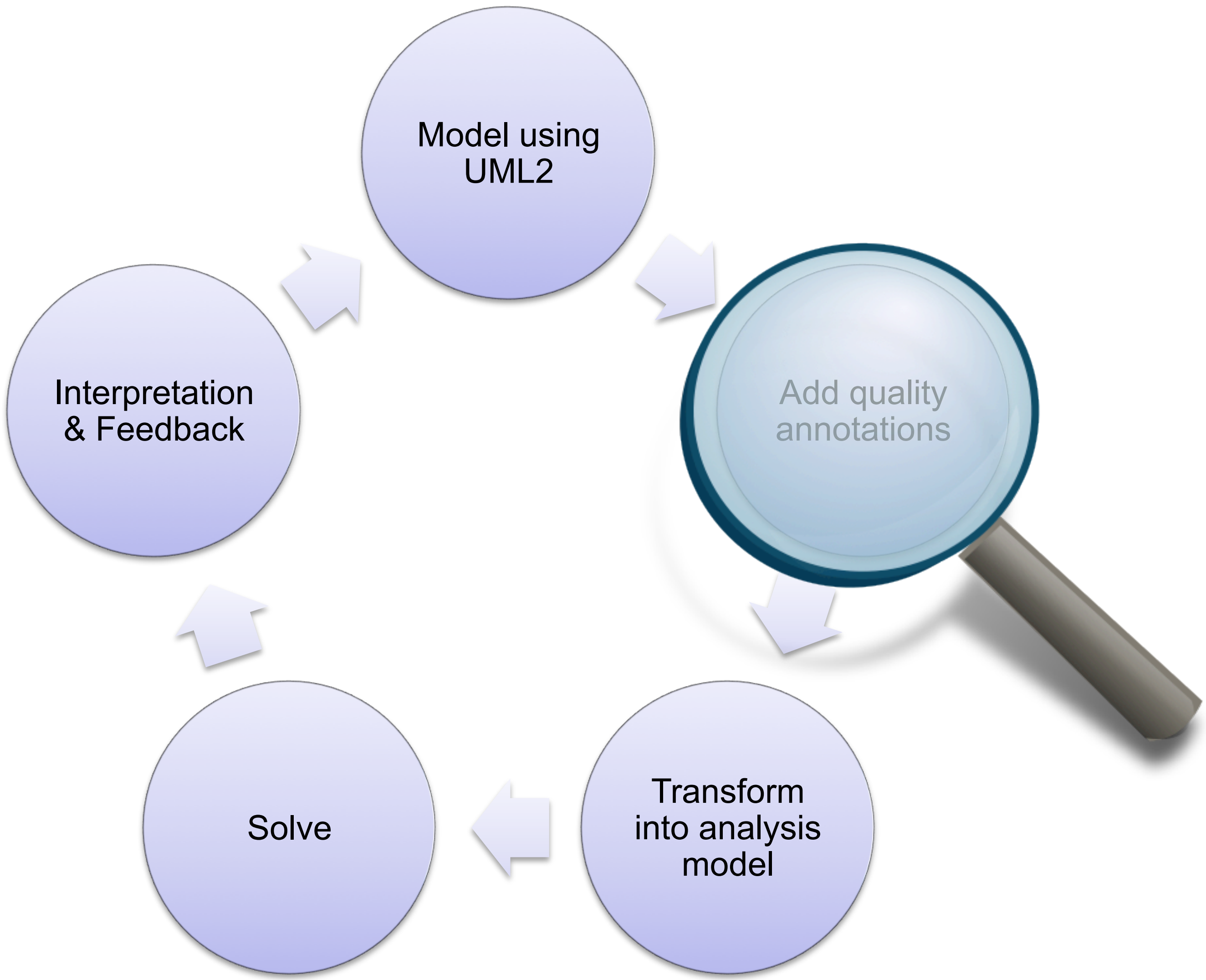
Process



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UML MARTE

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- UML Profile for MARTE
  Modelling and Analysis of RT Embedded Systems
- Current Version: 1.0
- Released in 2009
- Maintained by OMG
- Successor of UML SPT which it is supposed to replace
- Uses UML QoS & FT to define quality characteristics
- Slight overlap with SysML, supposed to be aligned
- Extensive Standard, >700 pages
- Defines several profile packages

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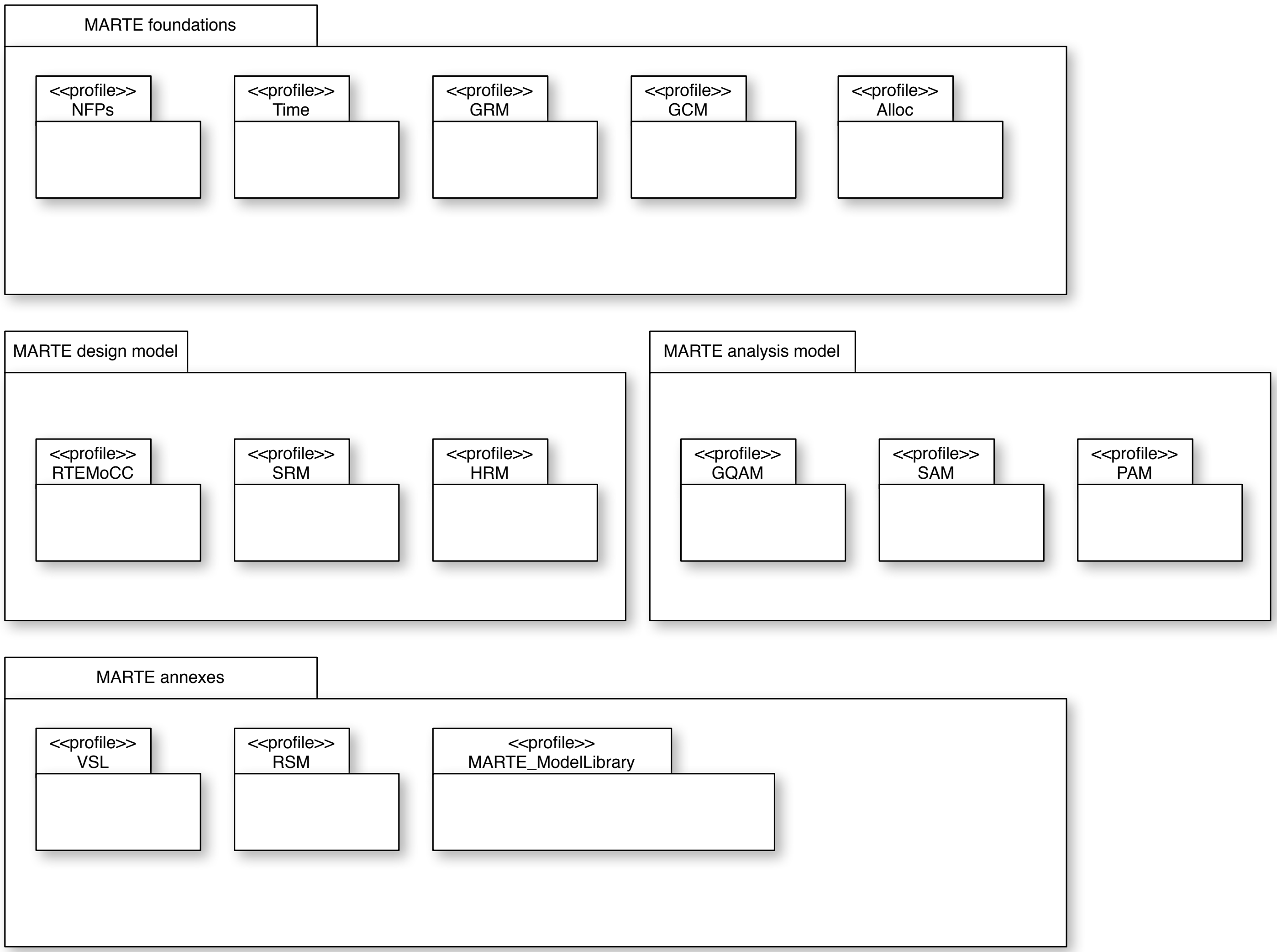
MARTE Layout



[http://www.omg.org/omgmarte/]

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Main Usecase

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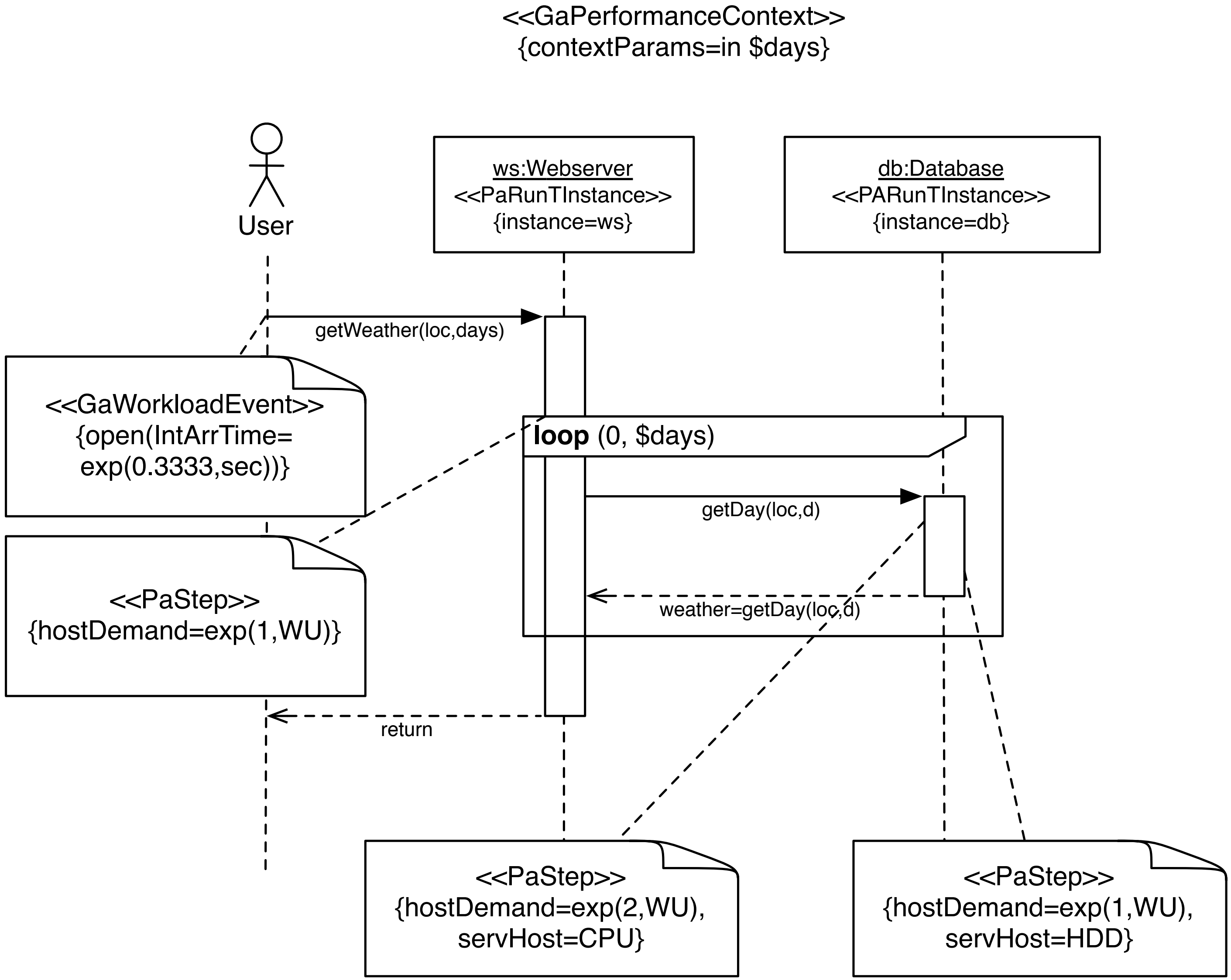

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Annotated Deployment

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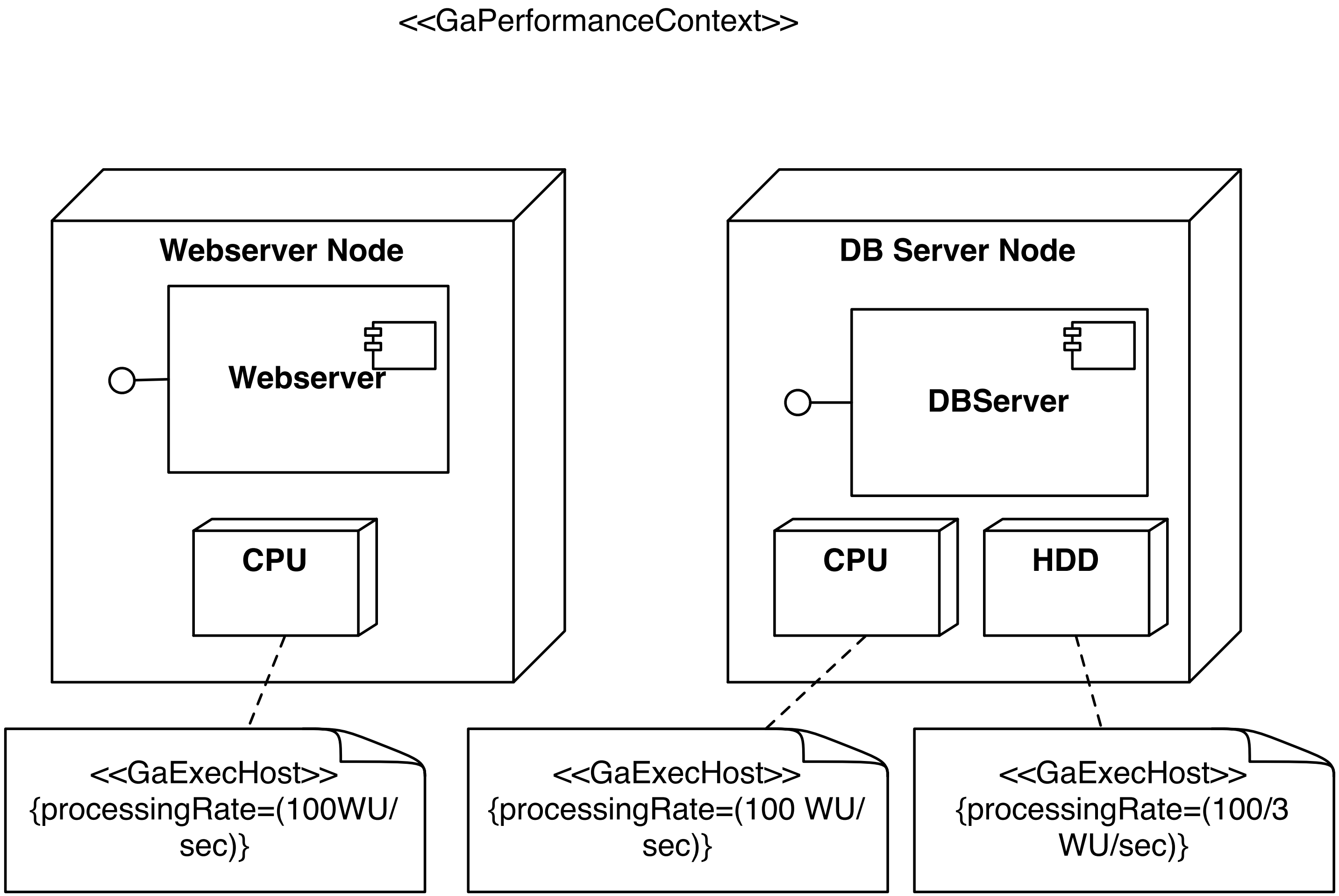

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Analysis Model

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Process

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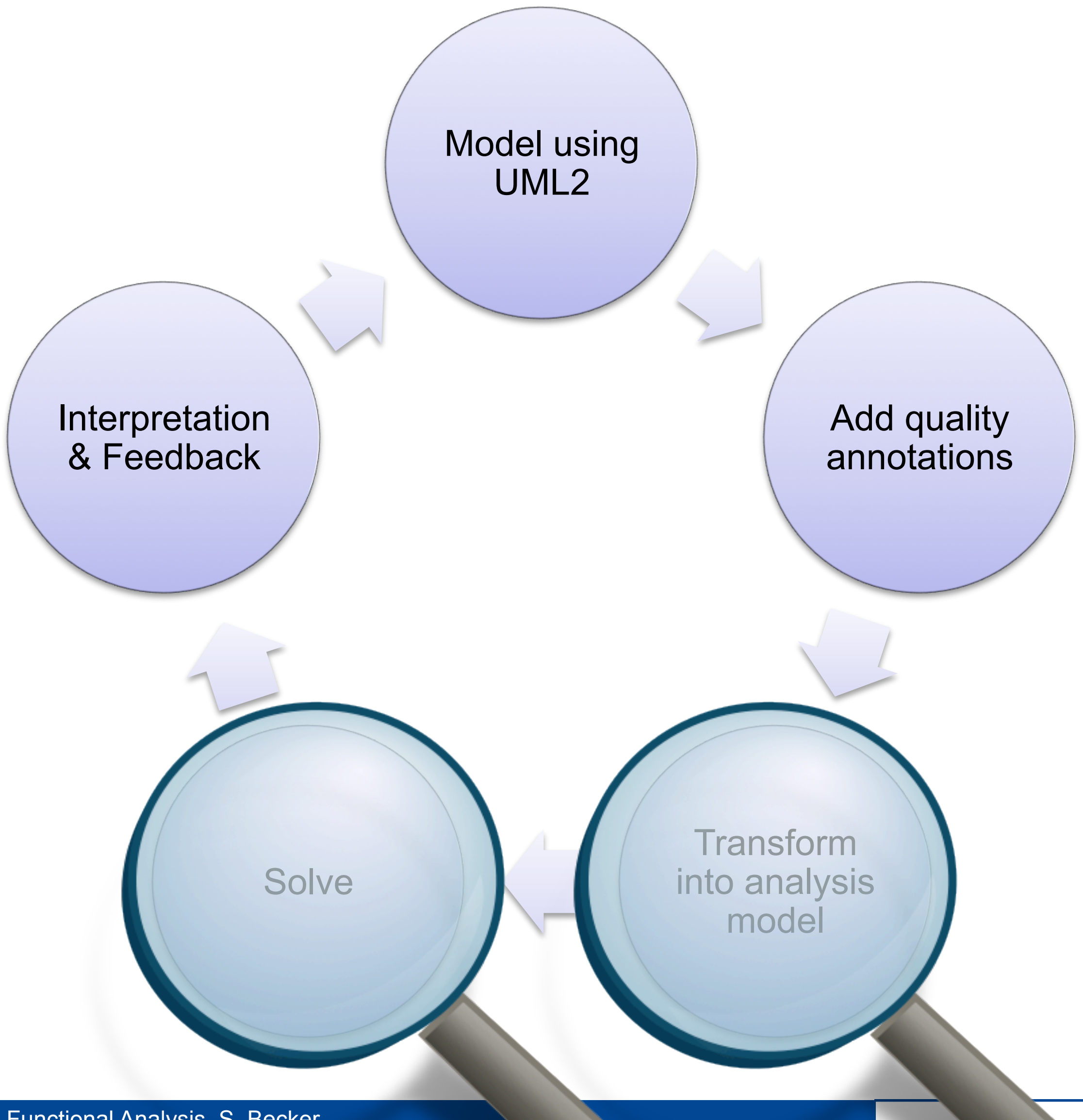

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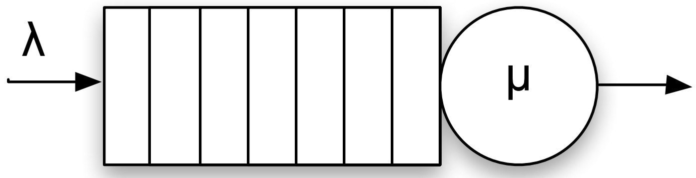
Queuing systems

- Mature analysis model for computer system performance
- Idea: Represent **active resources** as **waiting queues**
- Graphical notation:



E.g. queues for
  - CPUs
  - Disks
  - Network
- Reflects waiting times due to **contention**
- Underlying formalism is **Continuous Time Markov Chains (CTMCs)**

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Queuing network

- Queuing network
  - Directed graph
  - Nodes are service centre
  - Edges represent potential paths of jobs
  - Multiple job classes
    - Each having homogeneous service demands
    - Homogeneous routing probabilities
    - I.e., jobs in a class cannot be distinguished
- Widely used
  - Offer decent performance prediction accuracy
  - Good modelling paradigm and usability

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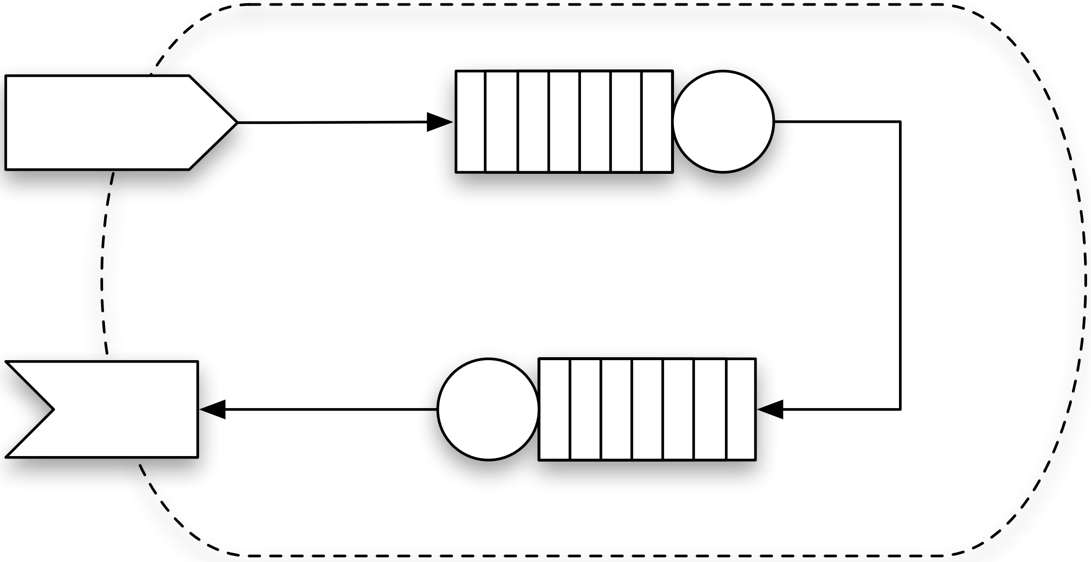
Open network



- Jobs enter net at source nodes
- Jobs leave net at sink nodes
- I.e., number of jobs not defined upfront
- Arrival process characterised by inter-arrival time
- Each queue is characterised in Kendall notation

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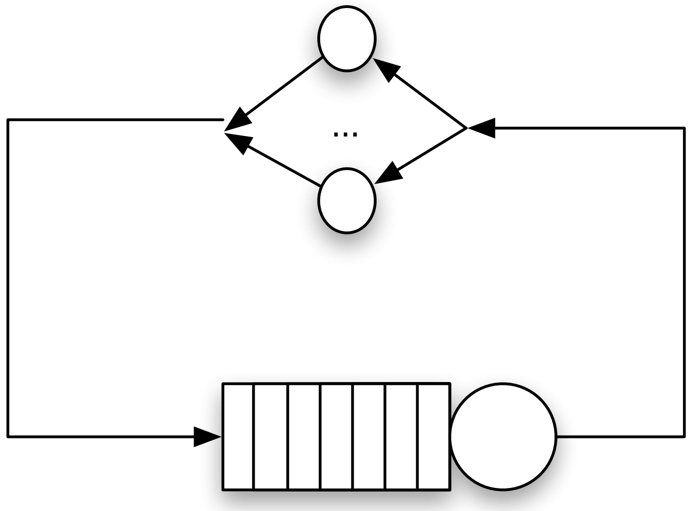
Closed network

