Engineering Self-Adaptive Software Systems with Runtime Models

Symposium on Future Trends in Service-Oriented Computing

Potsdam, Germany, June 14-15, 2012

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Motivation

- Need to continuously change software
  - Lehman's laws of software evolution [Lehman and Belady, 1985]
  - Software aging [Parnas, 1994]

⇒ **Software evolution and maintenance**

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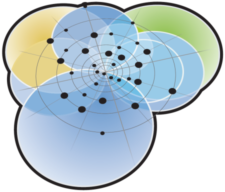
- Software systems that are…
  - self- or context-aware
  - mission-critical
  - ultra-large-scale (ULS)
  - …



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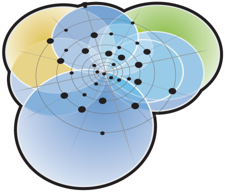

*"Evolution in ULS systems will rarely occur in discrete, planned steps in a closed environment; instead it will be continuous and dynamic. The rules for continuous evolution must therefore be built into ULS systems [...] so that they will be [...] able to cope with dynamically changing environments without constant human intervention. Achieving this goal requires research on **in situ control, reflection, and adaptation** to ensure continuous adherence to system functional and quality-of-service policies in the context of rapidly changing operational demands and resource availability."*
[Northrop et al., 2006, p.33]

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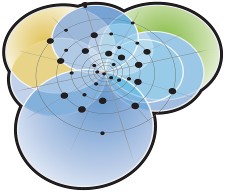


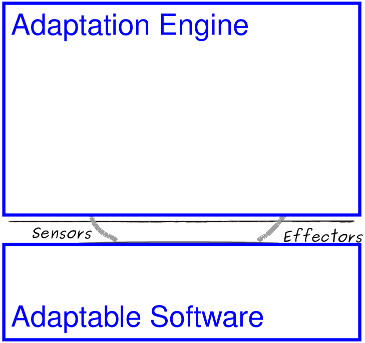
⇒ **Self-adaptive Software** [Cheng et al., 2009, de Lemos et al., 2012]

⇒ Autonomic Computing [Kephart and Chess, 2003]

Remark: Co-existence of evolution/maintenance and self-adaptation

Engineering Self-Adaptive Software

(1) Cost-effective development
(2) Reflection capabilities
(3) Making feedback loops explicit
(4) Flexible (runtime) solutions


Adaptation Engine

Adaptable Software

Related approaches, e.g.:

- *Rainbow* [Garlan et al., 2004] : (1), (2), (3), (4)
- *J3 Toolsuite* [Schmidt et al., 2008] : (1), (2), (3), (4)

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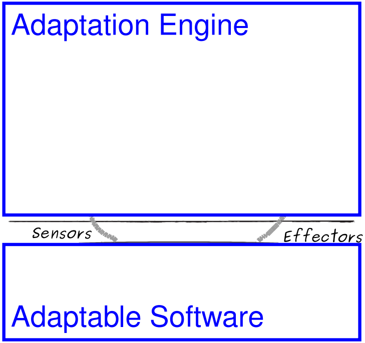

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Models@run.time for engineering adaptation engines: (1)-(4)

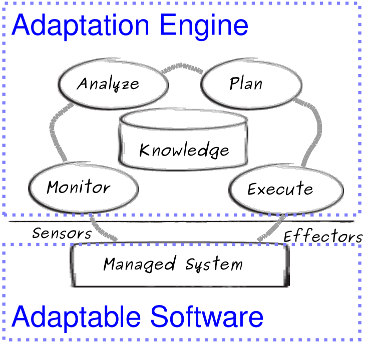
Adaptation Engine

Feedback Loop consisting of

- **Adaptation steps**

  Monitor, Analyze, Plan, Execute
- **Knowledge**

  about the managed system and its context
- MAPE-K [Kephart and Chess, 2003]



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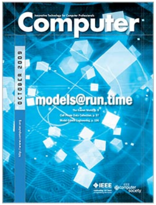
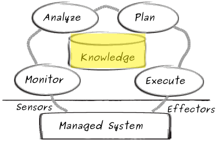