- Network of a fixed number of jobs
- Contains a set of terminals
- Jobs circulate in network
- Jobs delay in terminals for a given think-time interval
- Sometimes also modelled by IN and OUT ports which are connected in a loop



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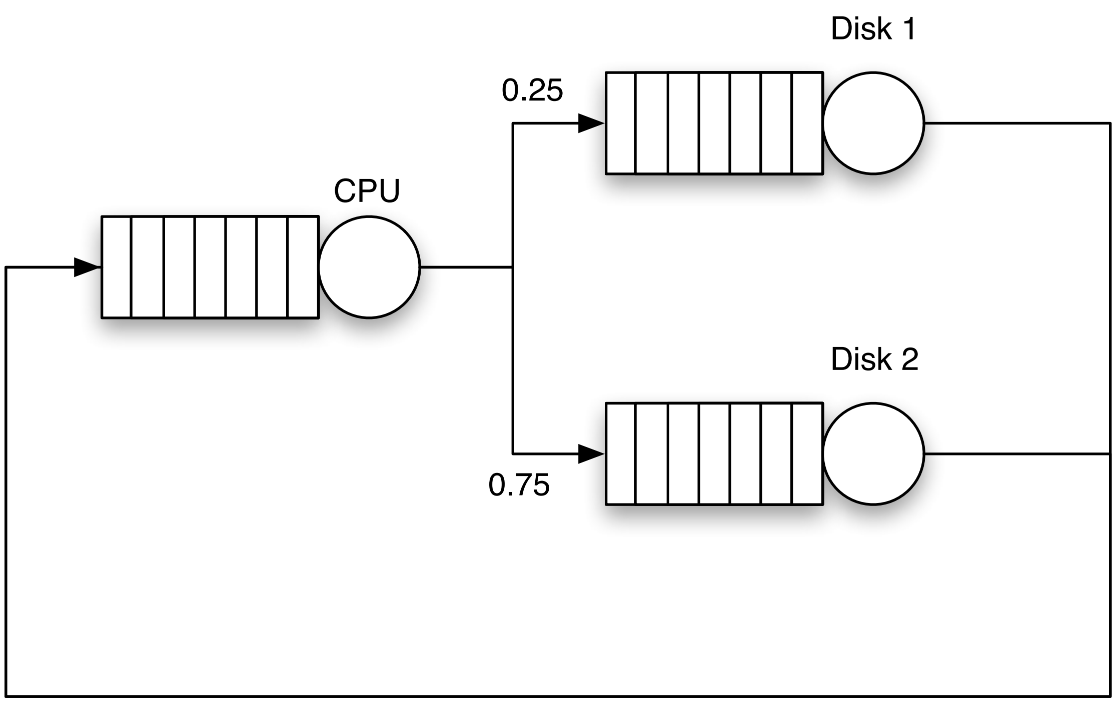
Routing in QNs

- Jobs take probabilistic routes
- Route specified via transitions probabilities
- Given per class of jobs for multiclass networks



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QN for our example…

Highlighting the core ideas of the transformation step

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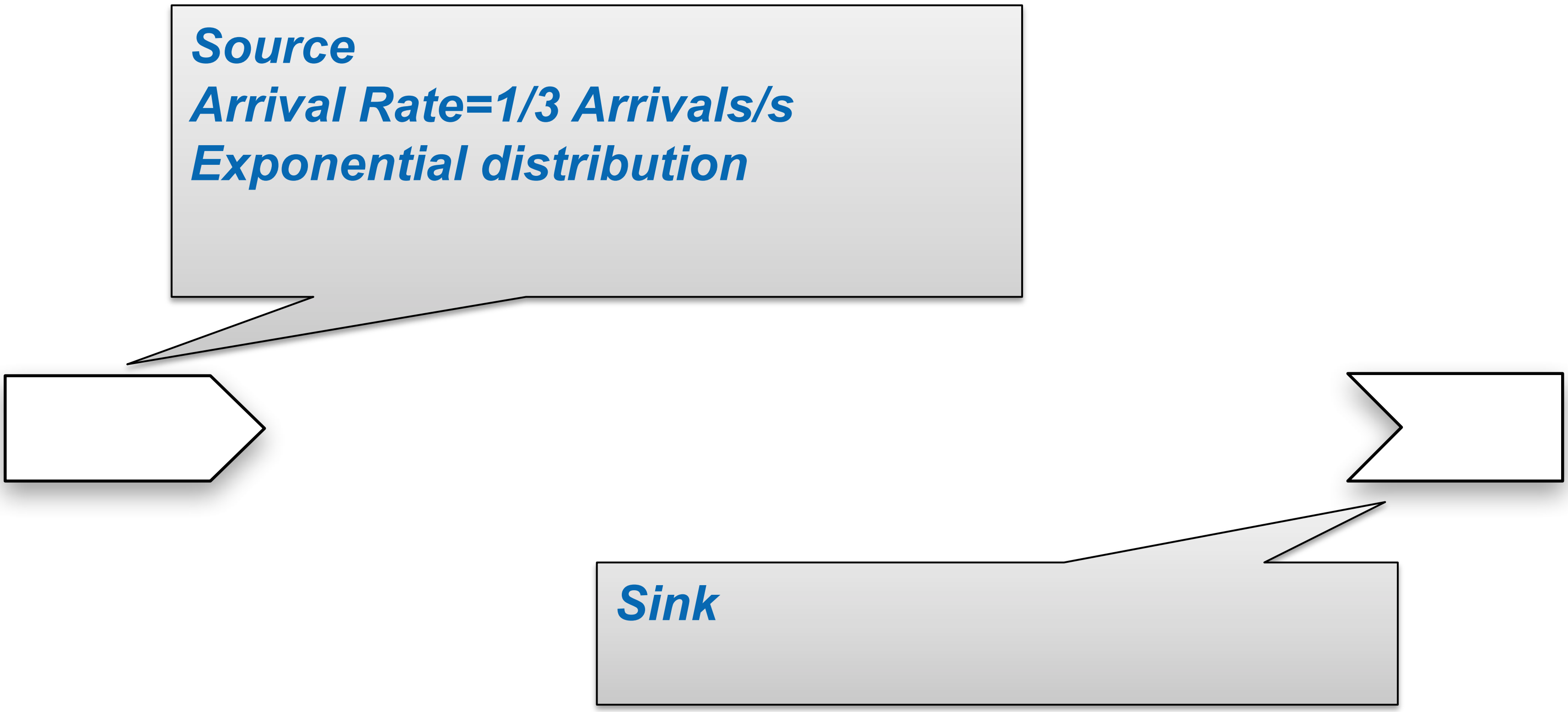
Performance: Derive QN



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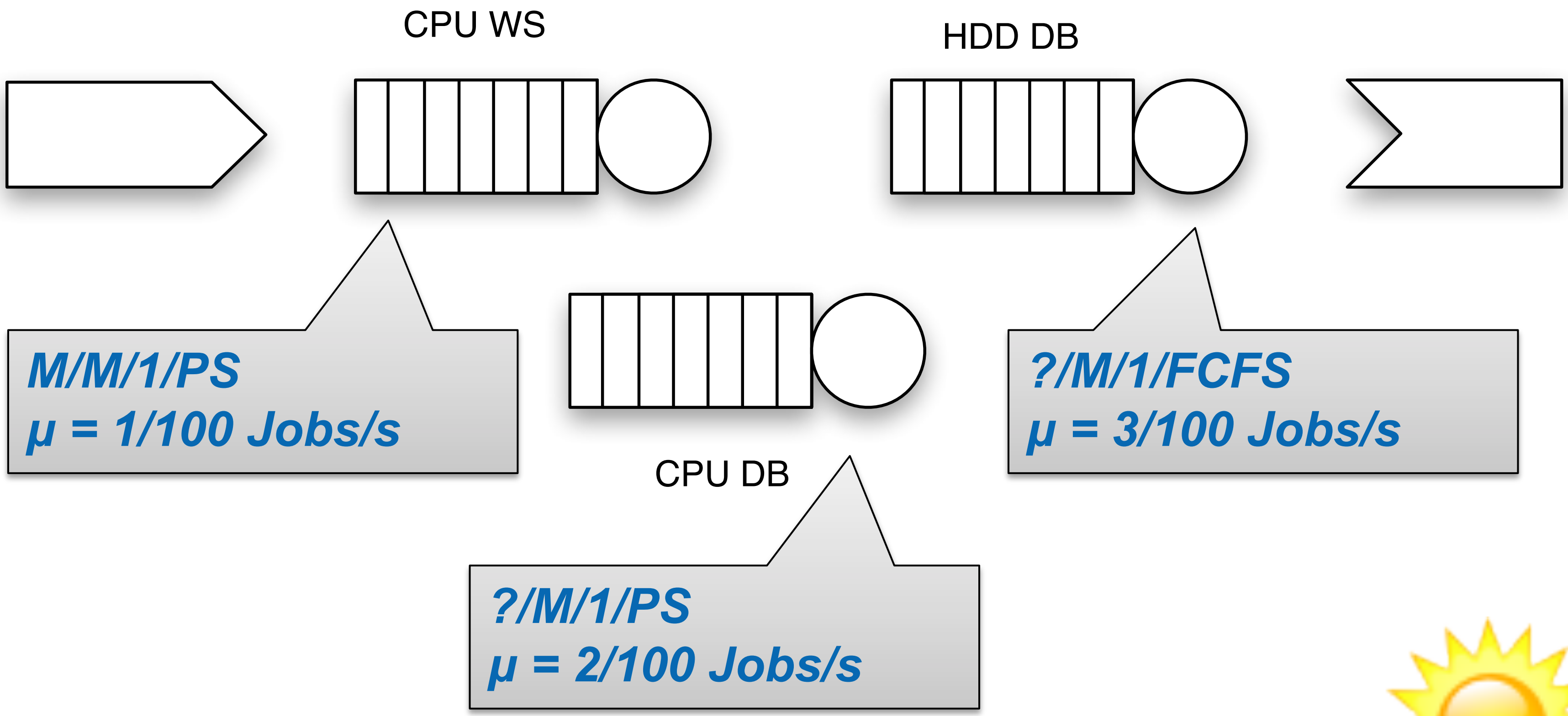
Derive QN

Add a queue per GaExecHost and their parameters



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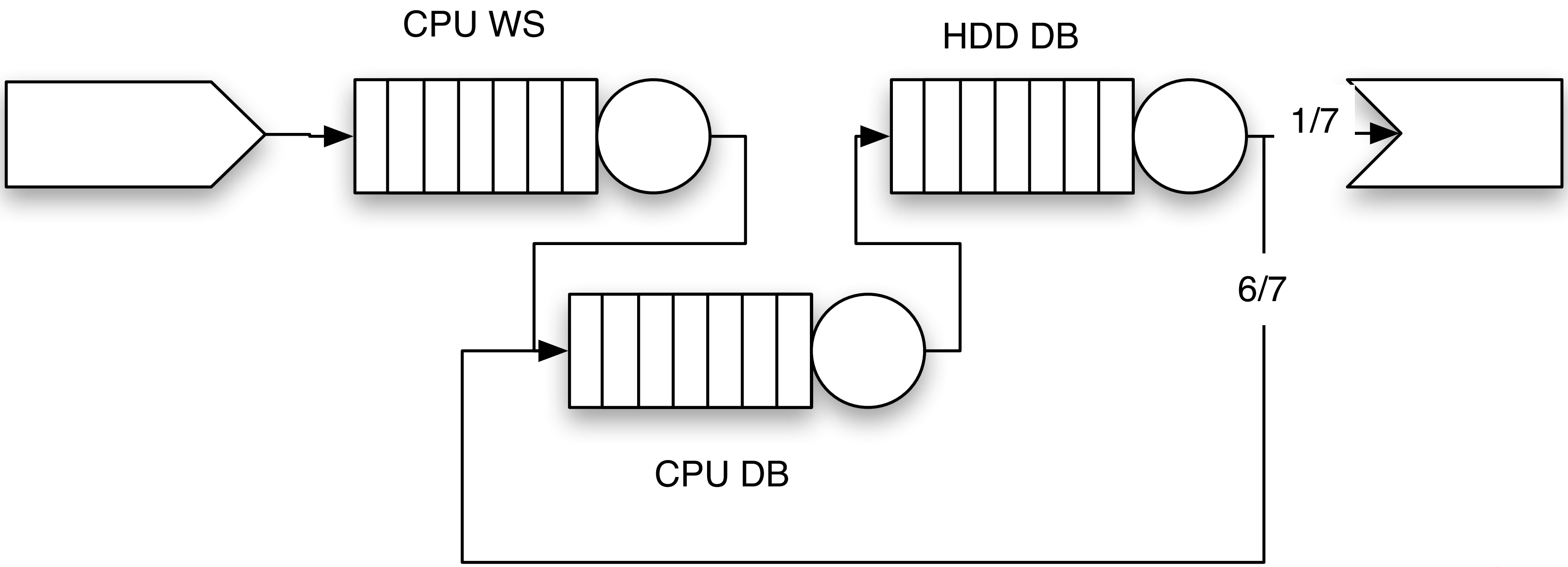
Derive QN

Add routes and their probabilities



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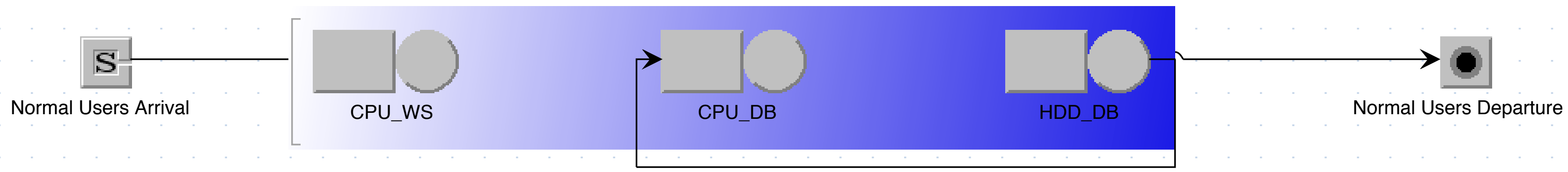
Put it in a Solver

JSimGraph Model



- Results (according to jMVA)
  - Mean System RT = 0.5502 sec
  - Util CPU_WS = 0.33%
  - Util CPU_DB = 2.33 %
  - Util HDD_DB = 6.99 %

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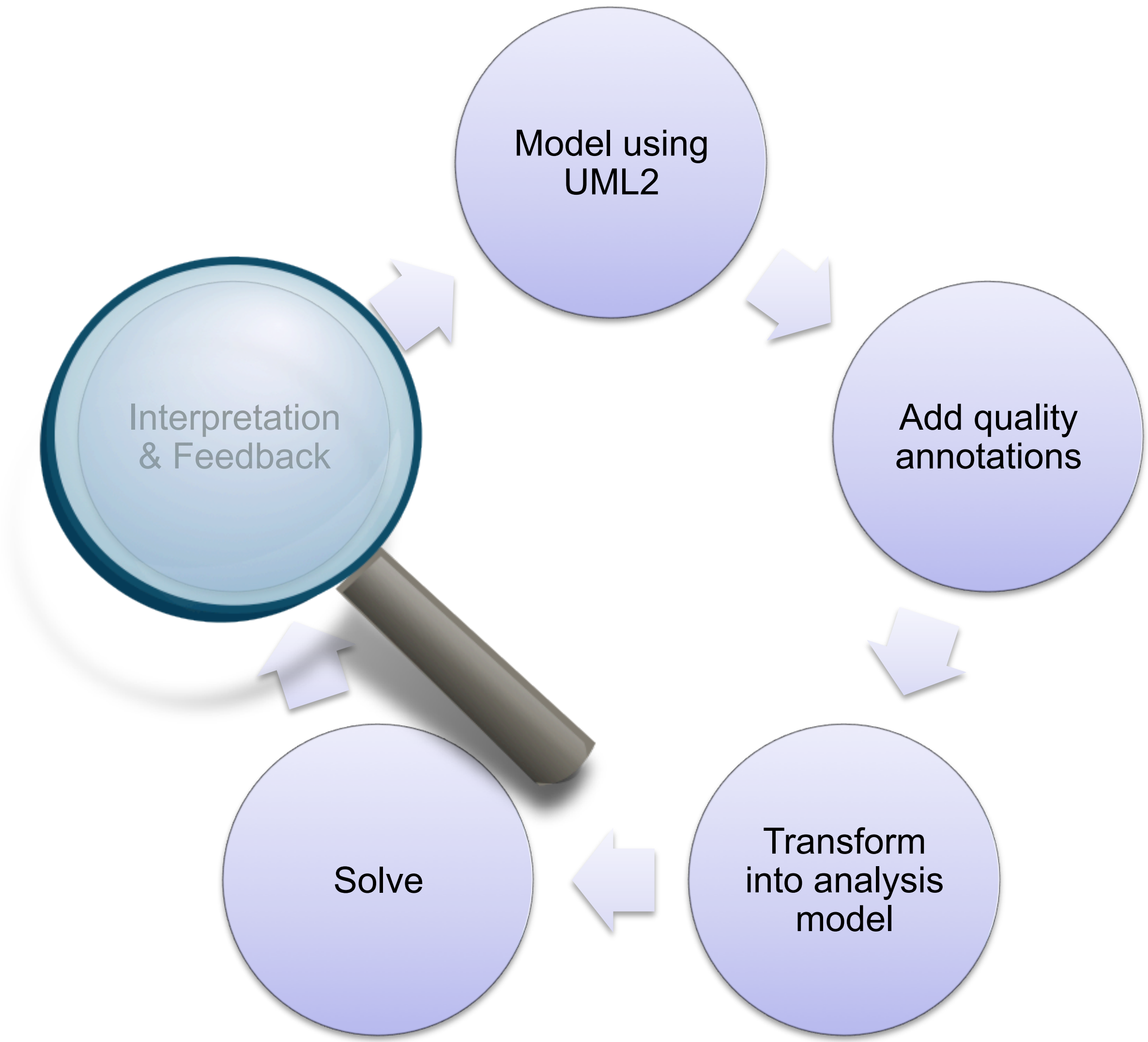
Process



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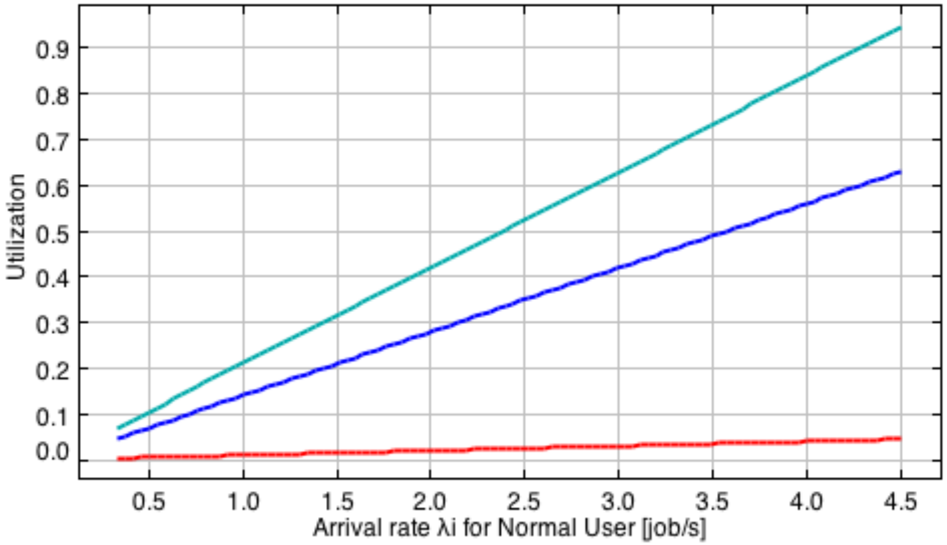
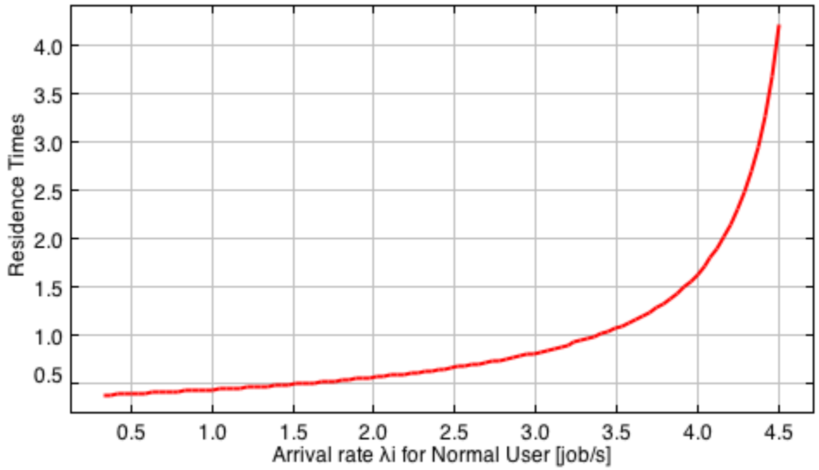
What-if analysis for arrival rate



- At arrival rate 4.5 the DB HDD (cyan) becomes the bottleneck
- The HDD queue starts to overload

- RT constraint from our requirements is violated at arrival rate of > 3.5 job/s
- Starting from a rate of 2.5 jobs/s the system shows overload effects



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Reliability

- Common method is to create a Discrete Time Markov Chain (DTMC), i.e., disregard time
- Each step of the system becomes a state of the DTMC
- In each state, system can fail according to a failure probability. It reaches an absorbing failure state in case of failure
- Loop can be either unrolled or approximated by a geometric distribution
- PROFOD is probability of reaching the success state, i.e., the state after the last system action