General goal: leverage MDE techniques and benefits to the runtime environment [France and Rumpe, 2007, Blair et al., 2009]

⇒ **Models@run.time for adaptation steps & knowledge**

Knowledge

Models causally connected to the running system



- Typically, **one** model is employed (often an architectural model emphasizing one concern)

  (cf. related work in [Vogel and Giese, 2010])

- Simultaneous use of multiple runtime models

→ **abstraction levels** — PSM vs. PIM (solution vs. problem space)

  - PSM: easier to connect to the running system
  - PIM: easier to use by adaptation steps

→ **concerns** — failures, performance, architectural constraints, . . .

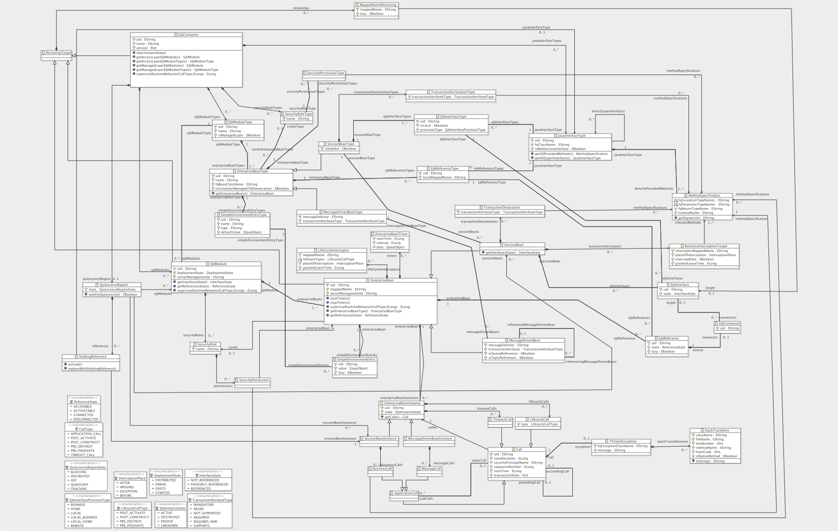
⇒ Different views on a running system

⇒ **reflection capabilities** enabled and used by adaptation steps

[ICAC09,MiSE10,SEAMS10]