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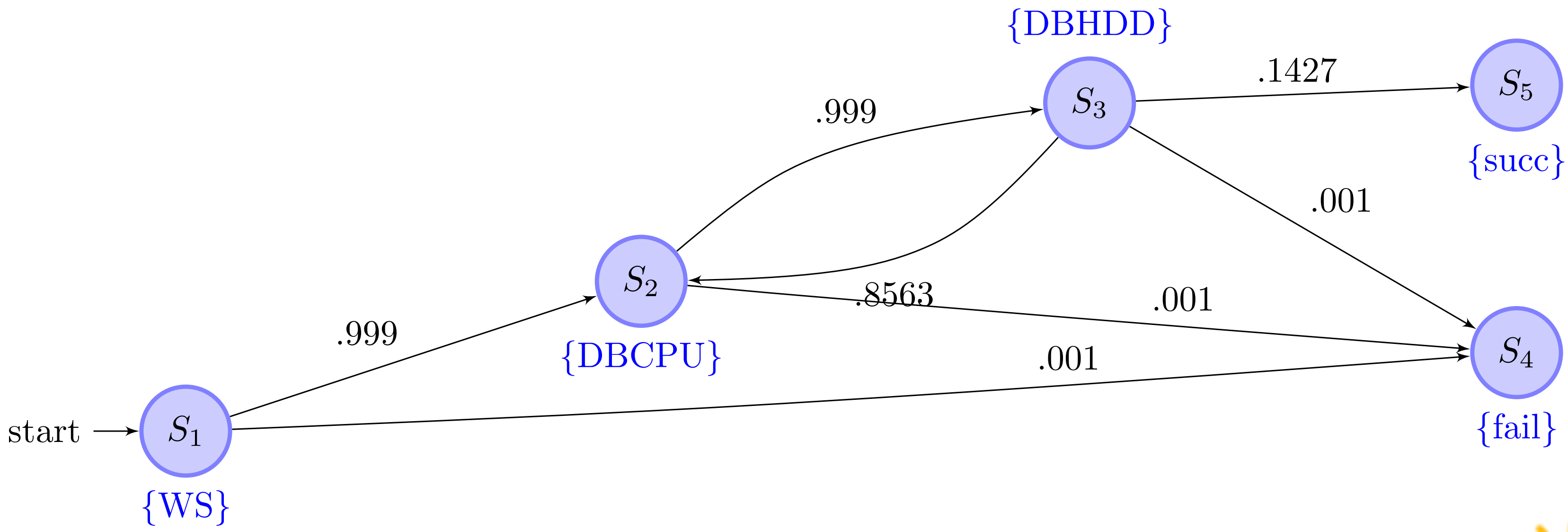
- Create a DTMC for our SuS. Here approx. of loop counts
- PROFOD approx. 1,48% according to PRISM



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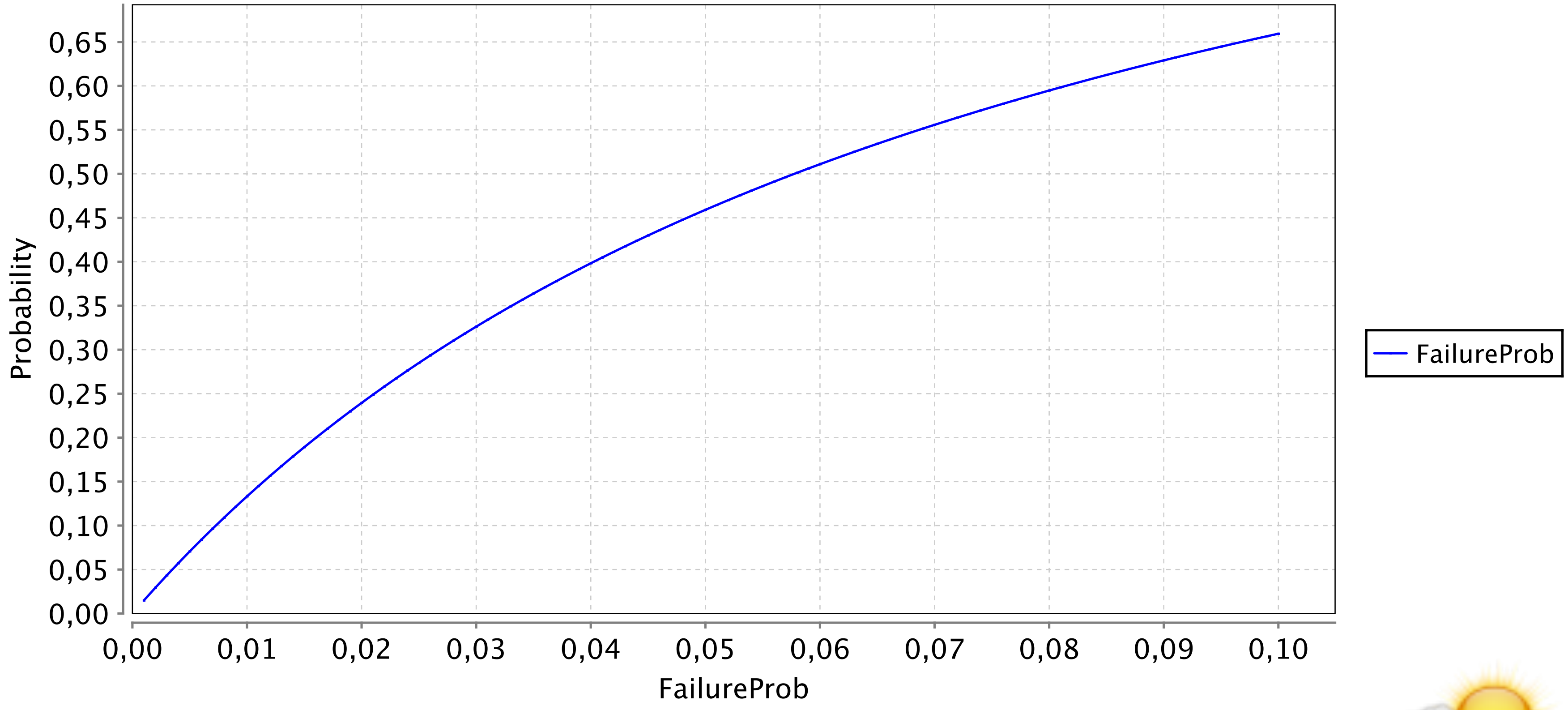
What if analysis



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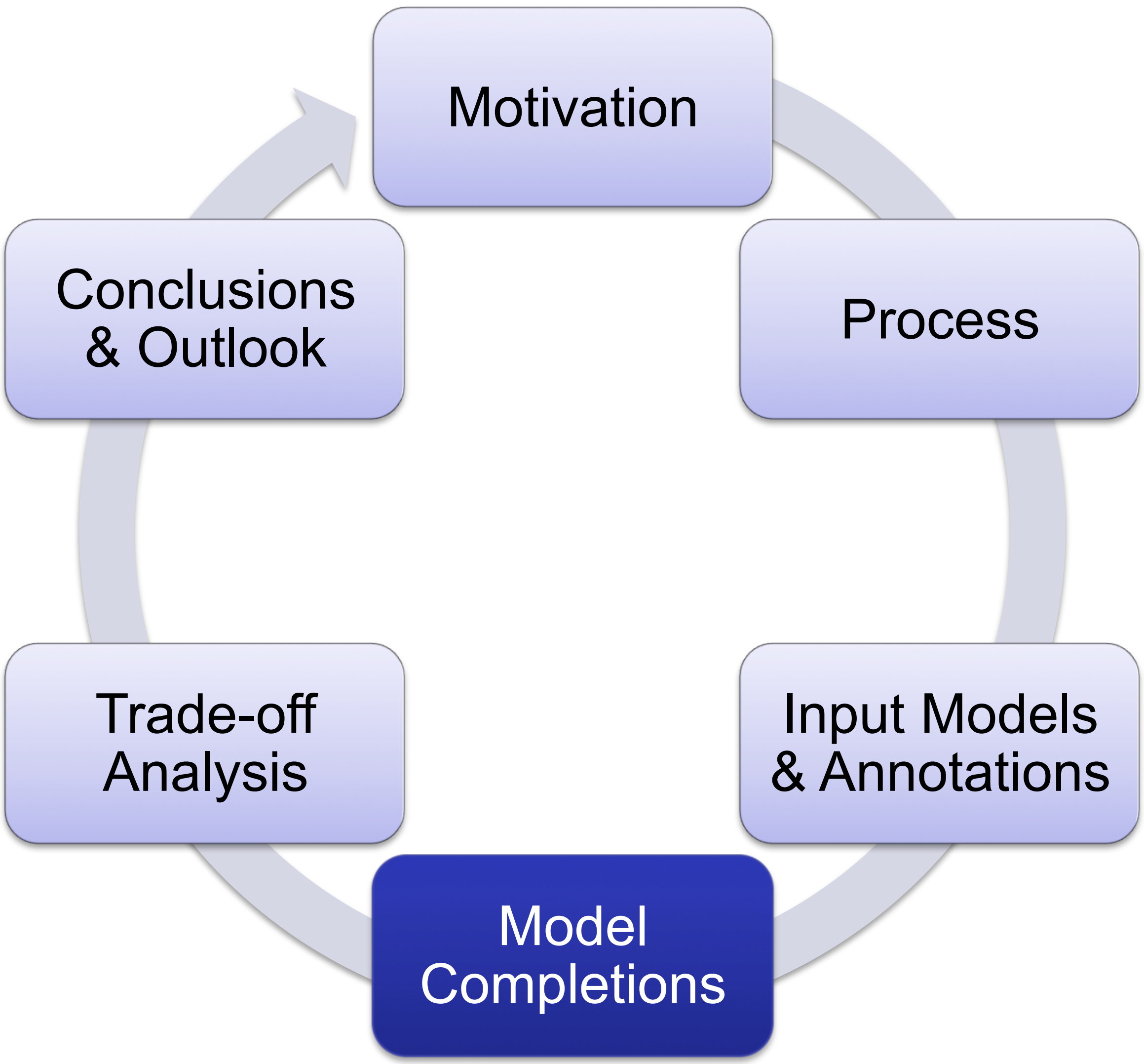
Outline



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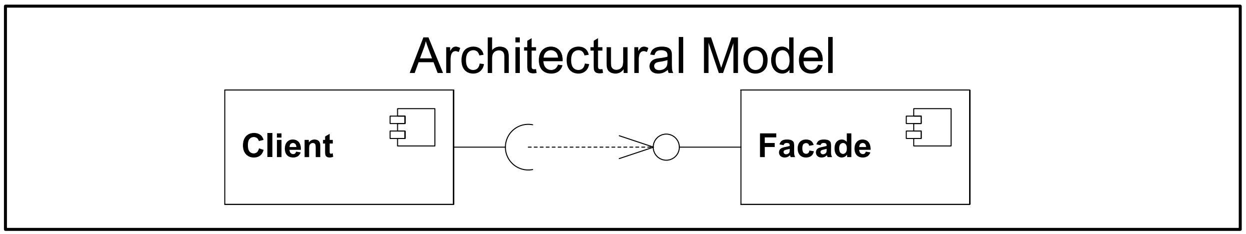
Motivation



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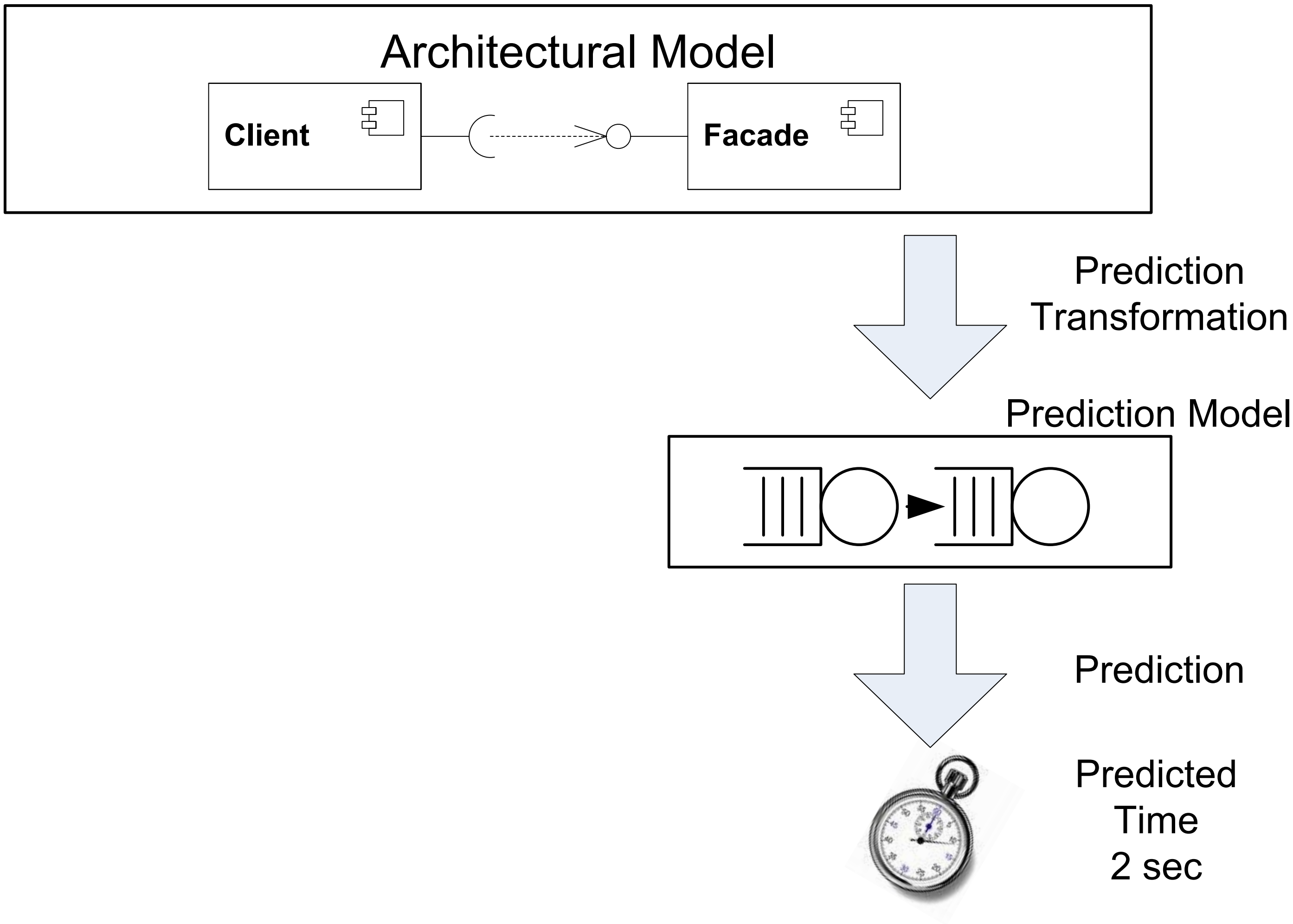
Motivation



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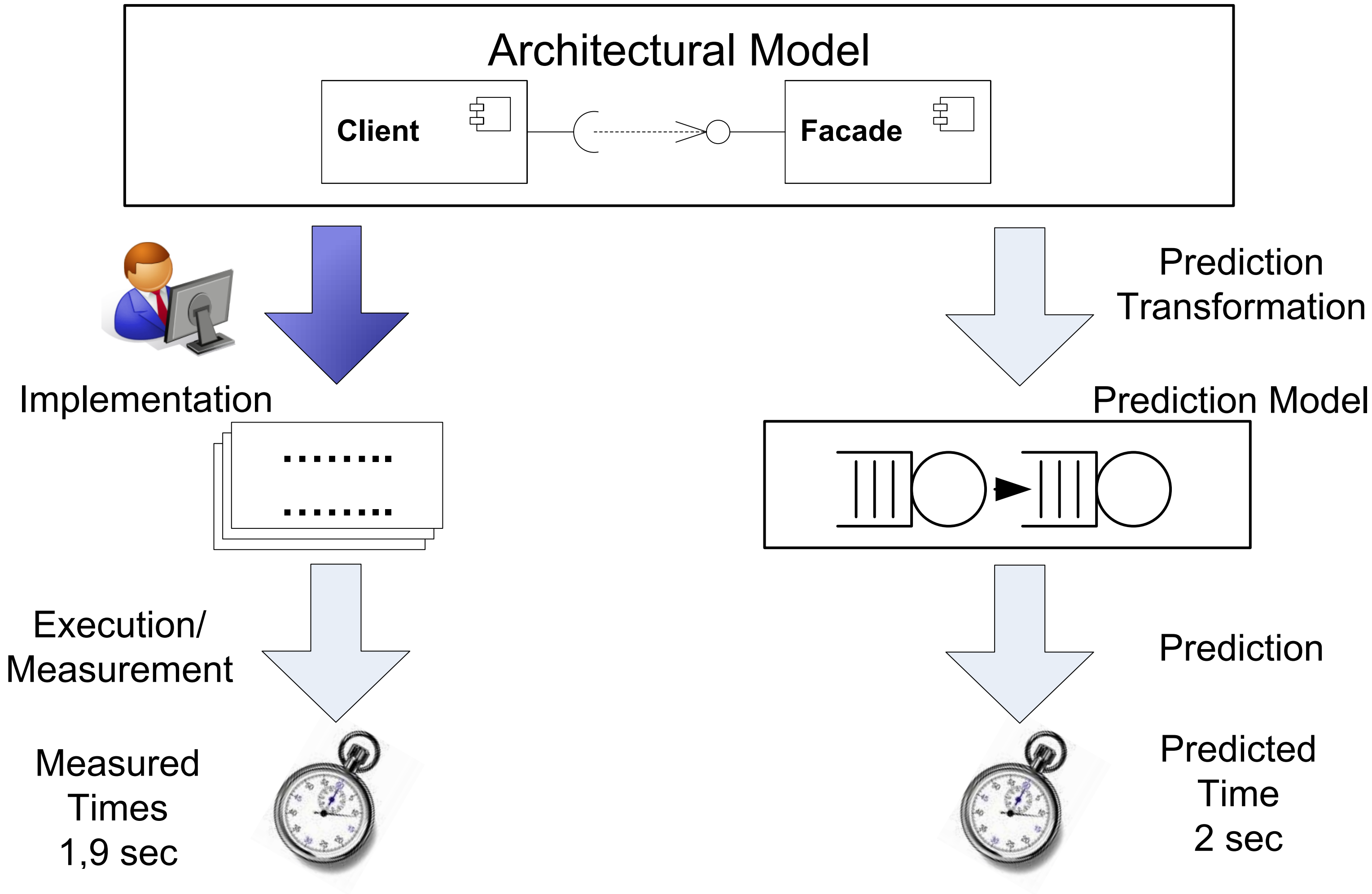

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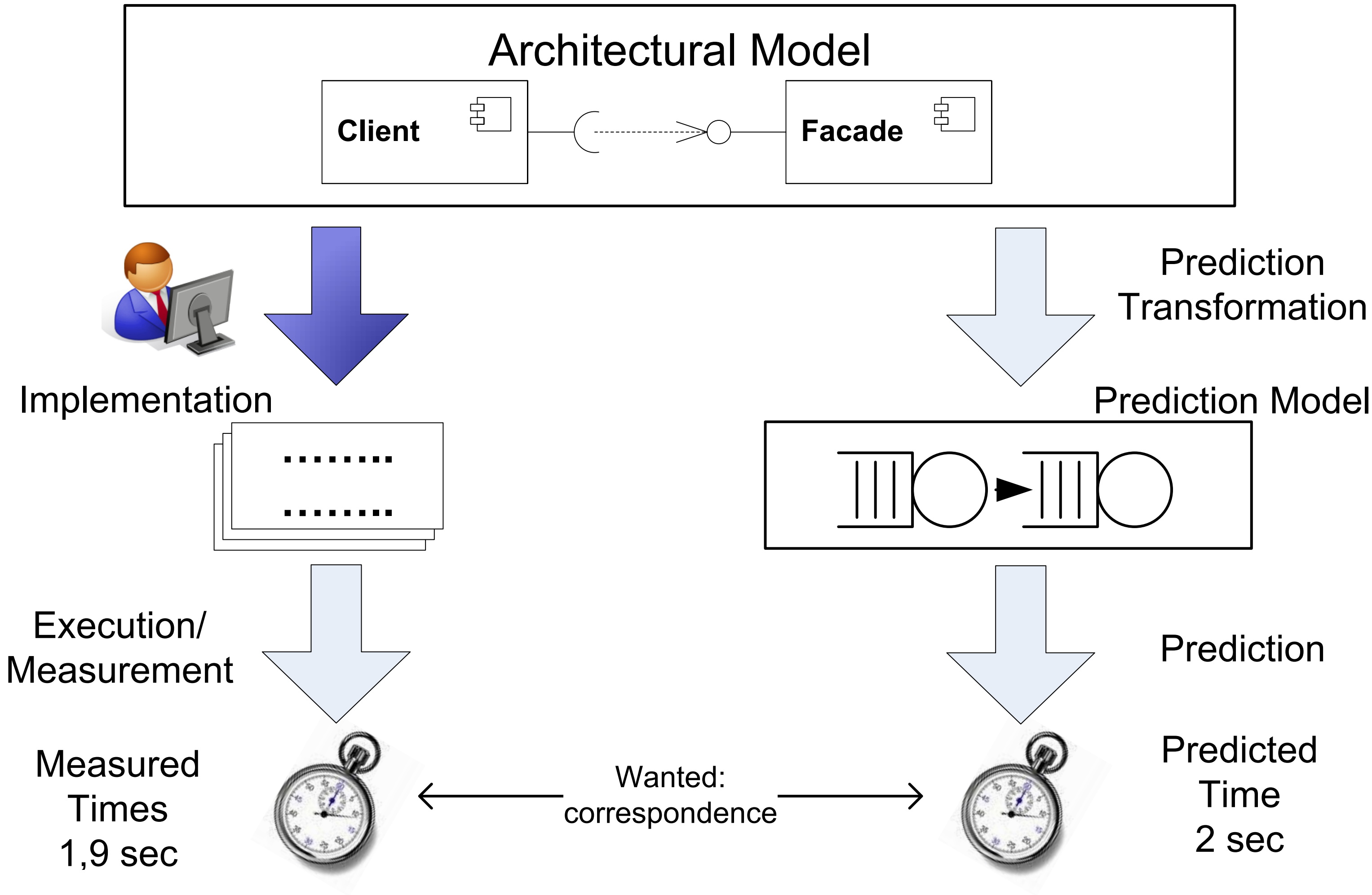

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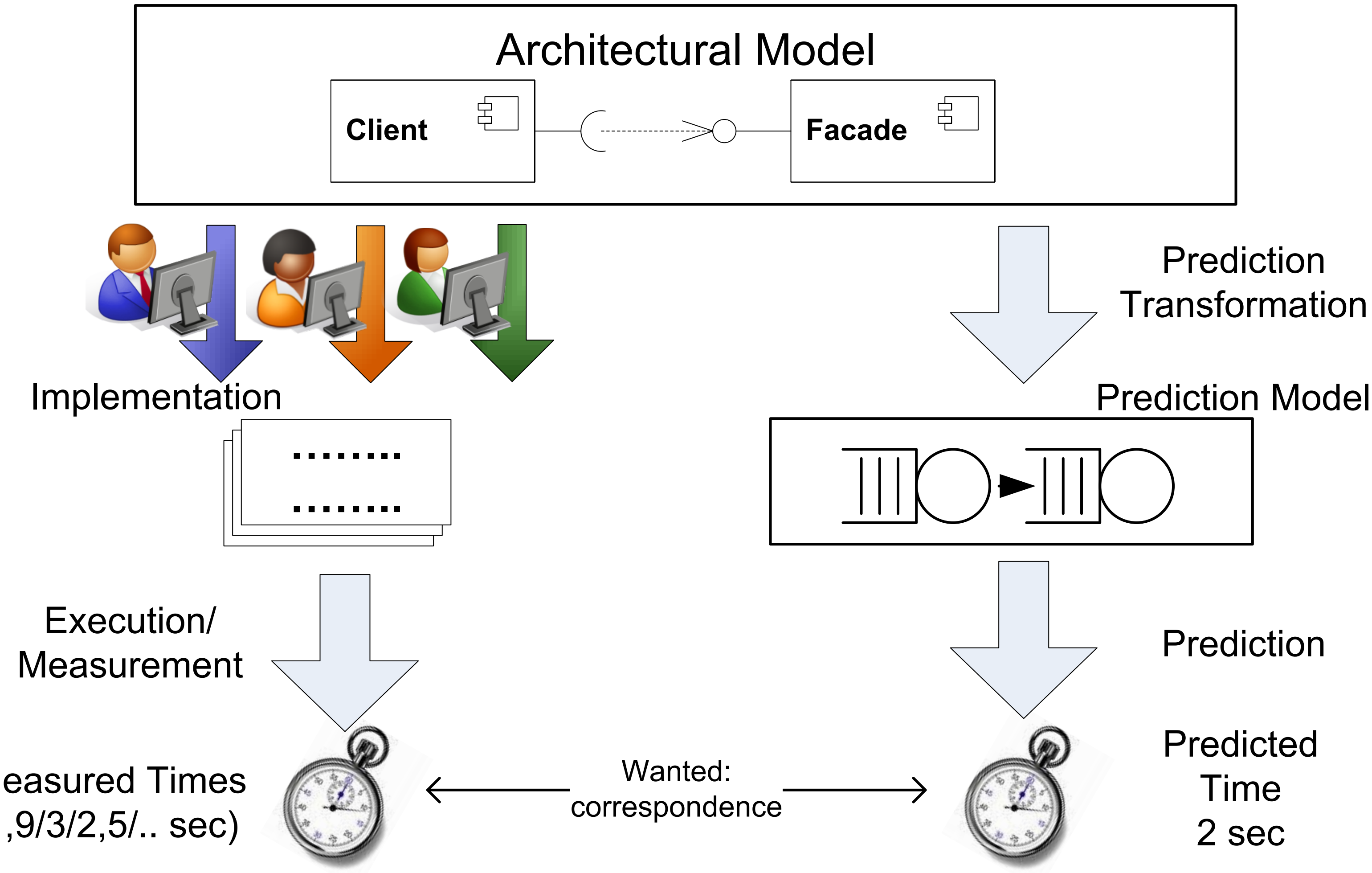