Knowledge — Reflection Models

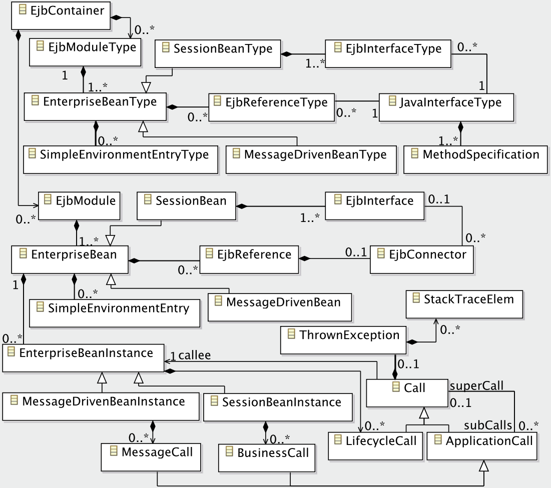
Metamodel of a PSM



Knowledge — Reflection Models

Metamodel of a PSM

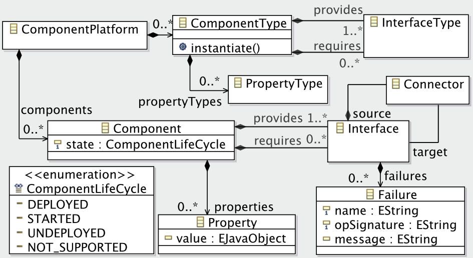
Simplified



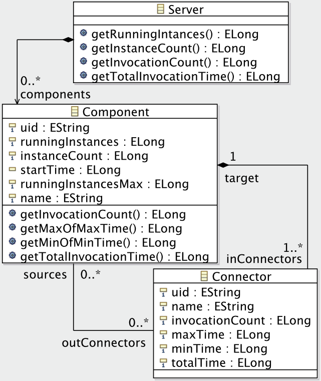
Knowledge — Reflection Models

Metamodels for PIMs

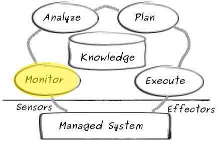
Failures



Performance



Monitor



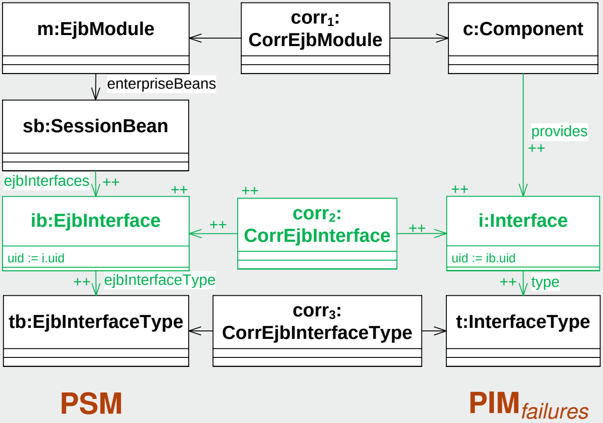
Synchronizing changes in the system to the reflection models

- Keeping runtime models up-to-date and consistent to each other
- Sensors (instrumentation): management APIs
- **Incremental**, event-driven updates: System → PSM
  (manually implemented adapter)
- **Incremental** model synchronization: PSM → PIM_1, PIM_2, ...
  (Model synchronization engine based on Triple Graph Grammars (TGG))

[MRT09,MiSE10]

Monitor — TGG Rules

TGG rule for PSM → PIM$_{failures}$



- Overall, 11 rules for PSM → PIM$_{failures}$

Monitor — Development costs

generated code from TGG rules

	Proposed solution			**Batch**
PIMs	#Rules	#Nodes/Rules	LOC	LOC
Simpl. Architectural Model	9	7,44	15259	357
Performance Model	4	6,25	5979	253
Failure Model	7	7,14	12133	292
Sum	20		33371	902

- **Proposed solution** — **incremental** synchronization
  - System → PSM: 2685 LOC for the reusable adapter
  - PSM → 3 PIMs: 20 TGG rules (generated >33k LOC)
- **Batch** — creates PIMs directly from scratch (**non-incremental**)
  - 902 LOC (≈ 20 TGG rules)
- Declarative vs. imperative approaches

Remark: done for slightly different metamodels than shown here

Monitor — Performance

Size	Proposed Solution						Batch
	n=0	n=1	n=2	n=3	n=4	n=5	
5	0	163	361	523	749	891	8037
10	0	152	272	457	585	790	9663
15	0	157	308	472	643	848	10811
20	0	170	325	481	623	820	12257
25	0	178	339	523	708	850	15311
System → PSM	0%	92.8%	94.1%	95.6%	95.2%	96.3%	-
PSM → 3 PIMs	0%	7.2%	5.9%	4.4%	4.8%	3.7%	-

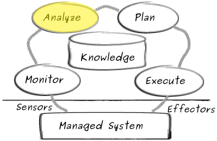
[ms]

- **Size**: number of deployed beans
- Structural monitoring through event-driven sensors
- Processing **n** events and invoking **once** the model synchronization engine

Remark: done for slightly different metamodels than shown here

Analyze

Analyzing the running system based on reflection models (PIMs)



- Identifying needs for adaptation (reactively)
- Structural checks expressed in **Story Patterns**

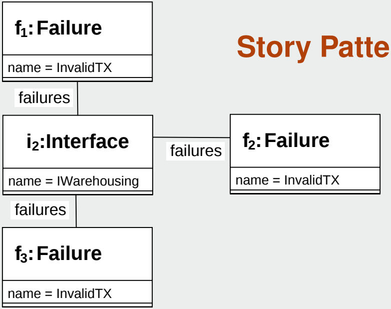
  (Story Pattern and Story Diagram Interpreter)
- Under certain conditions, **incremental** execution of Story Patterns
- Constraints expressed in the **Object Constraint Language (OCL)**