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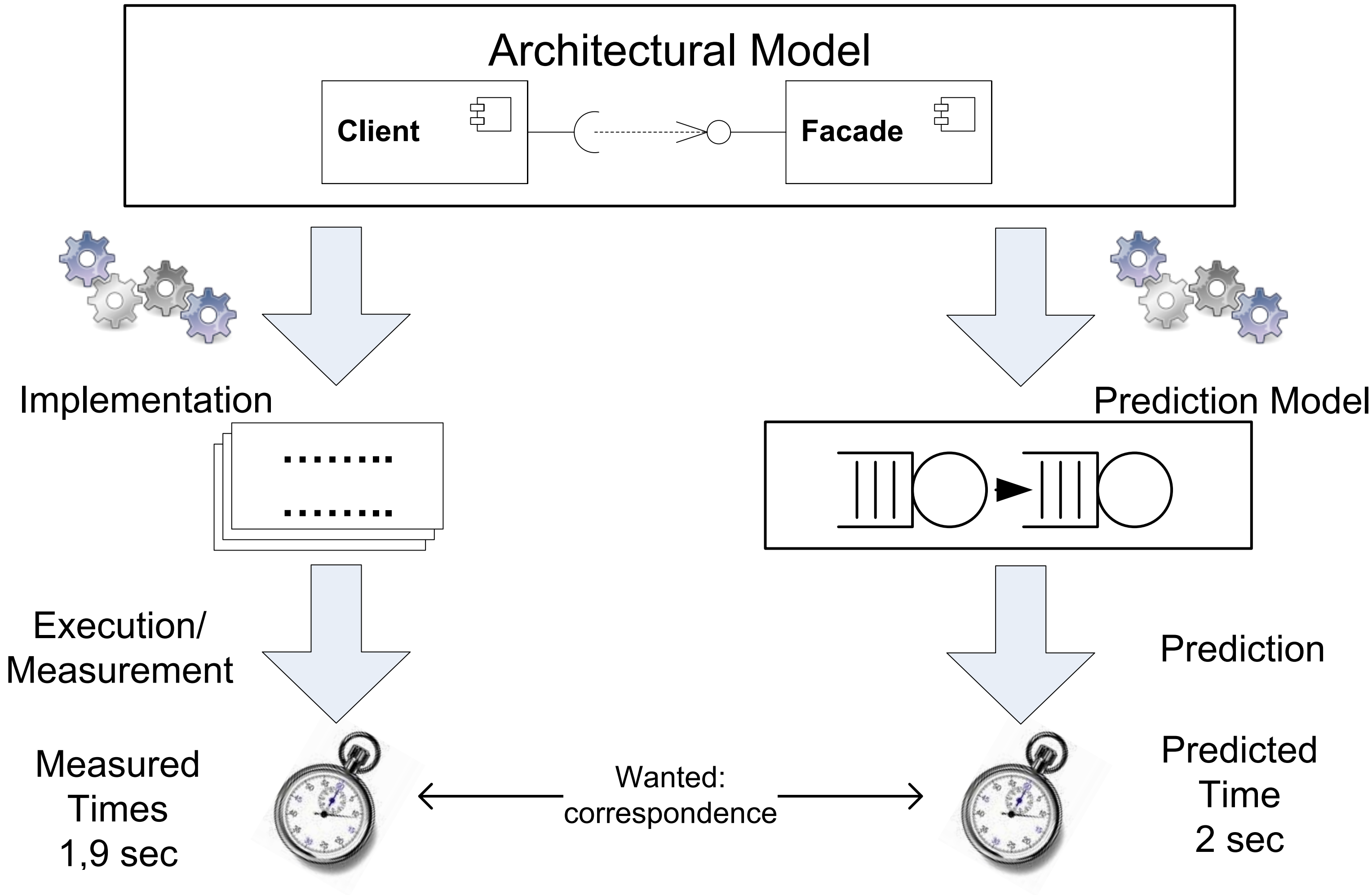

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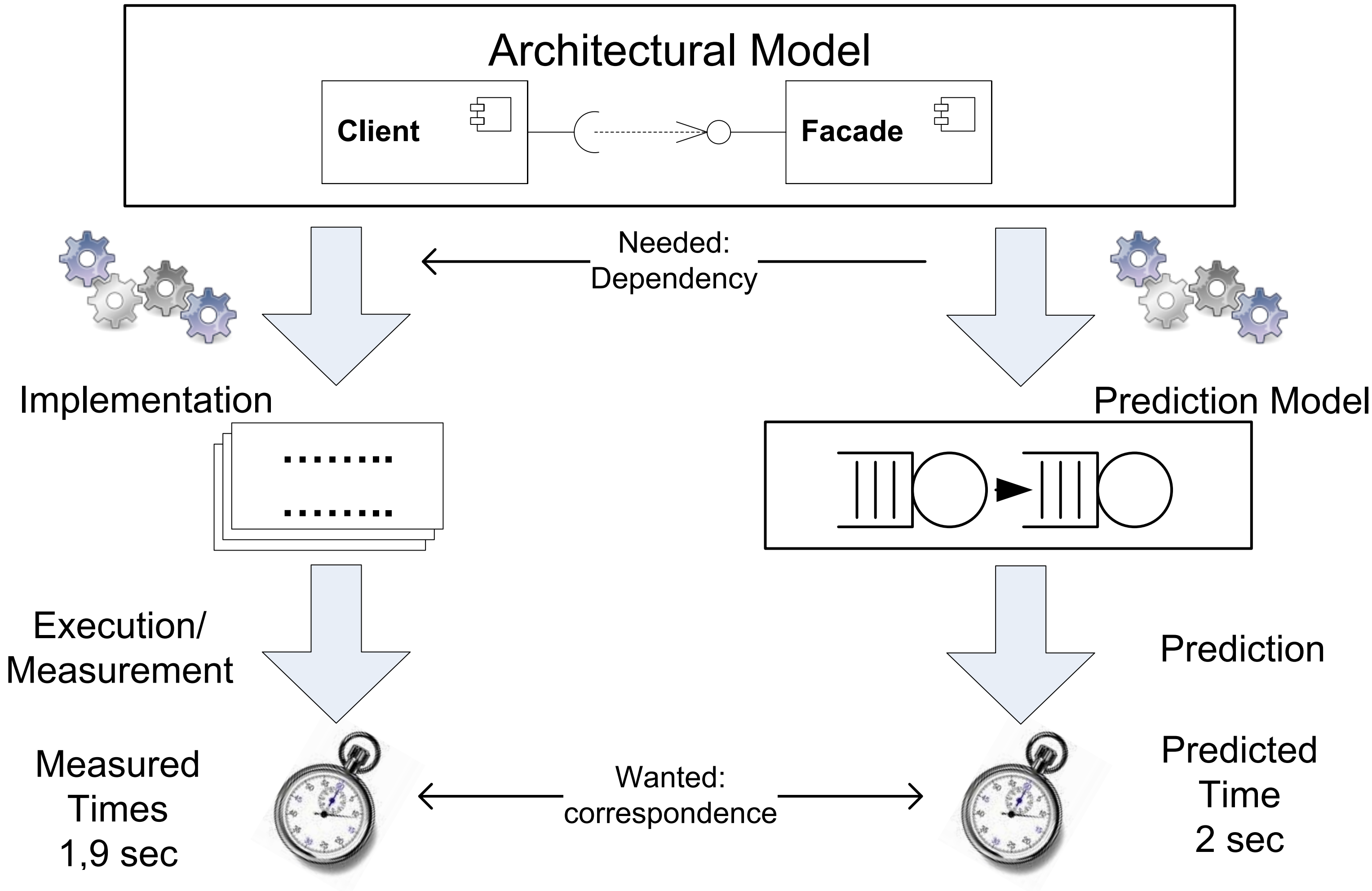

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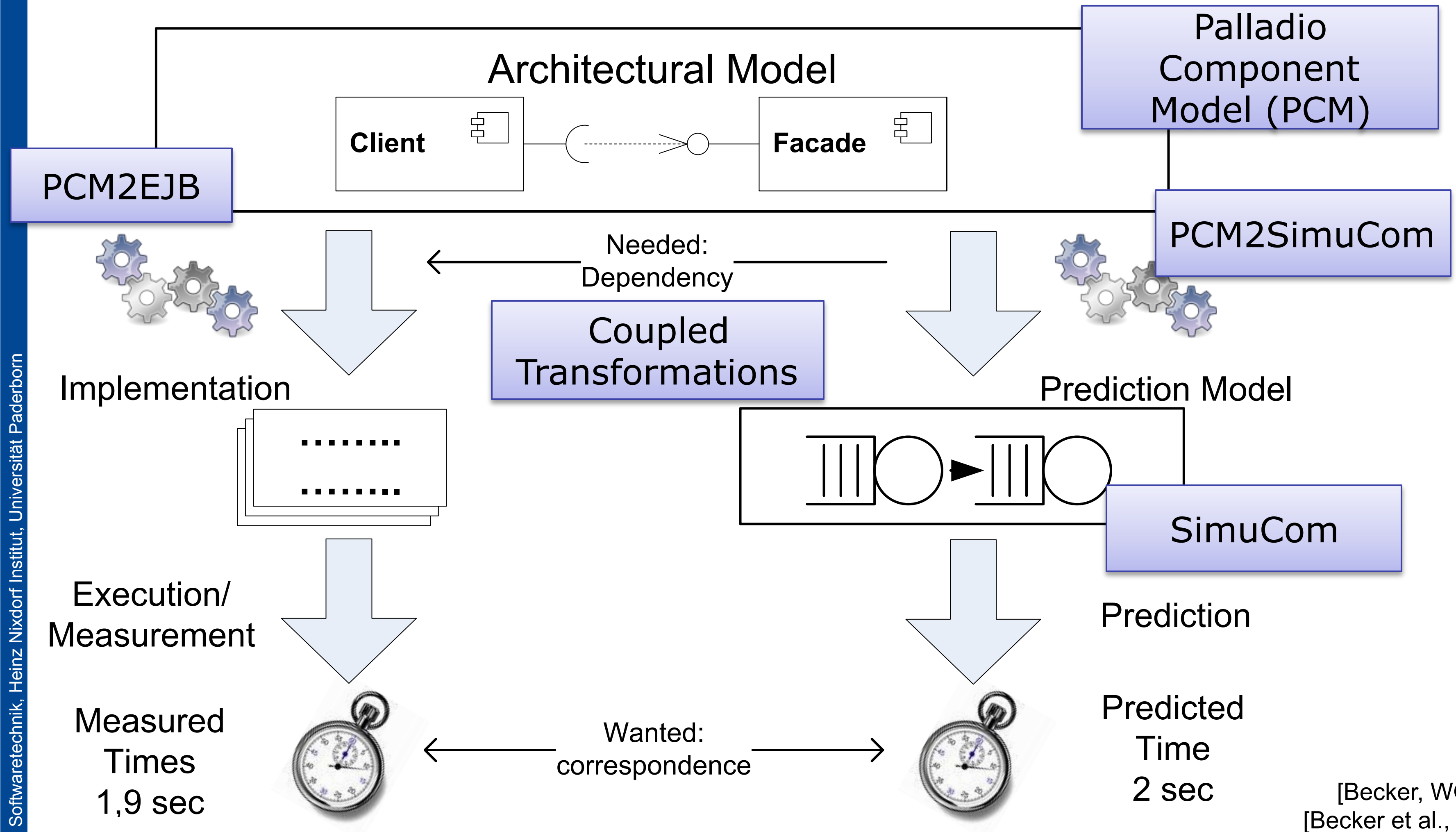

[Becker, WOSP, 2008]
[Becker et al., JSS, 2008]

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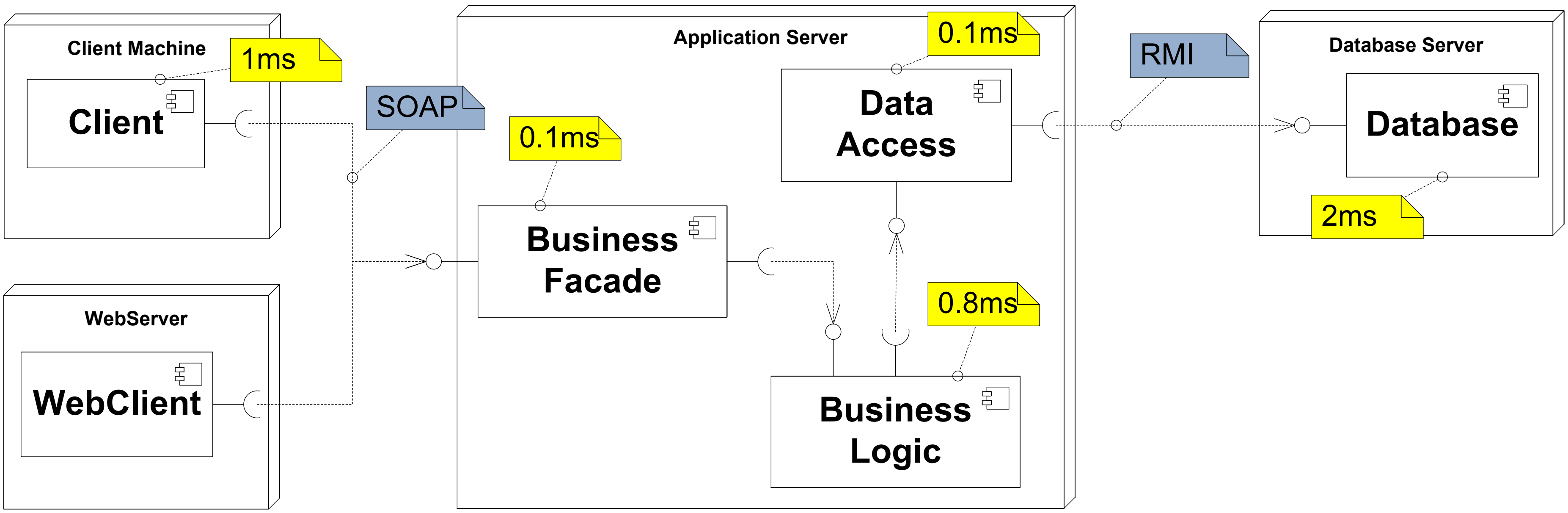
Example cont.



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Example cont.

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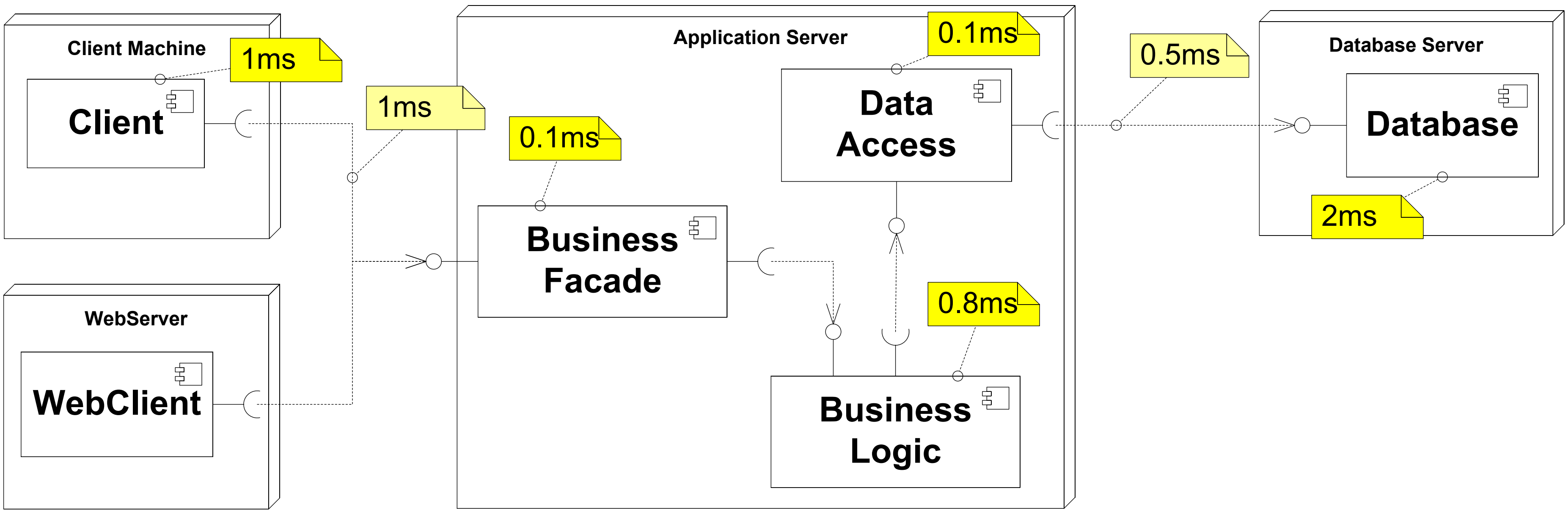

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Connector Completion

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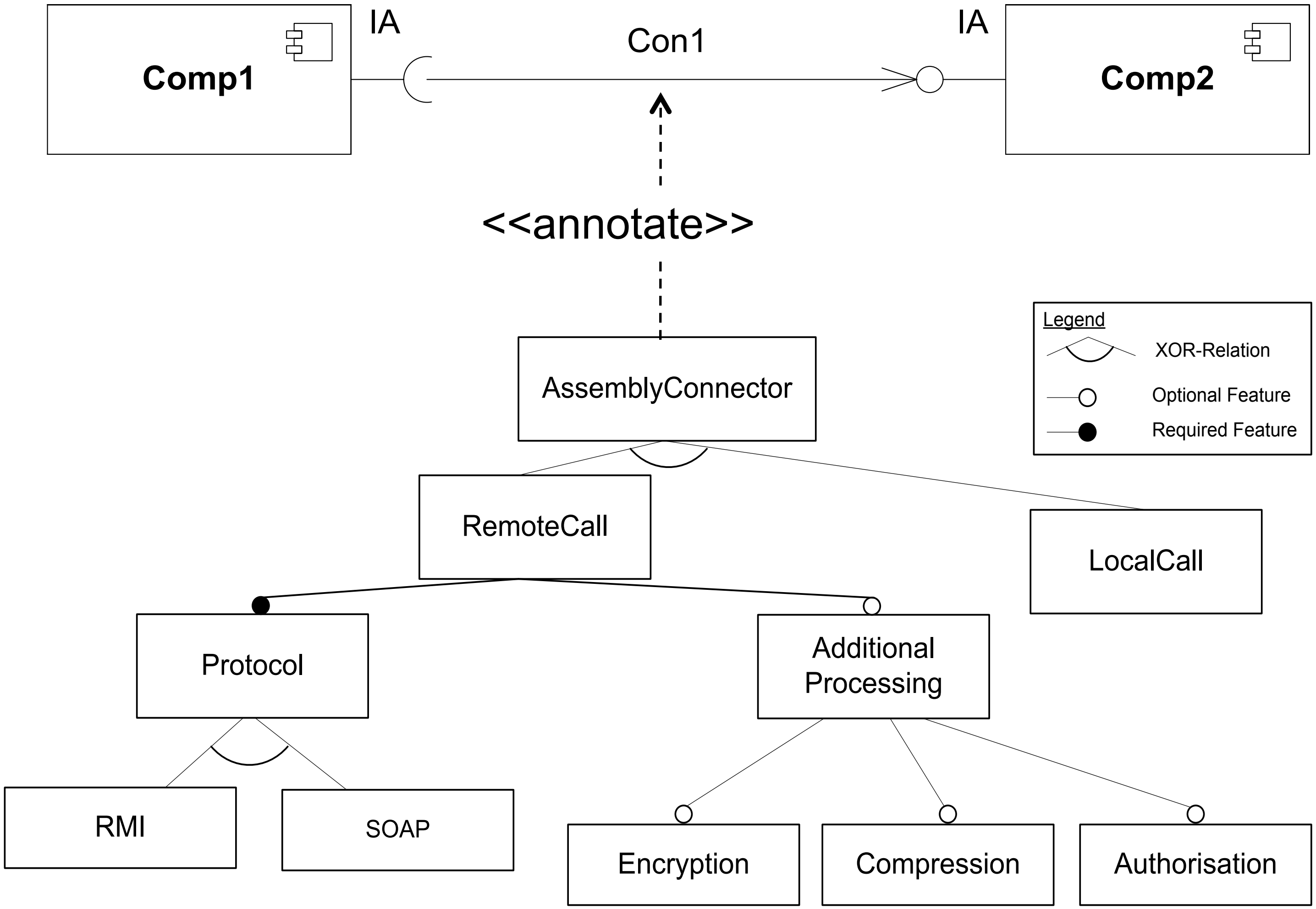

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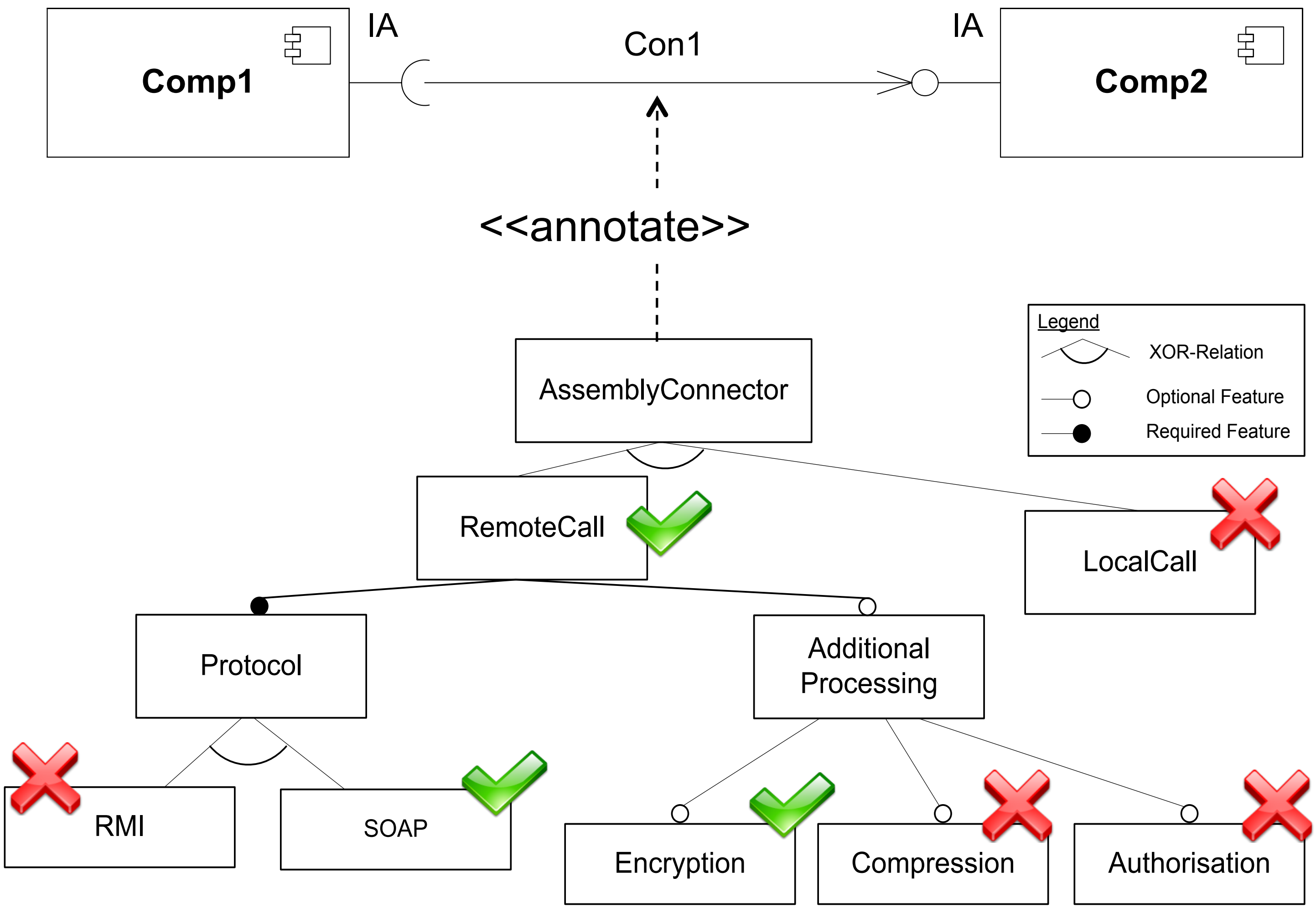

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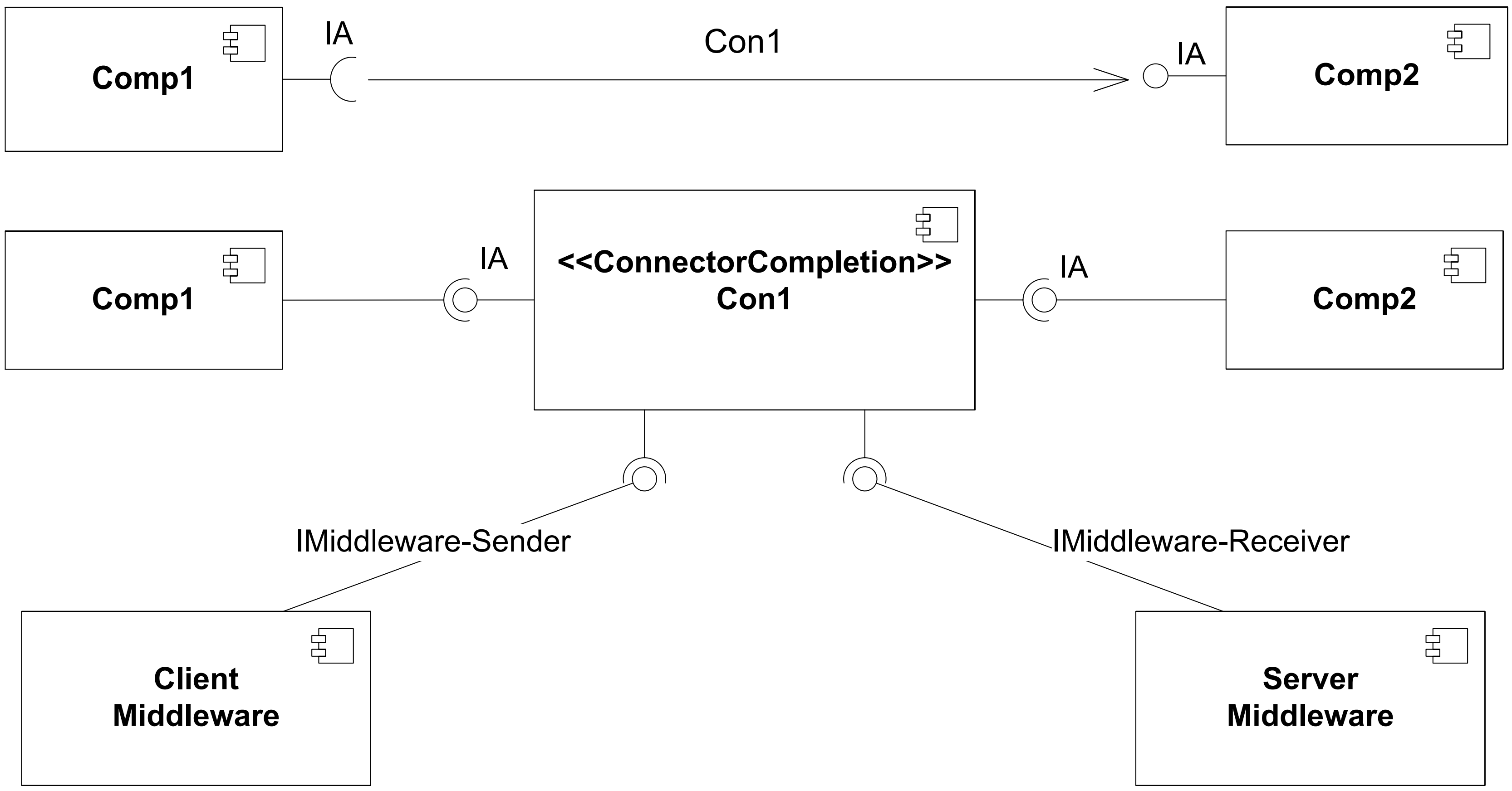

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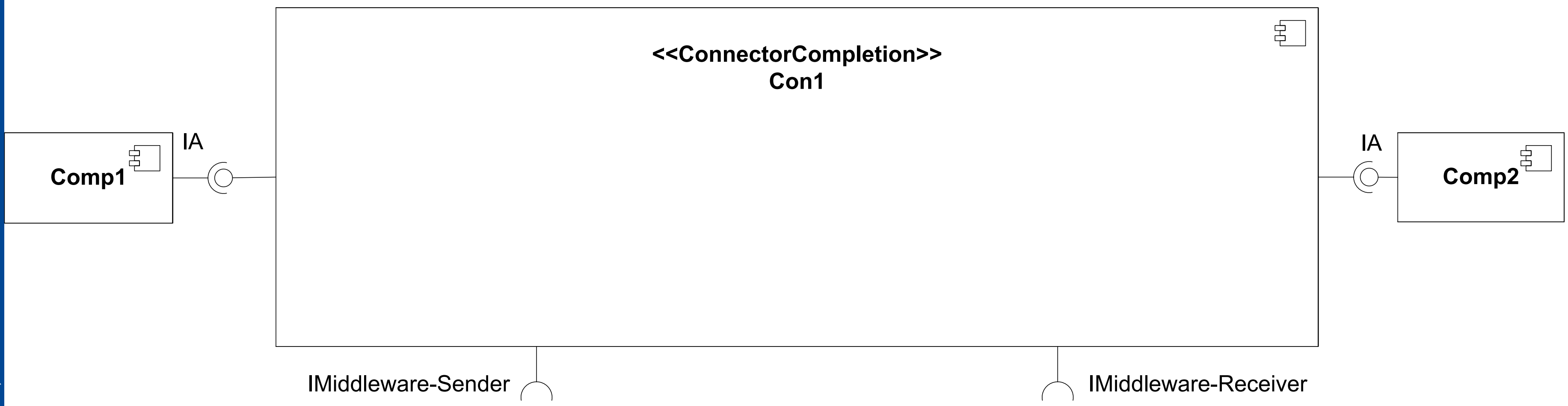

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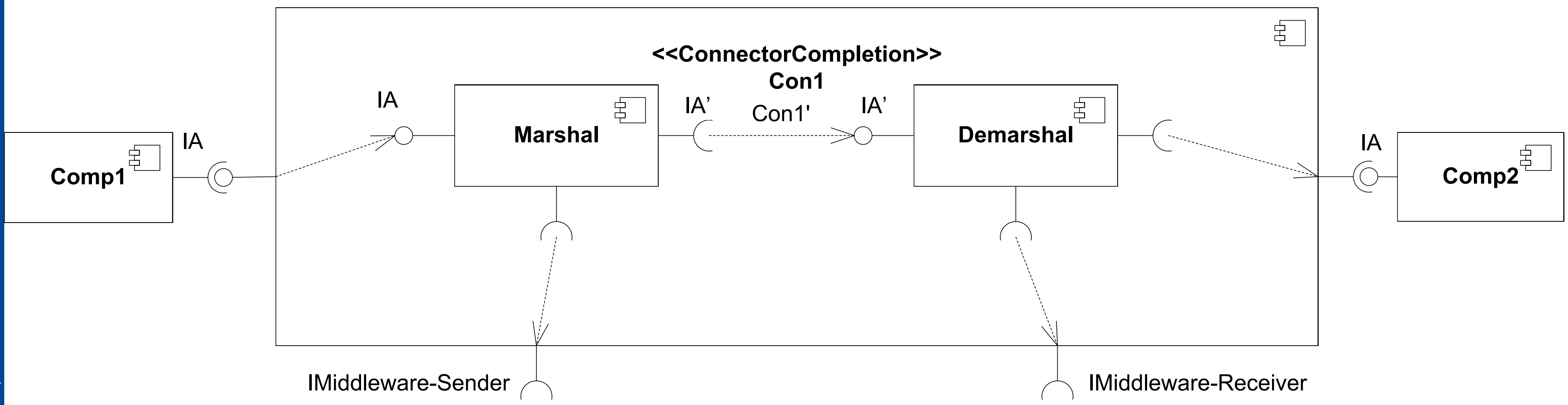

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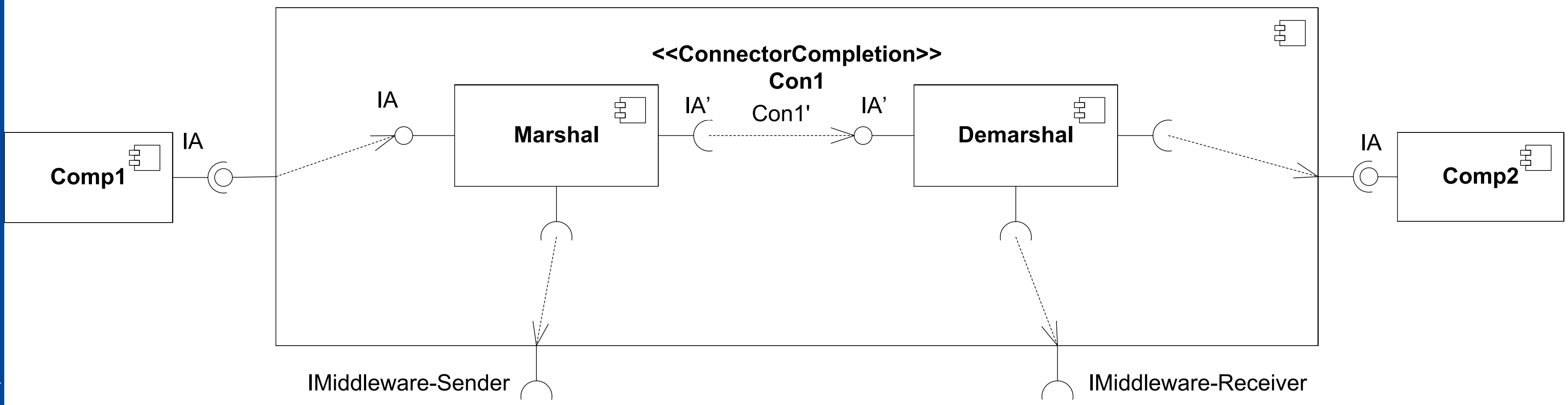

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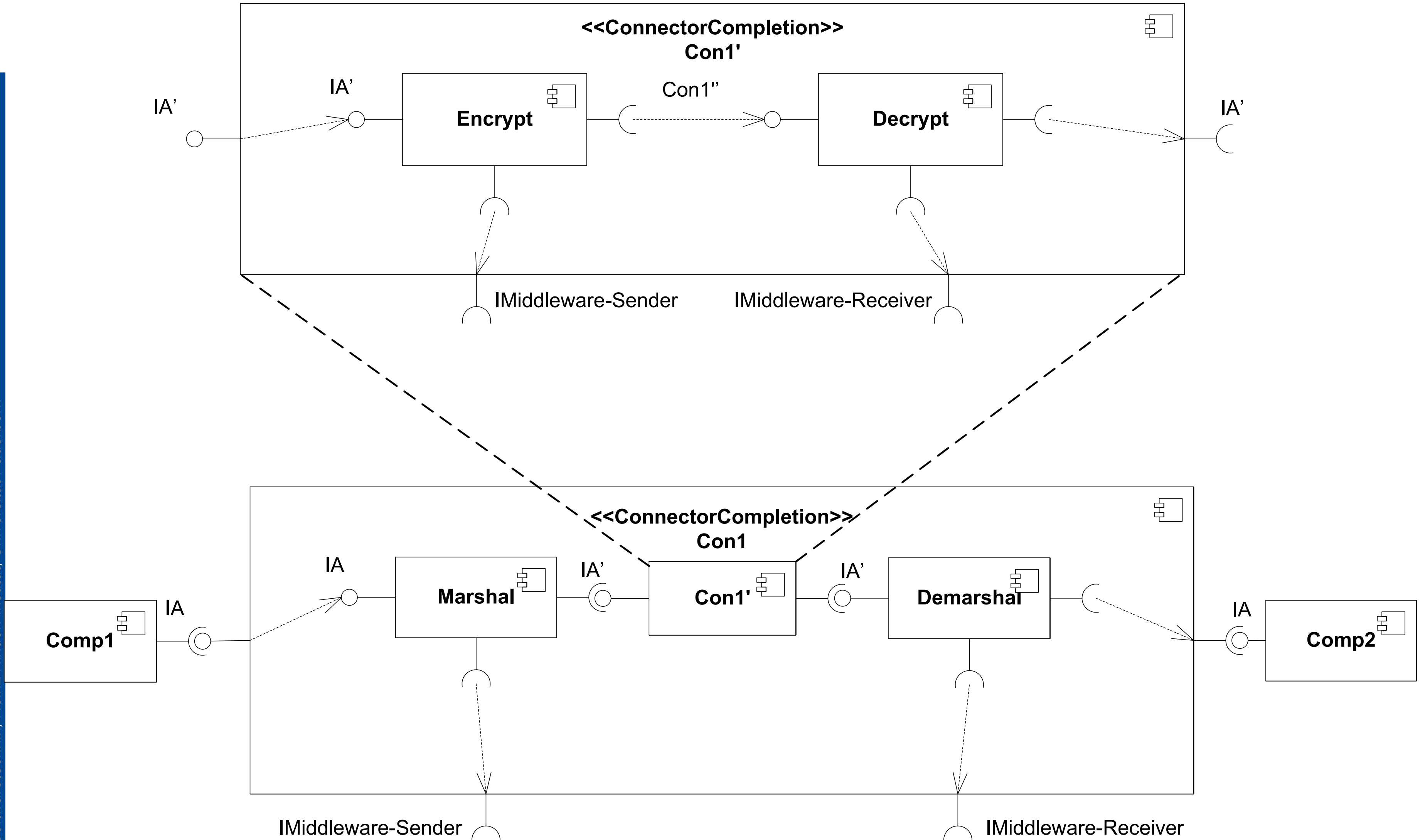

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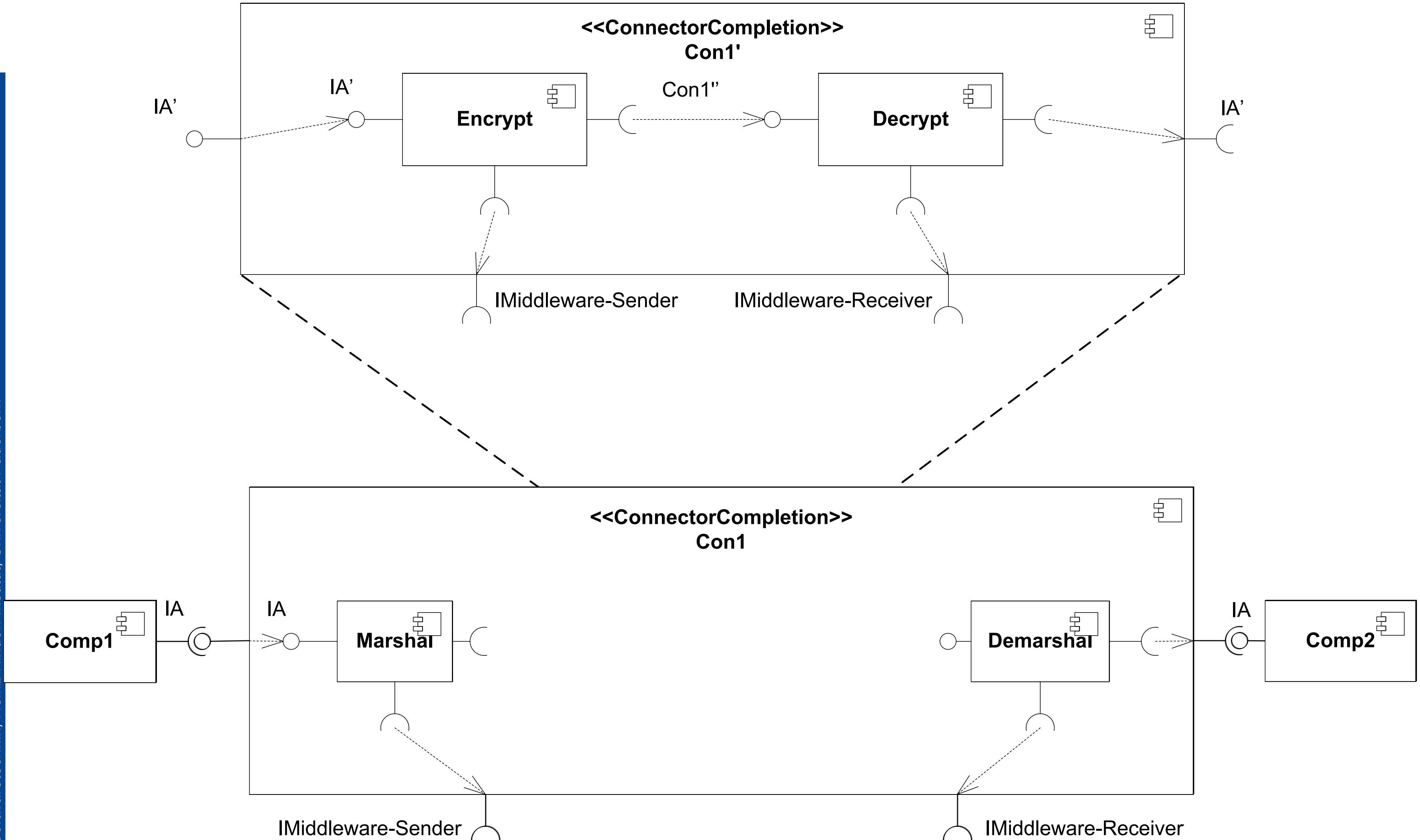

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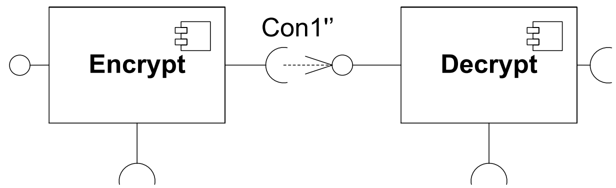

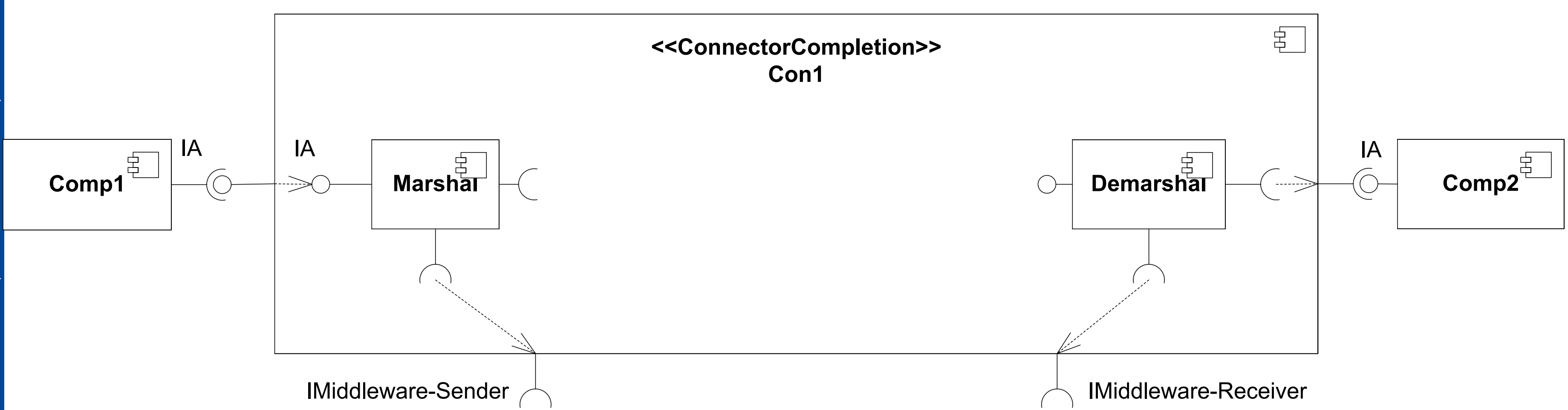

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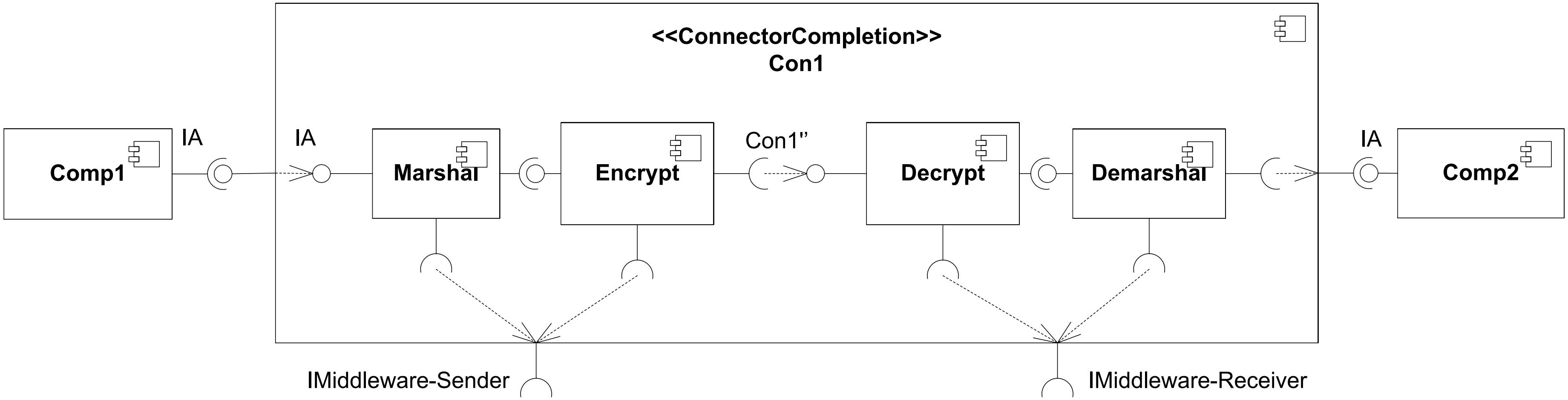