  (Existing engine from the Eclipse Model Development Tools)
- Model-based analysis techniques

[MRT11,MiSE12,SFM12]

Analyze — Evaluation Models

Identifying failures or violations of architectural constraints

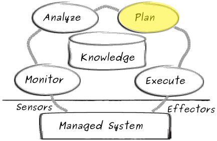


Story Pattern

OCL expression

```
if self.name = 'TShop'
then self.components.size() <= 1
else true
endif
```

Plan



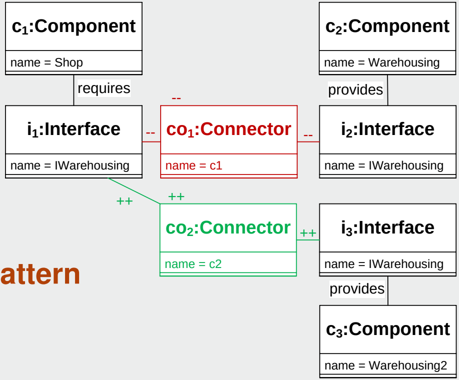
Planning adaptations based on analysis results

- Changing reflection models (PIMs) (and in the end the system)
- **Story Patterns** defining in-place transformations
  (Story Pattern and Story Diagram Interpreter)
- Under certain conditions, **incremental** execution of Story Patterns
- **OCL expression** to check and manipulate models
  (Existing engine from the Eclipse Model Development Tools)

[MRT11,MiSE12,SFM12]

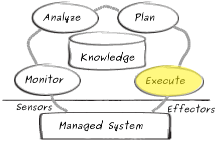
Plan — Change Models

Switching connections between components



Story Pattern

Execute



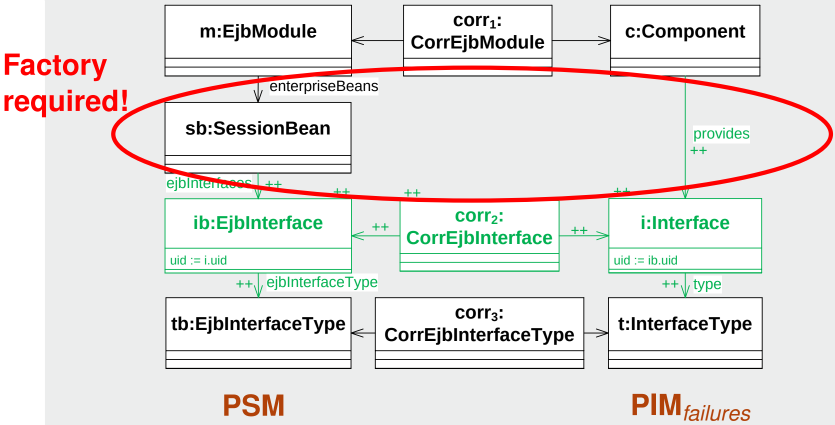
Synchronizing changes of reflection models to the system: PIMs → PSM → System

- PIM → PSM
  - **Incremental** model synchronization: same rules as for monitoring due to bidirectionality of TGG
  - Story Patterns for default creation patterns in refinement transformations (**Factories**)
- PSM → System
  - Observing PSM changes performed by the model synch. engine
  - Incrementally enacting these changes through effectors (management APIs)

[SEAMS10]