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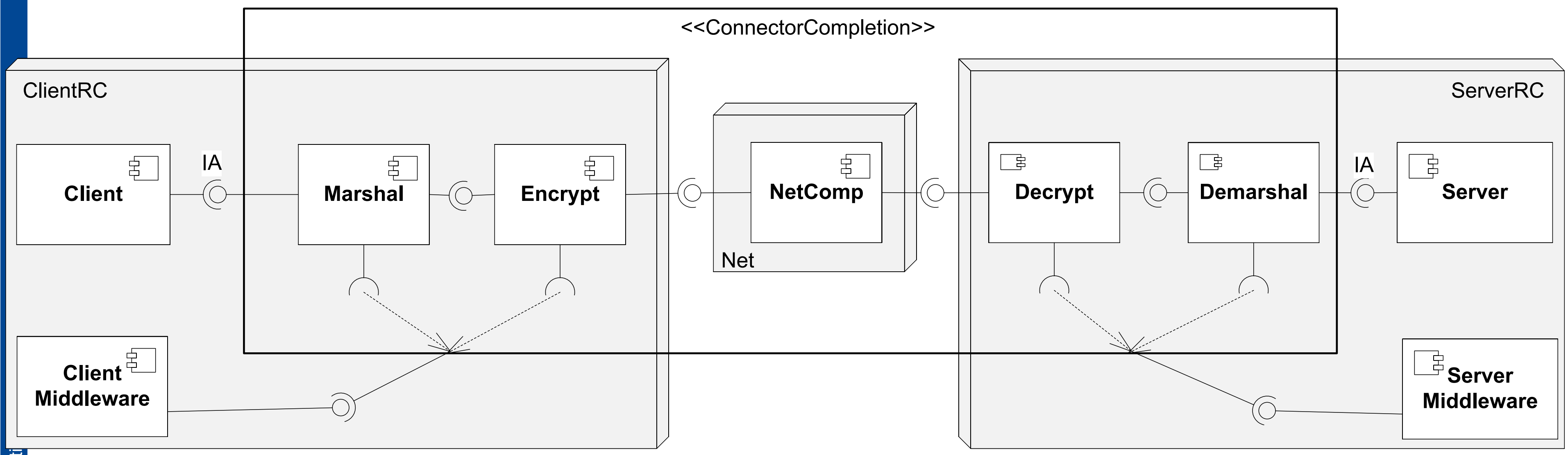

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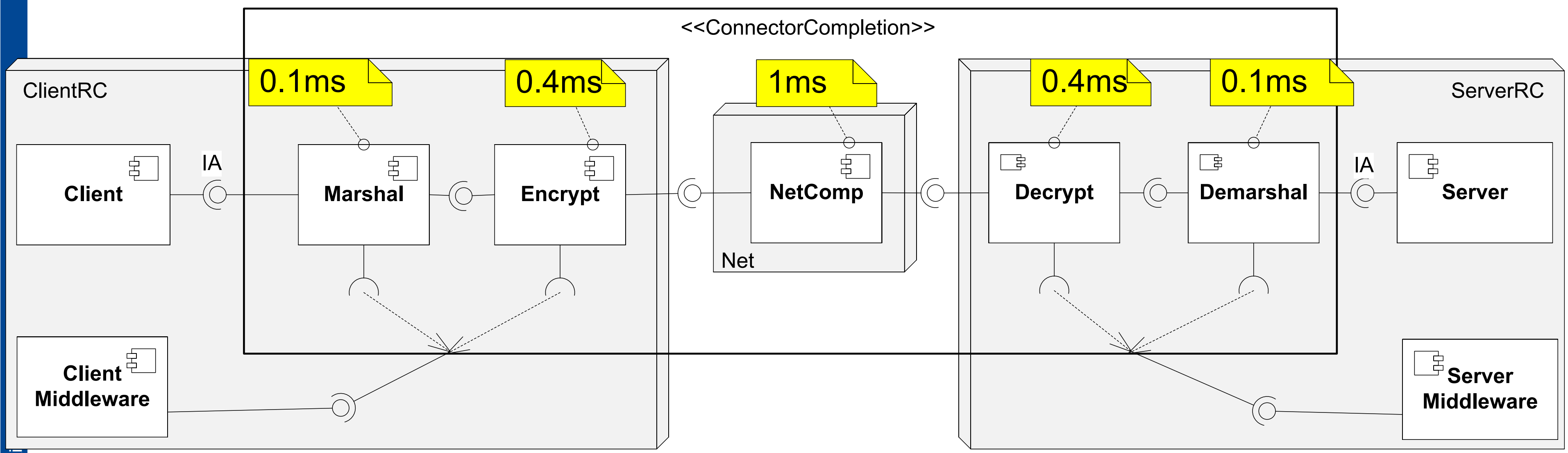

SOAP & Encryption

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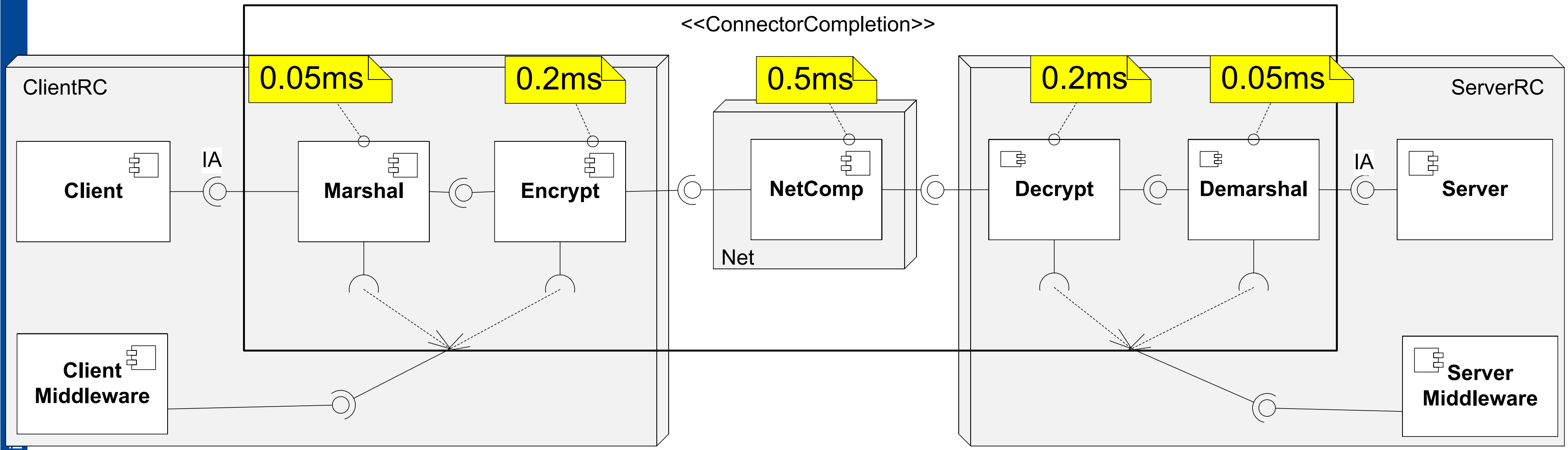

RMI & Encryption

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Model-Driven Completions: Evaluation

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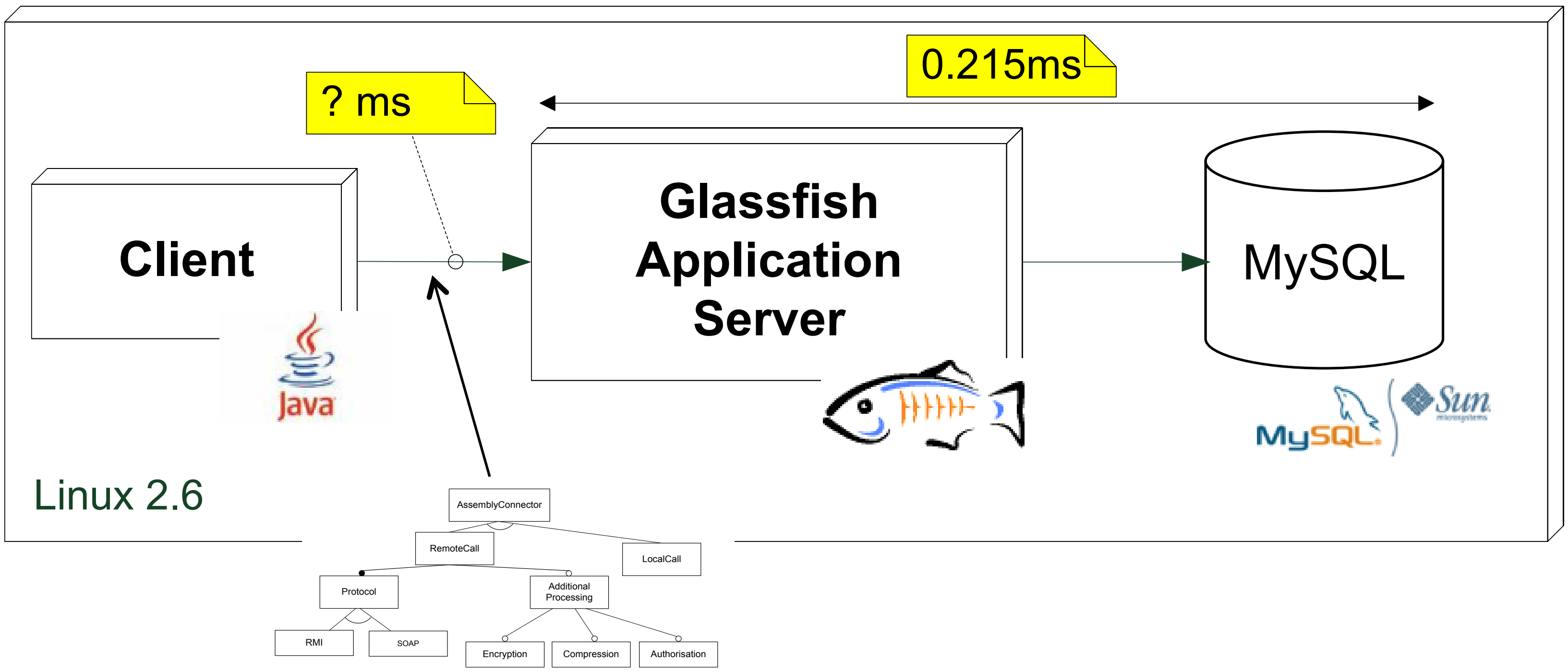
Measurement Setting



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Results

Protocol	Auth	Enc	E(Meas) [ms]	E(Pred) [ms]	Diff. [ms]	Diff. [%]
None	✗	✗	n/a	0.215	n/a	n/a

Prediction Error > 400%

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Results

Protocol	Auth	Enc	E(Meas) [ms]	E(Pred) [ms]	Diff. [ms]	Diff. [%]
None	✗	✗	n/a	0.215	n/a	n/a
RMI	✗	✗	0.988	0.971	0.017	1.7
RMI	✓	✗	1.941	1.871	0.070	3.6
RMI	✗	✓	1.113	1.111	0.002	0.2
RMI	✓	✓	2.060	2.011	0.049	2.4
SOAP	✗	✗	1.329	1.283	0.046	3.5
SOAP	✗	✓	1.498	1.463	0.035	2.3

Prediction Error < 3.6%

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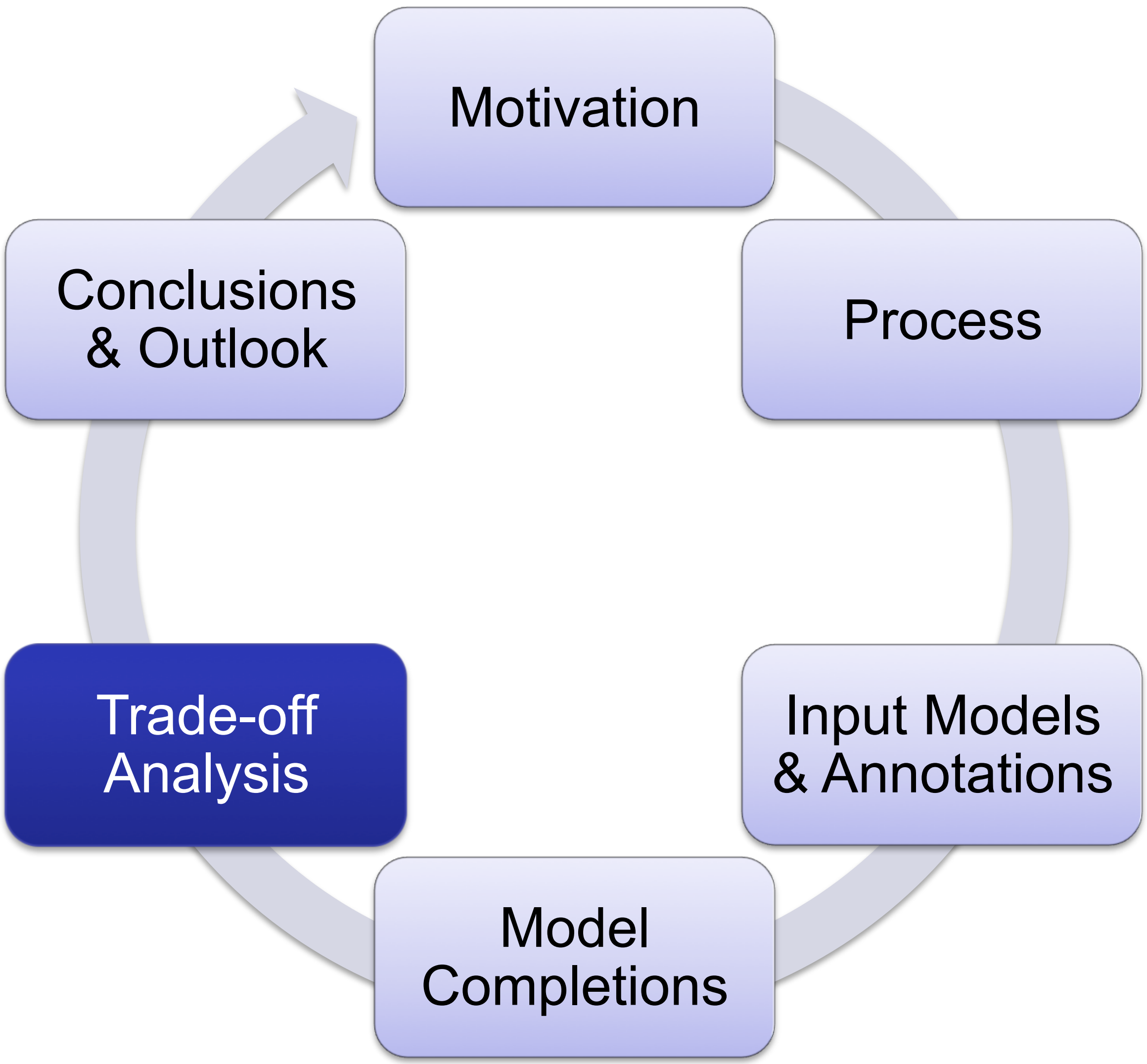
Outline



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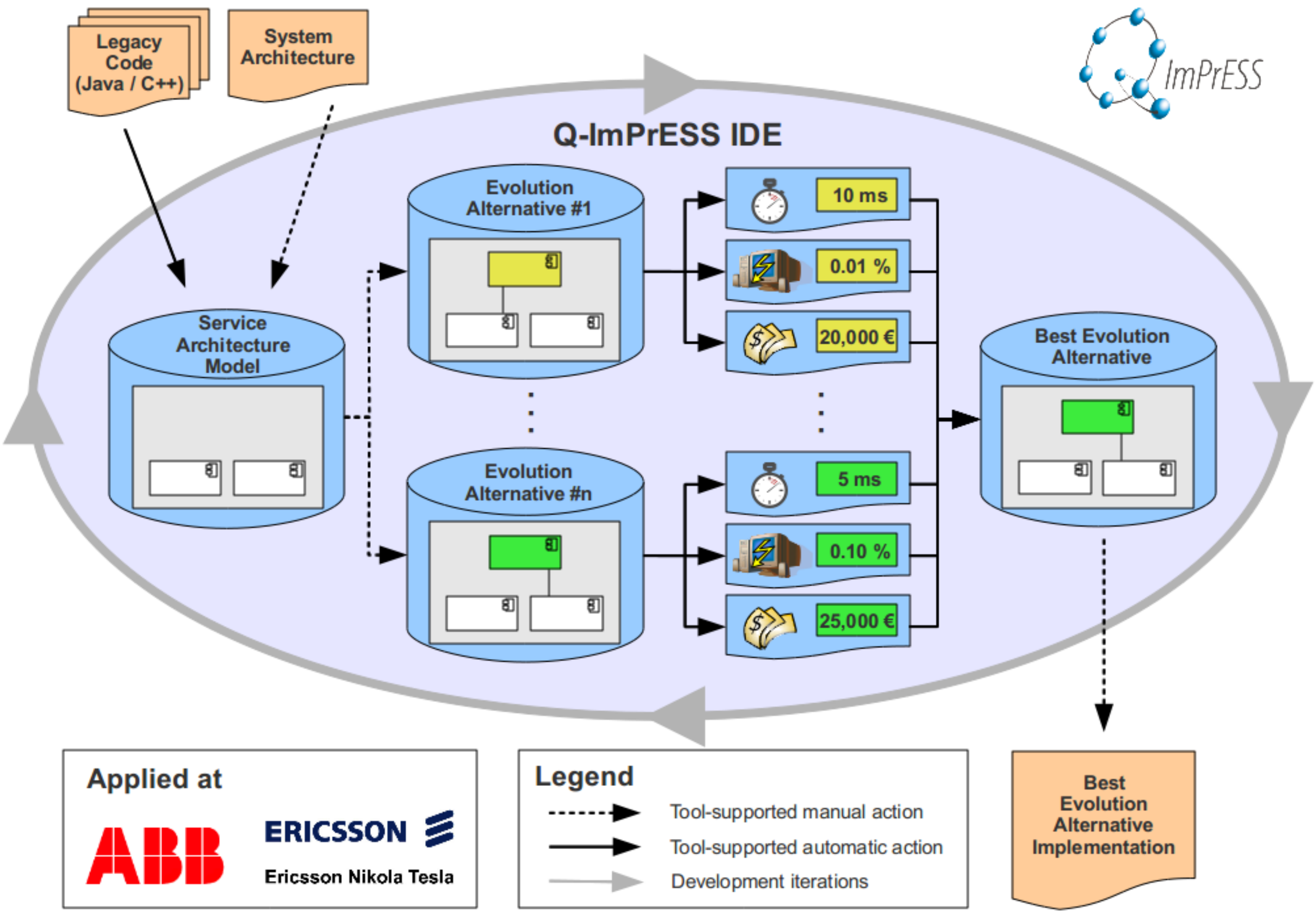
Trade-off Analysis
Example: Q-ImPrESS



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Analytic Hierarchy Process

- Decision support method developed by the mathematician Thomas Saaty in the 1970s
- General method for multi-criteria decision making (not only software, but, e.g., also politics)
- Works quantitatively with qualitative inputs
- Goals
  - Make decisions rationally
  - Make decision preferences explicit and understandable
  - Support group/team decisions
  - Discover inconsistent decisions/preferences

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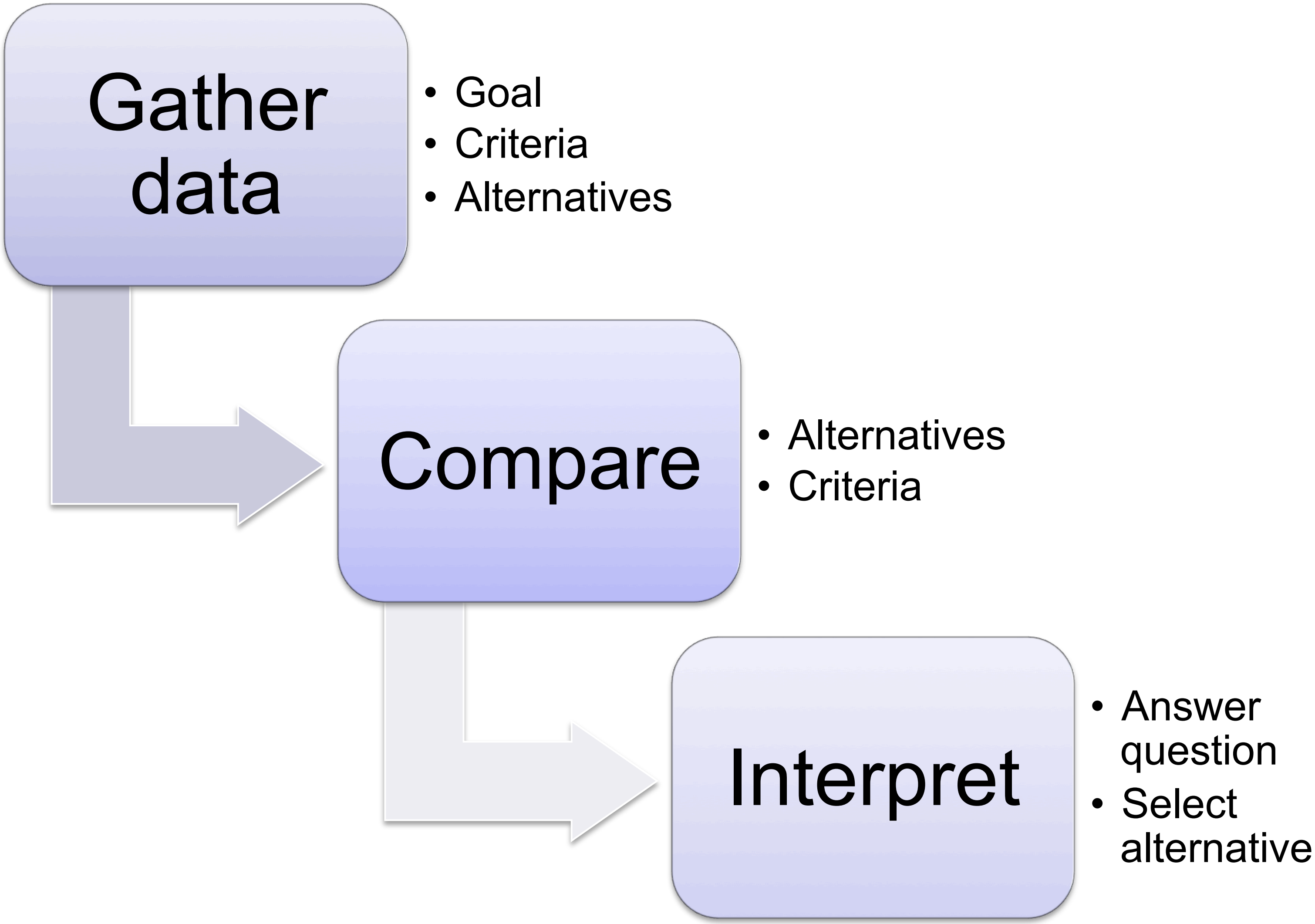
Process Overview



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1st Step: Gather Data

- Goal (here): „Which architectural alternative offers the best trade-off among the quantitative properties?“
- Criteria
  - Quantitative measurements/predictions on architecture metrics
  - We can also include non-quantitative criteria if we like
  - E.g., response time, PROFOD, etc.
  - Exclude direct alternative costs, they are normally included in step 3
- Alternatives
  - Alternative architectures

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Alternatives and criteria

	Avg. Job / s = 1 / Avg. RT	1 - PROFOD	Ease of impl. [5 = easy, 1 = hard]
Alternative 1	1 / 1s	0.99	3
Alternative 2	1 / 2s	0.9	2
Alternative 3	2 / 3s	0.9	5
Alternative 4	1 / 3s	0.9999	1

Values e.g. from a QN

Values e.g. from a DTMC

Manual input

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Dominance & Pareto front

- If an alternative A is better in *all* criteria values than an alternative B, A is said to dominate B → B can be removed from the list of alternatives
  - E.g. Alternative 1 dominates Alternative 2
- The set of alternative which are not dominated by any other alternative is called the Pareto-optimal set or (if shown in figures) the Pareto-front

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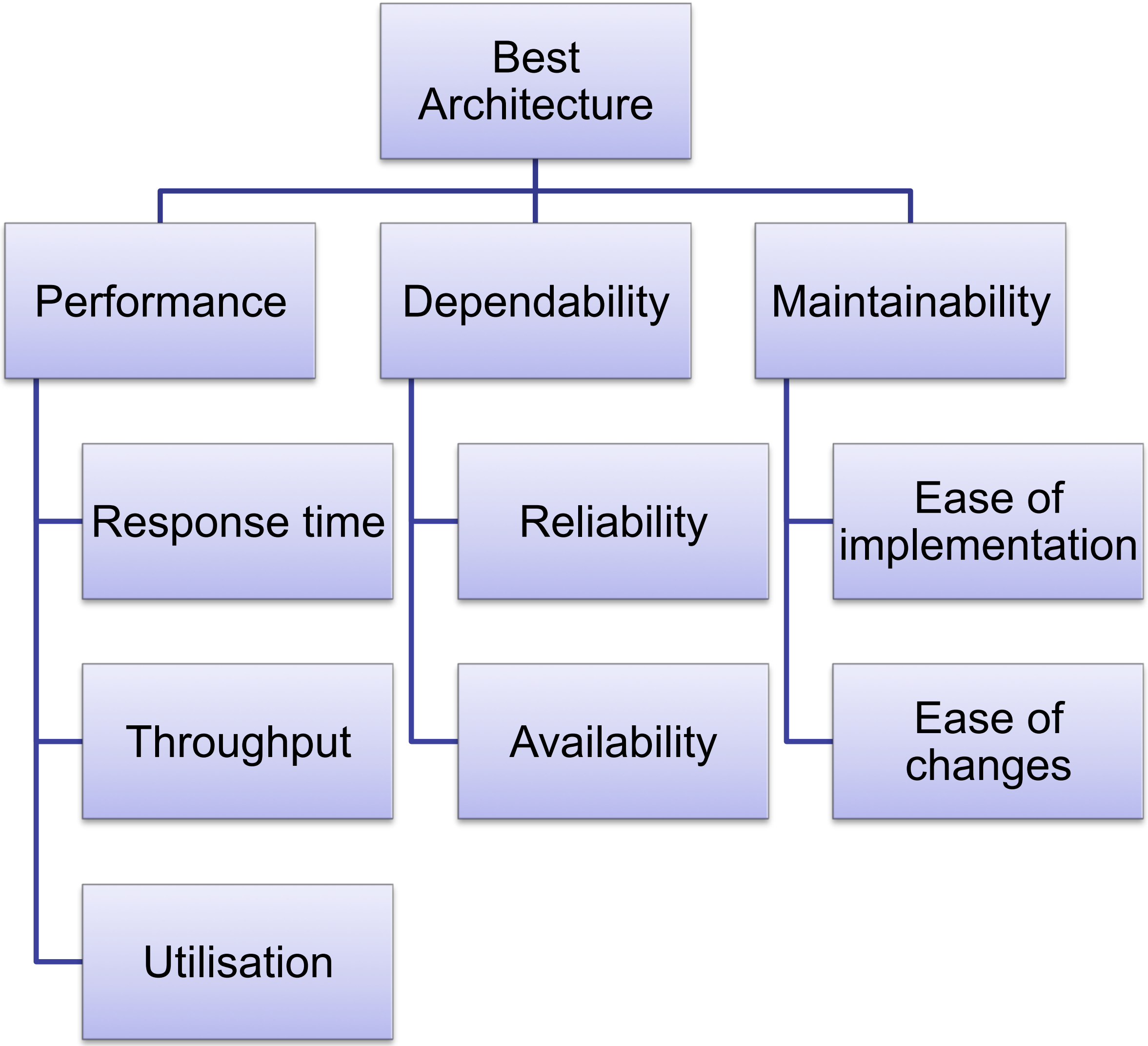
1st Step: Create a Hierarchy



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2nd Step: Priorities

- How to formalise priorities?
- Naive approach: Let stakeholders assign direct weights
- Problem
  - Decision theory research shows stakeholders give bad weights when asked to do it directly
  - Test yourself: Which weight is your preference for performance vs. reliability?
- Solution
  - AHP uses pair-comparisons
  - Compare two sub-goals of a given parent goal
  - Judge it quantitatively

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Priorities (cont.)

- Use Scale from 1 to 9 (1-5 or 1-15 also used)
  - 1 = equally important
  - 3 = a bit more important
  - 5 = more important
  - 7 = much more important
  - 9 = extremely more important
  - 2,4,6,8 = intermediate values
  - Use 1/5 for „less important“ and so on
- Advantages
  - Easier to judge and express
  - Pairwise comparison limits scope of comparison

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Priorities example

Derive a matrix from answers

	Performance	Reliability	Ease of Impl.
Performance	1	3	1/3
Reliability	1/3	1	1/9
Ease of Impl.	3	9	1

Matrix has "symmetry" if answers are consistent, AHP can also deal with some inconsistency

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Consistency

- Can be used to check consistency in the answers of the decision makers
- Let v^h_{ij} denote matrix entry ij in a matrix of the parent goal h
- The comparison matrix is consistent if

$$v^h_{ik} = v^h_{ij} \cdot v^h_{jk} \qquad \forall i, j, k \in U(h)$$

  holds.
  (with U(h) contains the indices of the criteria or alternatives)
- For consistent matrices it is sufficient to determine the first row, i.e., we have to determine $|U(h)| - 1$ pair comparisons

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Determining weights

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- Let $\vec{w}^h$ denote the weights of subgoals used to determine the value of the parent goal
- $\vec{w}^h$ should reflect the preferences of the decision maker as given in the matrix
- That is

  $$v_{ij} \approx \frac{w_i}{w_j}$$

  i.e. the weights should reflect the relative preferences
- To ensure comparability with other goals normalise $\vec{w}^h$

  $$\sum_{i=1}^{|U(h)|} w_i = 1$$

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Determining weights cont.

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- If matrix is consistent, take arbitrary column vector and normalise

$$w_i = \frac{v_{ij}}{\sum_{k=1}^{|U(h)|} v_{ki}}$$

- Example: 2nd column = (3,1,9), i.e., it follows

$$\vec{w} = (\frac{3}{13}, \frac{1}{13}, \frac{9}{13})$$

- Otherwise find a solution with as little deviation as possible
  → Heuristics exists

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Heuristic Solutions

- Determine eigenvector belonging to the maximum eigenvalue showed to be a good heuristic
- Process
  - Solve characteristic equation $det(V - I\mu) = 0$
  - Pick maximum eigenvalue μ_{max}
  - Determine the matching eigenvector by solving

    $$(V - \mu_{max} I)x(\mu_{max}) = 0$$

  - Let $\vec{w} = x(\mu_{max})$

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Quantify inconsistency

- There is a inconsistency index telling us the inconsistency of the matrix

$$IK(V) = (\mu_{max} - |U(h)|)/(|U(h)| - 1)$$

- Problem IK(V) depends on the size of V
- The larger V the more likely are violations of the consistency constraint
- Solution: Use randomly generated V's as reference to normalise the metric. This is called ZI(|U(h)|)
- Heuristic for too inconsistent matrices: If

$$\frac{IK(V)}{ZI(|U(h)|)} > 0.1$$ then redo pair comparisons

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Determine utility values

- Numeric values (1 / RT, 1 – PROFOD)
  - Normalise values
  - Multiply normalised vector with weight
  - Ensure larger values correspond to more utility
- Qualitative values (e.g. ease of implementation)
  - Again use pair comparisons
  - Determine utility in the same way as weights
  - Use normalised vector as utility

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Utility of our alternatives

	Avg. Job / s = 1 / Avg. RT	1 - PROFOD	Ease of impl. [5 = easy, 1 = hard]
Alternative 1	0.5	0.34	3/9
Alternative 3	0.33333	0.311	5/9
Alternative 4	0.16666	0.345	1/9

Maybe a better scaling is needed here??

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Solution for our simple example

- Solve (for Alternatives 1,3,4, i.e., removing the dominated)

$$\begin{pmatrix} 0.5 & 0.34 & 0.333 \\ 0.333 & 0.311 & 0.555 \\ 0.166 & 0.345 & 0.111 \end{pmatrix} \begin{pmatrix} 0.23 \\ 0.076 \\ 0.694 \end{pmatrix} = \begin{pmatrix} 0.372 \\ 0.485 \\ 0.141 \end{pmatrix}$$

- Select Alternative with maximum weighted value
- In this case, it is Alternative 3 with a value of 0.485

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Discussion

- Rank inversion
  - Adding alternatives may alter alternative ranking
  - Even for irrelevant alternatives
  - One reason is normalisation over the range of values
- Number of pair comparisons
  - Min |U(h)|-1, Max |U(h)|(|U(h)|-1)/2
  - More comparisons allow to judge inconsistency
  - However, people get tired answering pair comparisons
- Scale
  - Good scale for AHP determined in practice
  - However, no rationale for the scales used
- Nevertheless, helpful in practice for small numbers of alternatives

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Automated Quantitative Approach

Using Meta-Heuristics

[Slides with kind permission from Anne Koziolek]

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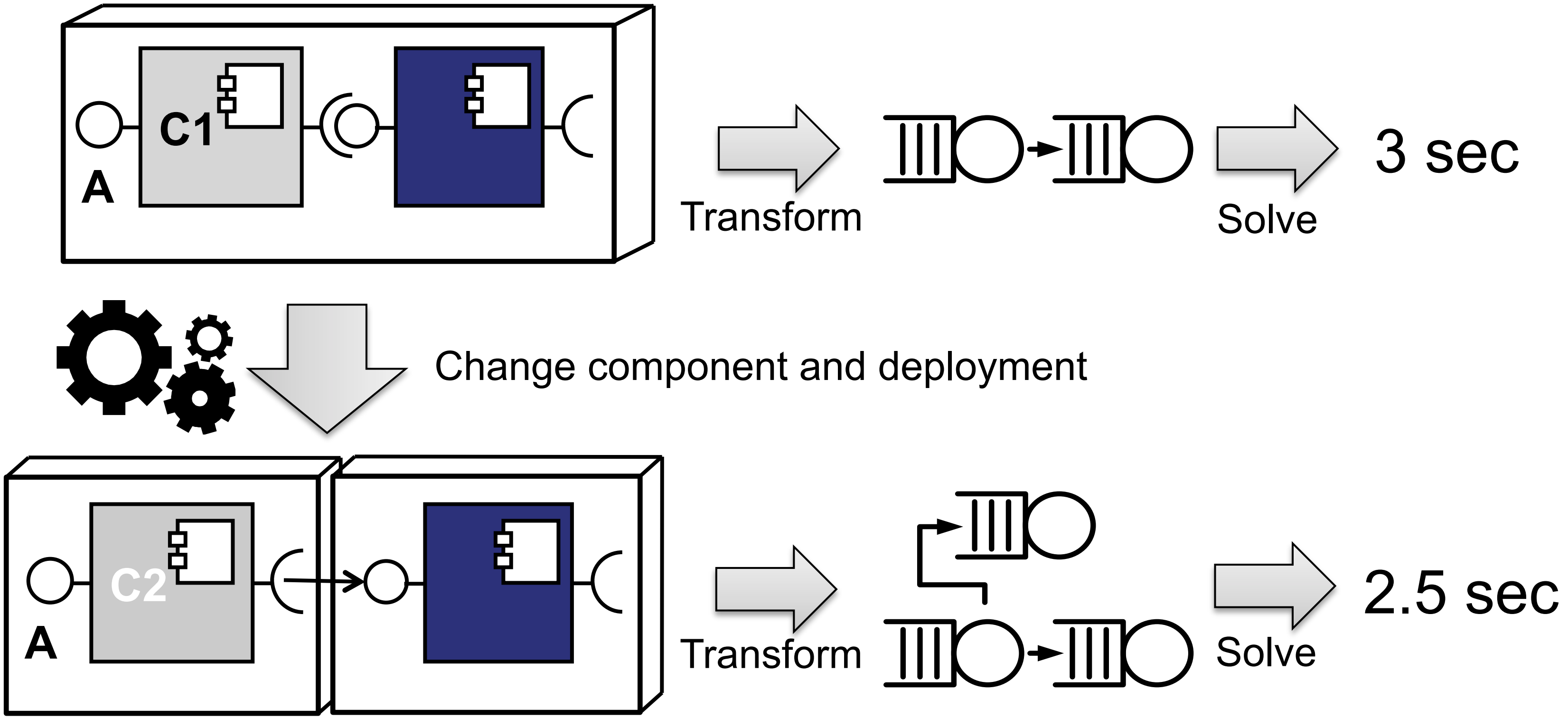
Idea



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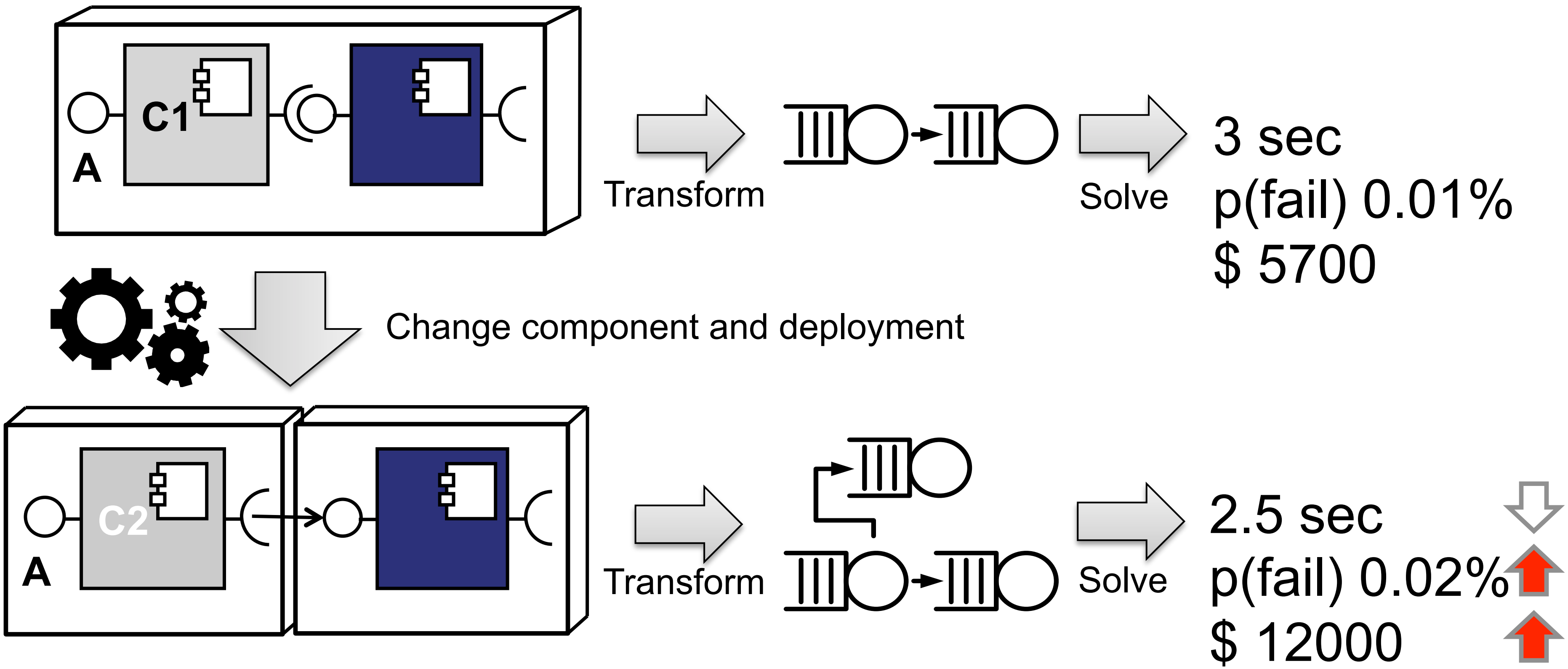
Idea



➔ Optimise multiple criteria at once

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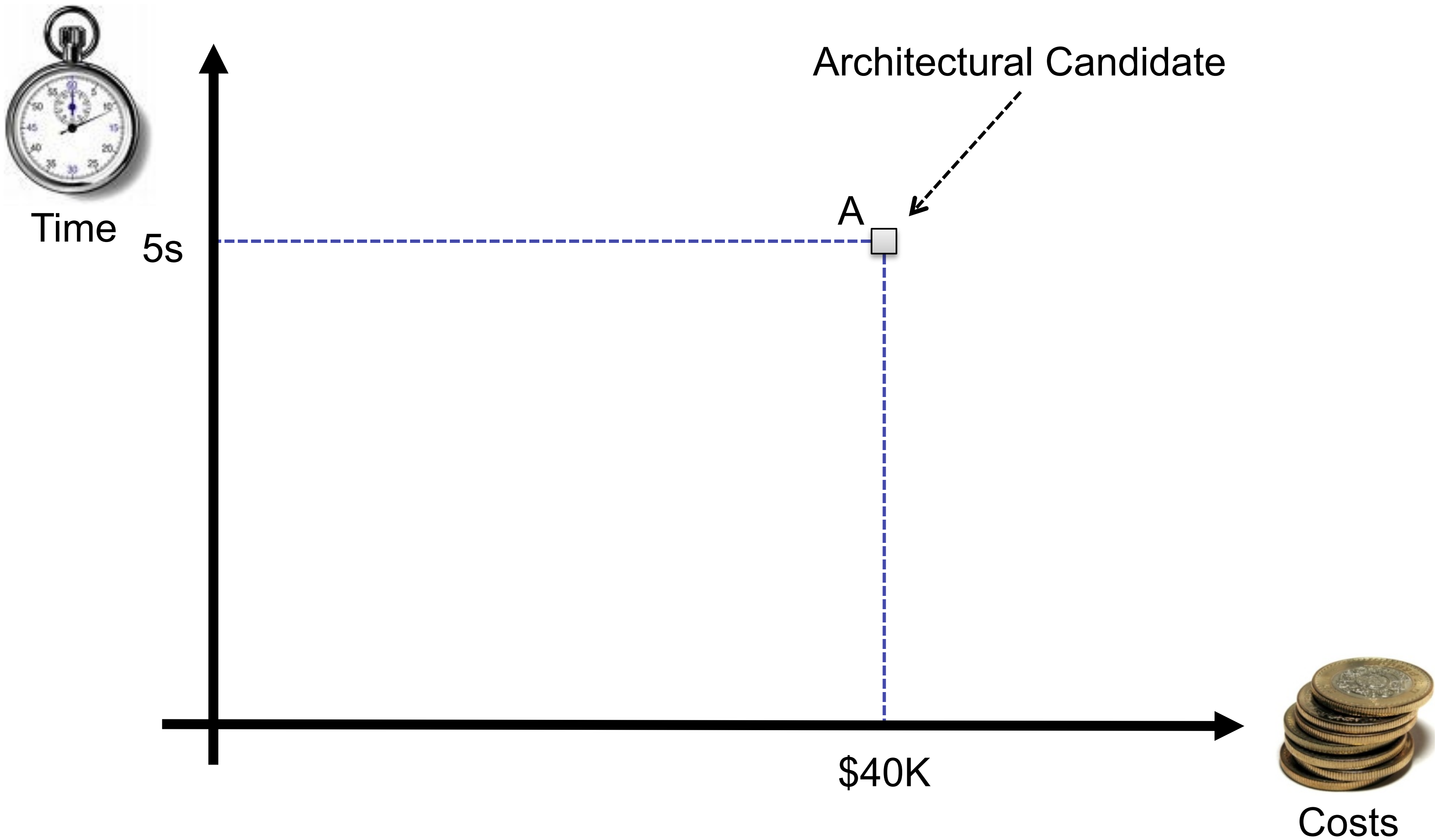
Multi-criteria optimisation