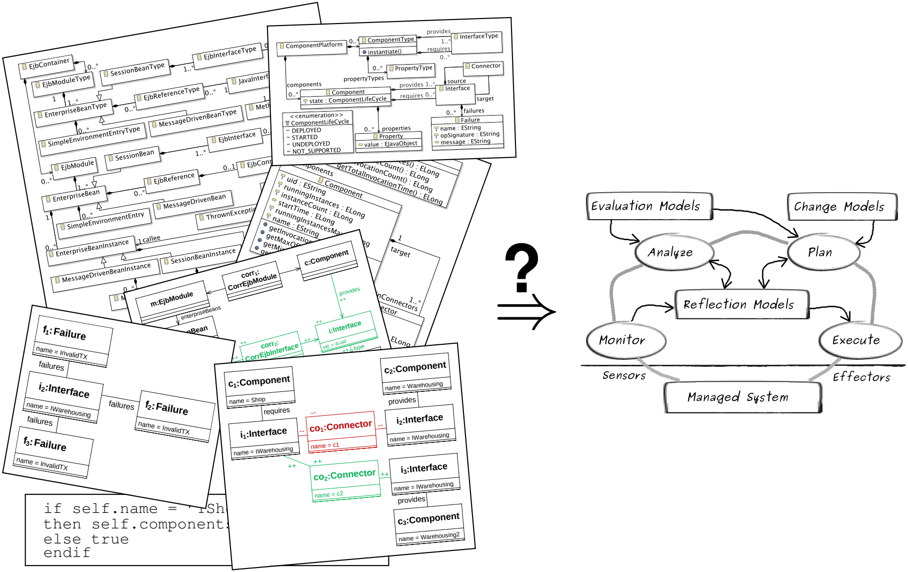
Execute — TGG Rules

TGG rule for PSM ↔ PIM$_{failures}$



- Overall, 11 rules and 1 factory for PSM ↔ PIM$_{failures}$

Interplay of all those models?



```
if self.name = 'ISh
then self.component
else true
endif
```

[MRT10,MiSE11,SEAMS12]

Specifying and executing feedback loops

Specification — Modeling language

- Capturing the interplay of multiple runtime models [Vogel et al., 2010b, Vogel et al., 2011]
- Making feedback loops **explicit** in the design of self-adaptive systems [Müller et al., 2008, Brun et al., 2009]

Execution — Model interpreter

- Coordinated execution/usage of multiple runtime models
- **Flexible** solutions and structures for feedback loops
  - Adaptable feedback loops (adaptive control)
  - State-of-the-art frameworks often prescribe static solutions to single feedback loops (e.g., [Garlan et al., 2004, Schmidt et al., 2008])

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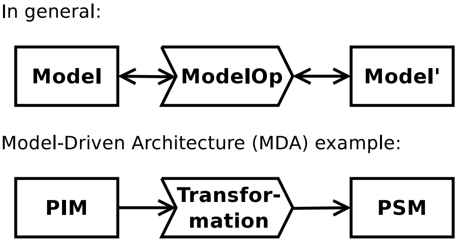
Executable Runtime Megamodels

Megamodels

Definition (Megamodel)

A *megamodel* is a model that contains models and relations by means of model operations between those models.



- Research on model-driven software development (MDA, MDE)

  [Favre, 2005, Bézivin et al., 2003, Bézivin et al., 2004, Barbero et al., 2007]
- “Toward Megamodels at Runtime” [Vogel et al., 2010b]

An Example: Self-repair

Analyzed
Start
Effected

Legend

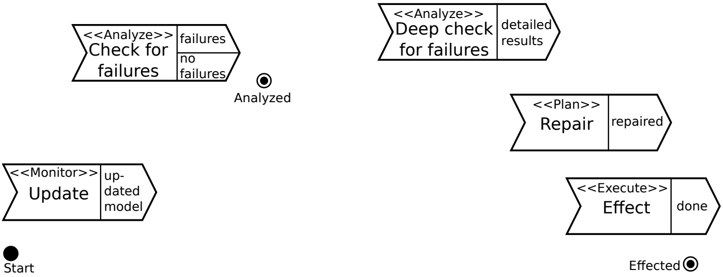
(concrete syntax)

● Initial state

◉ Final state

Remark: Abstract syntax defined by a metamodel [Vogel and Giese, 2012a]

An Example: Self-repair



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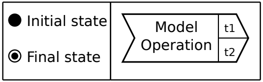