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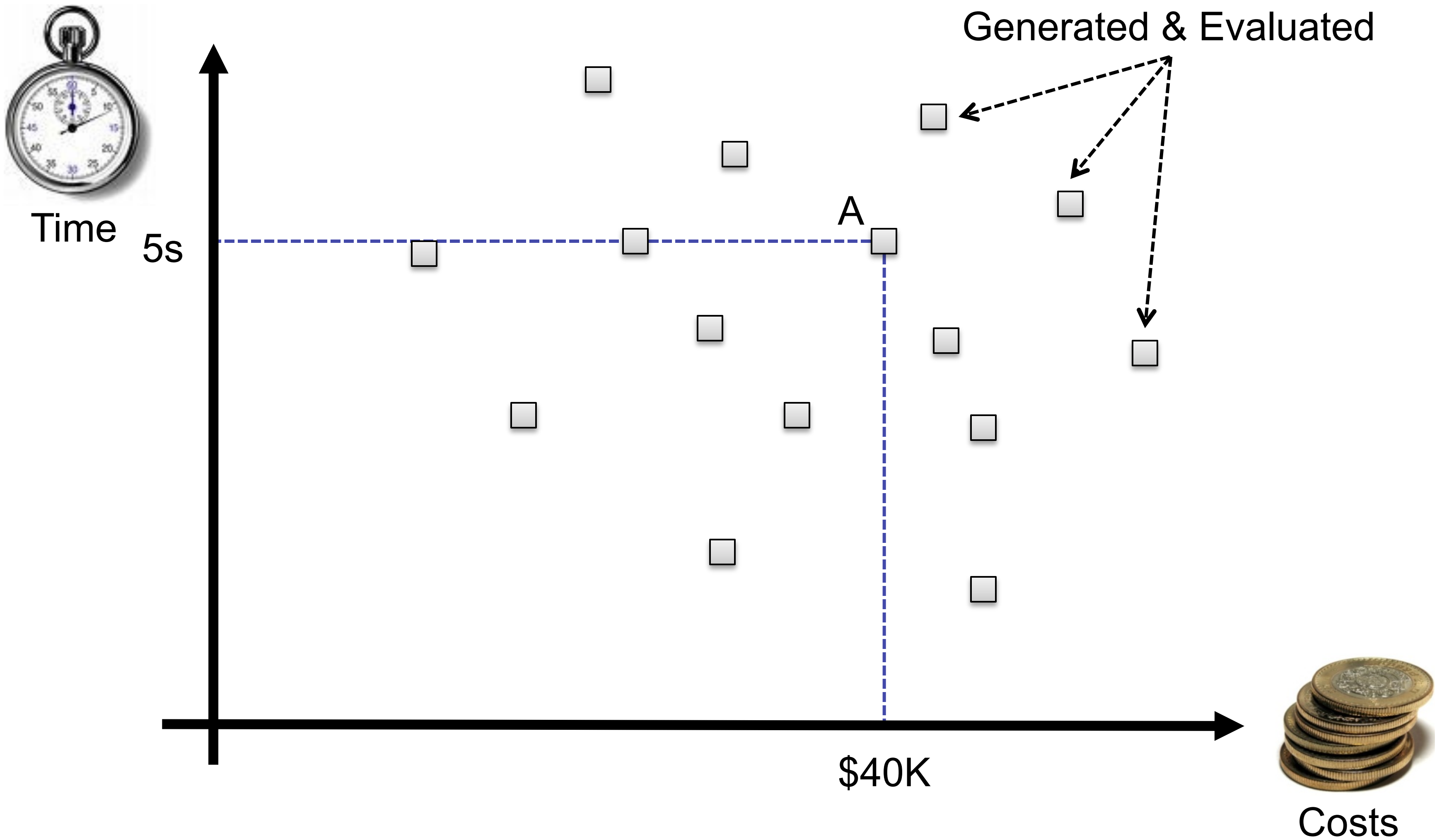
Multi-criteria optimisation



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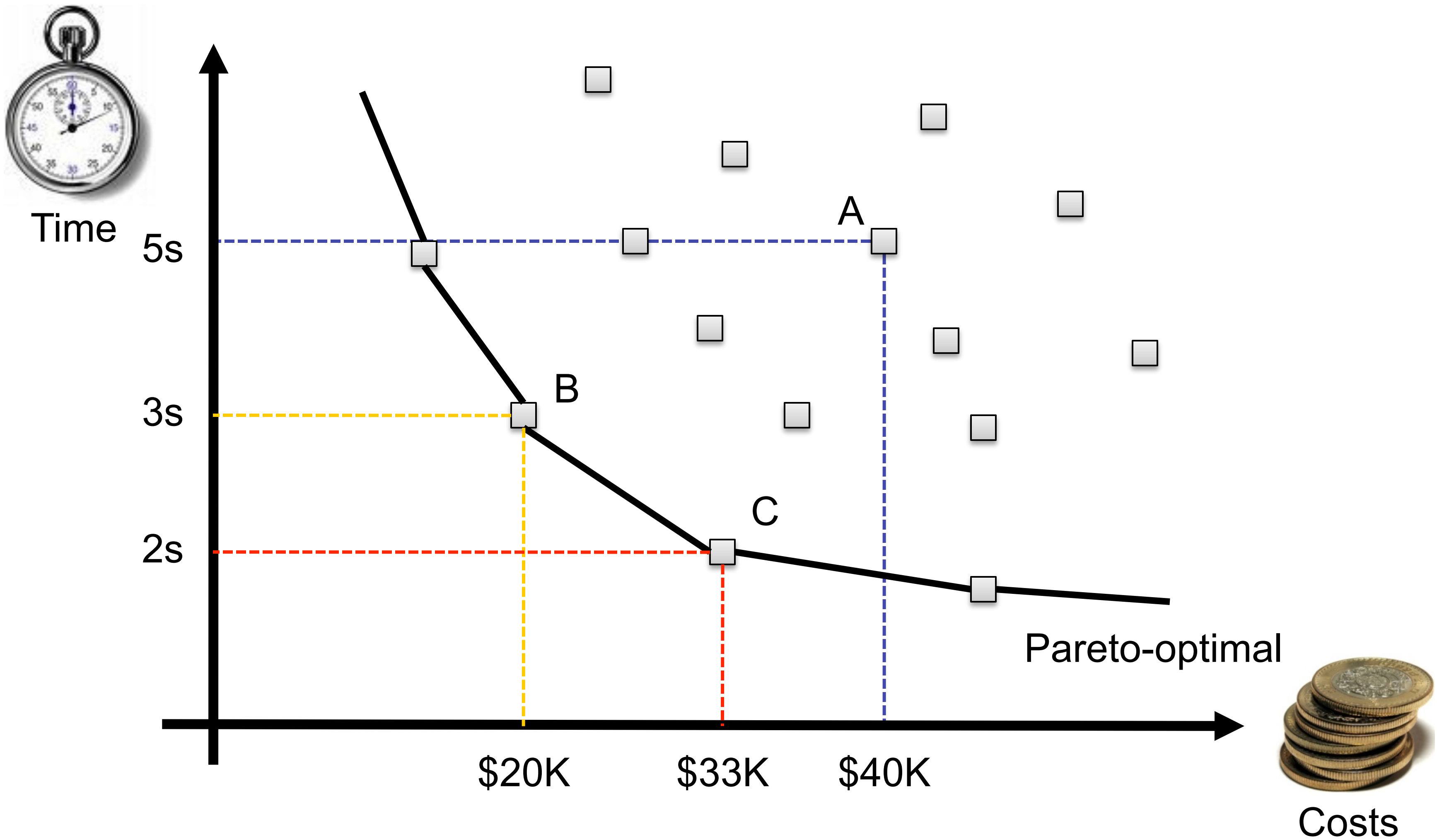
Pareto front



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Process

Initial candidate

Generic degrees of freedom

1. Search problem instantiation

[MKB10]

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Degrees of Freedom

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Software
Component selection
Middleware selection
Component replication
Software configuration

Deployment
Allocation
Processing Rate
Number of Servers

[MKB10]

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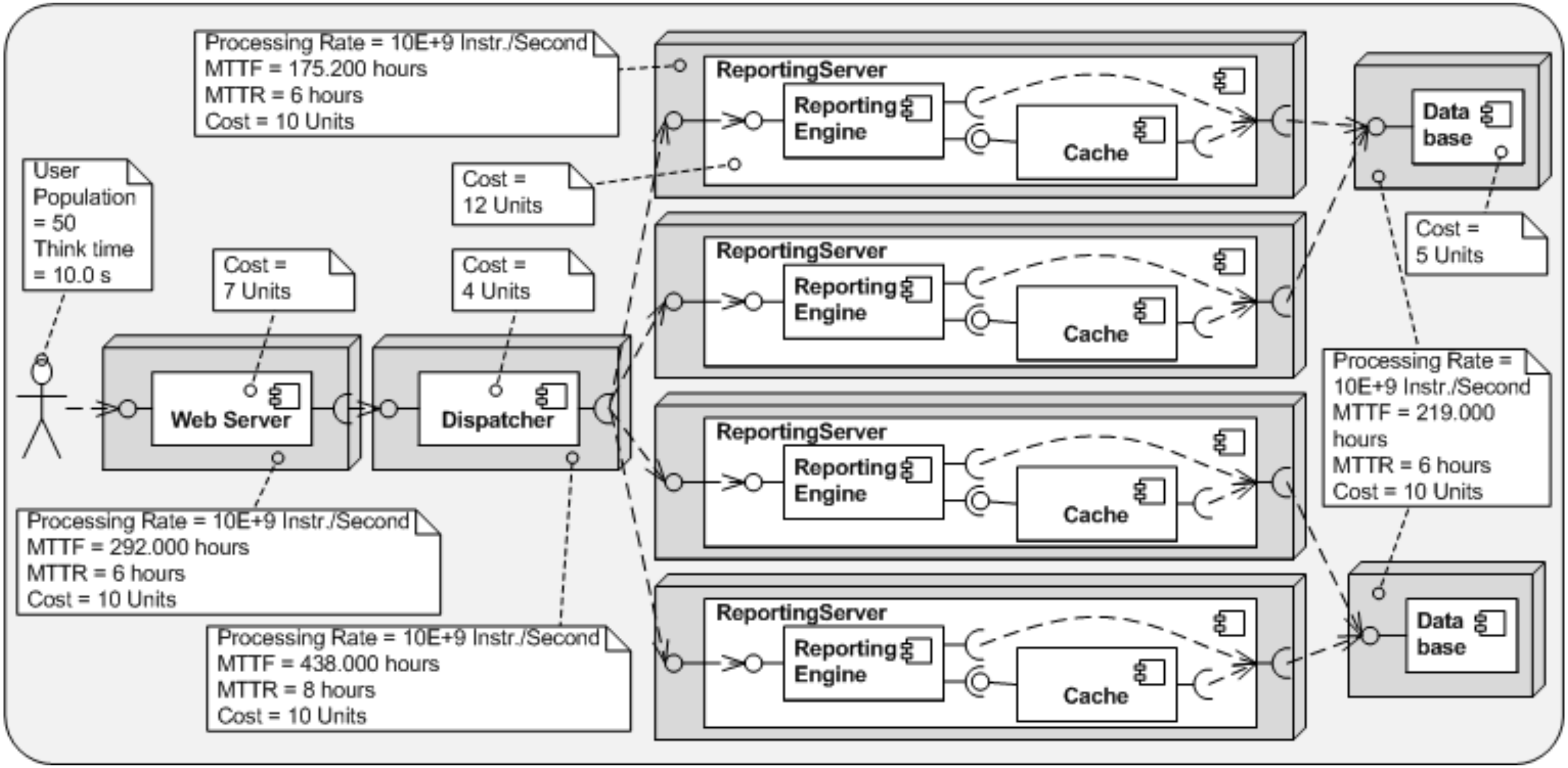
Case Study



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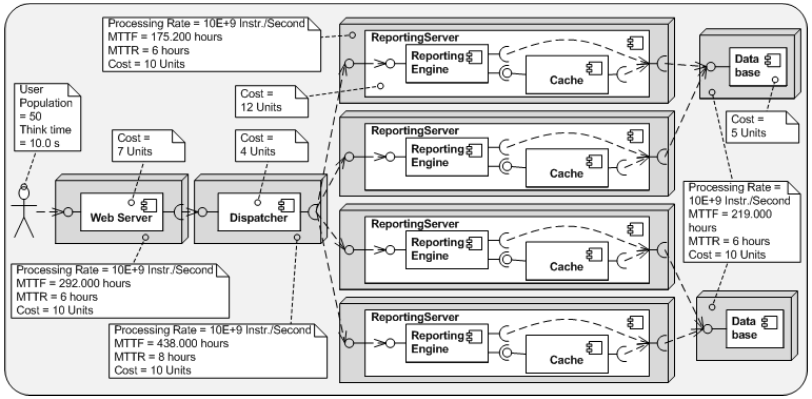
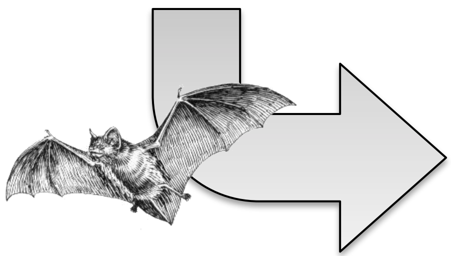
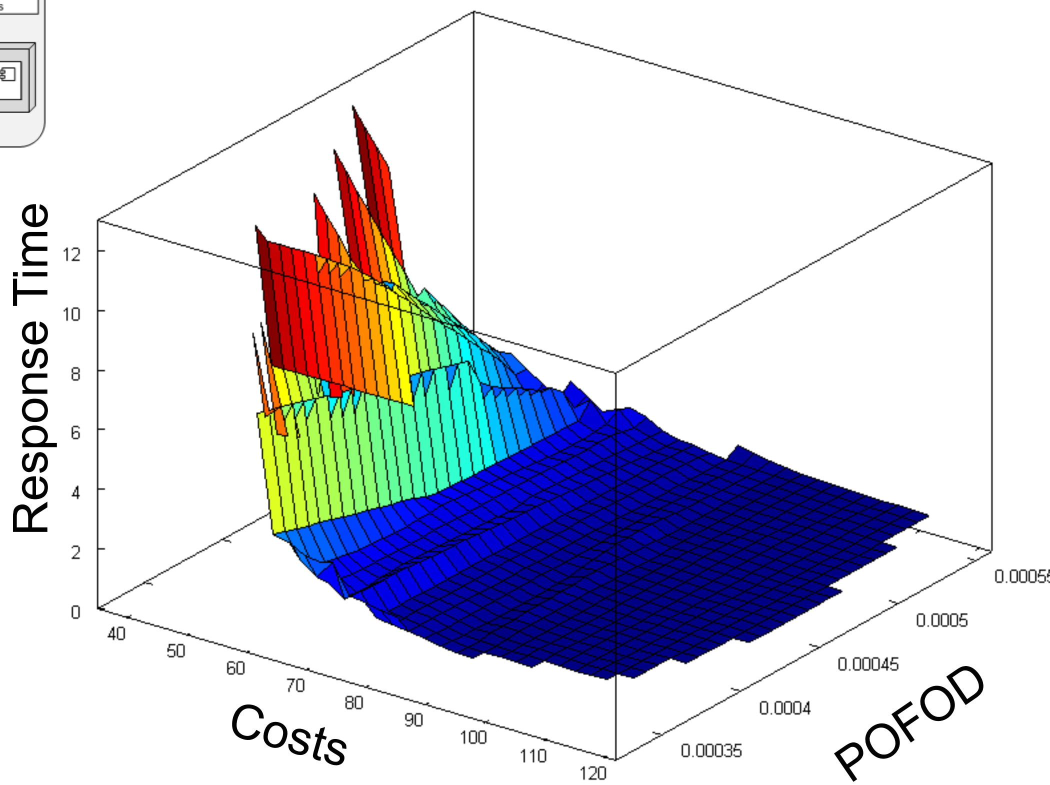
Results



- Component allocation
- Processing rates
- Component selection





- 1235 candidates
- 58 Pareto optimal
- 8h running time

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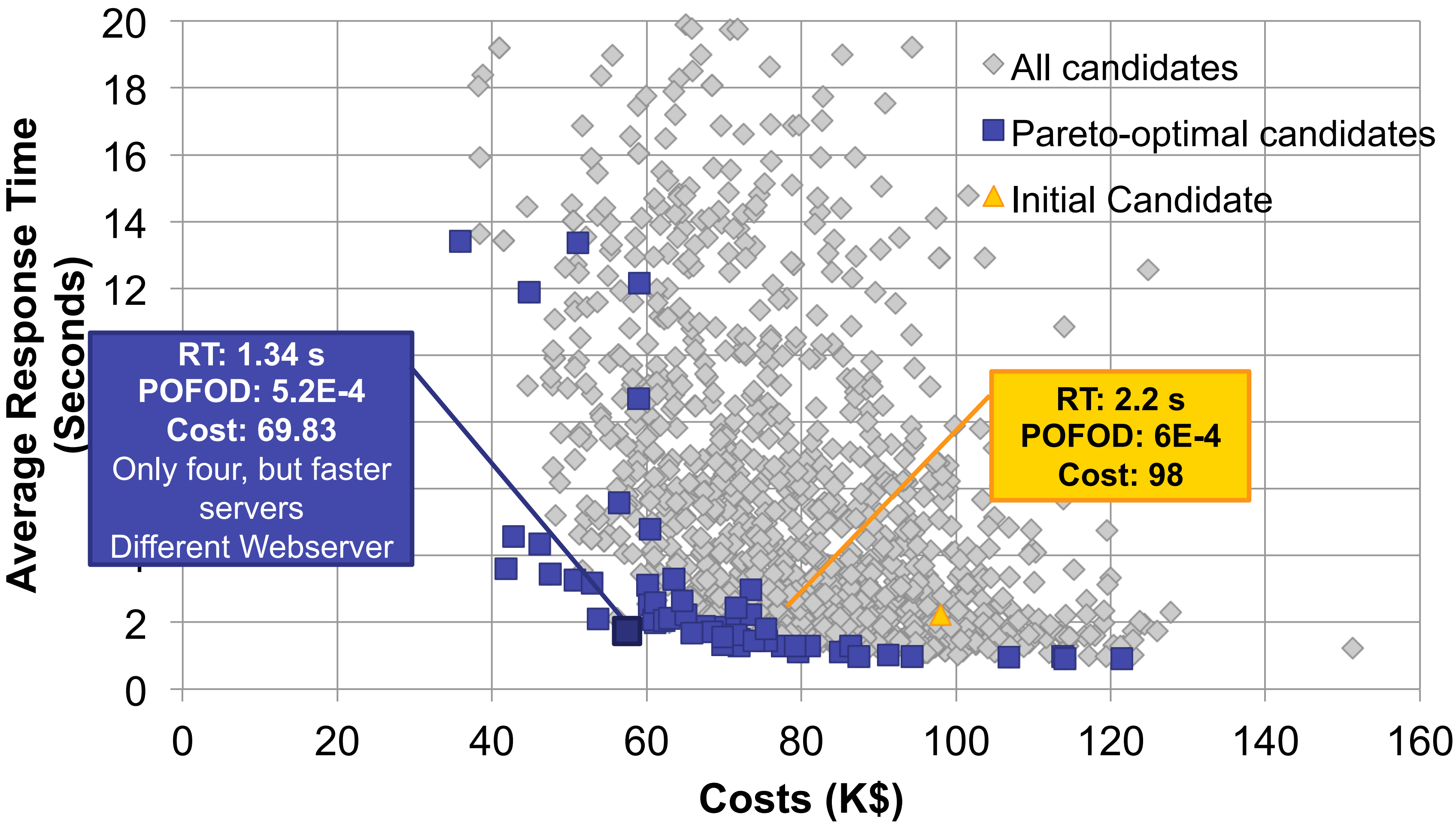
Results



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Other Approaches

ArcheOpteryx

- E.g., Allocation of Embedded Components
- Reliability and Cost

Deep Compass

- Robocop Component
- Schedulability and costs

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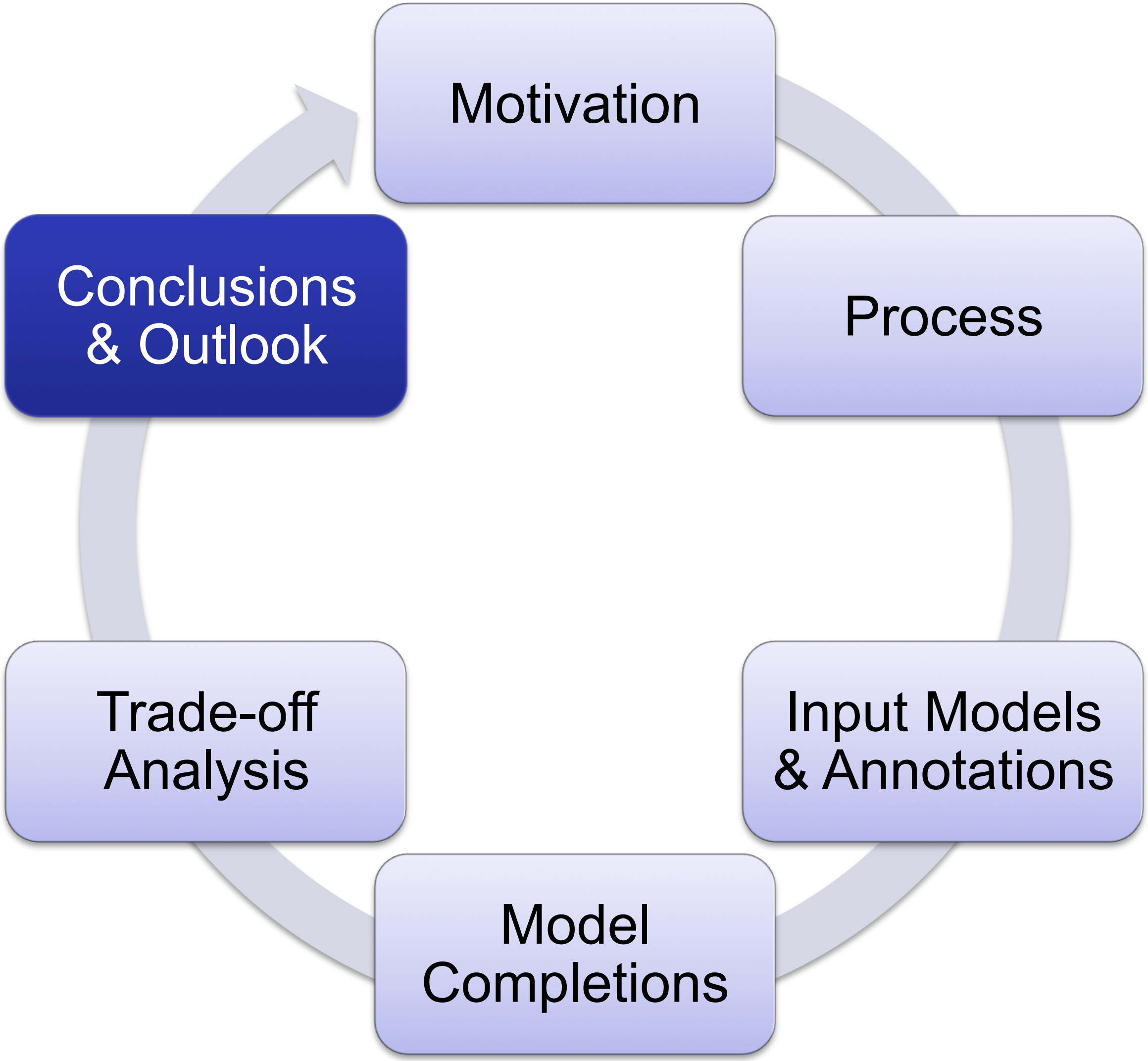
Outline



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Lessons Learned

- Motivation for Model-Driven QoS analysis
- Process for model-driven analysis
- Transformations & Refinements
- Trade-off Analysis

Outlook

- New input models and system types
  - Mechatronic systems
  - Self-adaptive systems
- Automated selection of right abstraction level

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Questions, Comments, Feedback?

Palladio
Component Model

SFB 901
ON - THE - FLY COMPUTING

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Further Reading

- Model-Based Software Performance Analysis, Vittorio Cortellessa, Antinisca Di Marco, Paola Inverardi
- Performance Solutions: A Practical Guide to Creating Responsive, Scalable Software, Connie Smith, Lloyd G. Williams
- The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modelling: Techniques for Experimental Design, Measurement, Simulation and Modelling, Raj Jain
- Queuing Networks and Markov Chains: Modeling and Performance Evaluation with Computer Science Applications, Gunter Bolch, Stefan Greiner, Hermann de Meer

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