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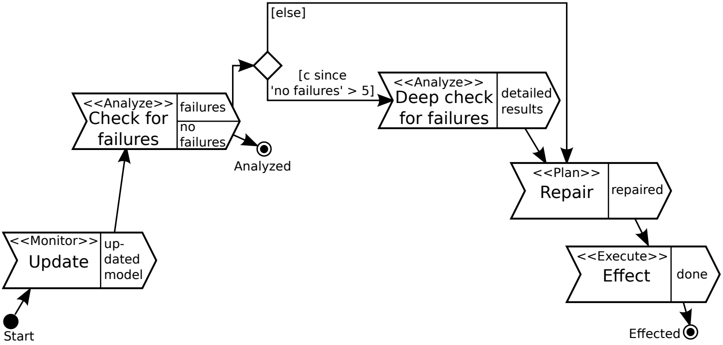

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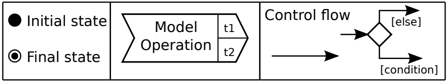

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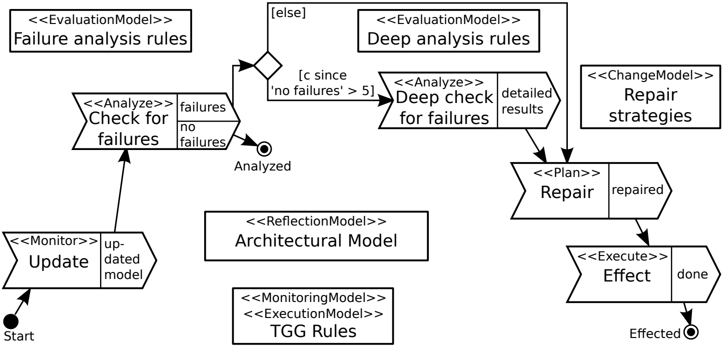

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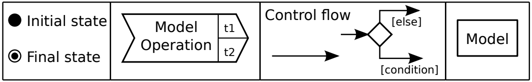

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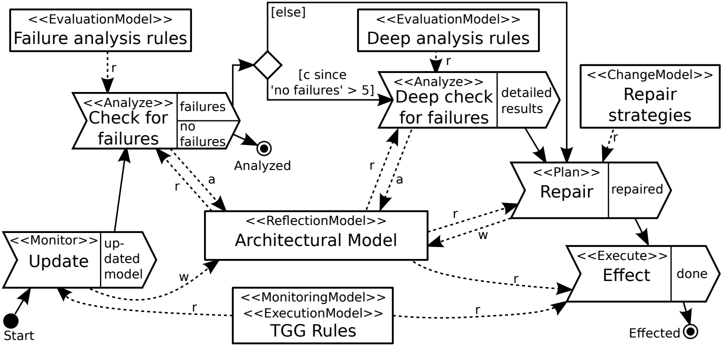

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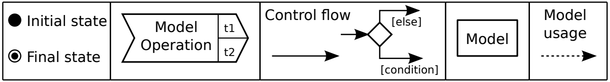

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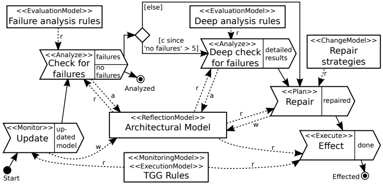
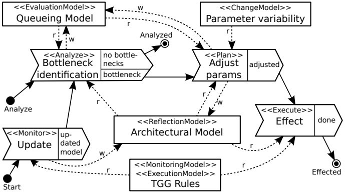
Modeling Interacting Feedback Loops

Self-repair



Self-optimization



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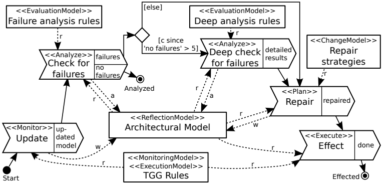

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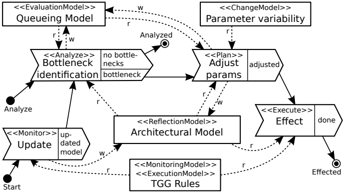

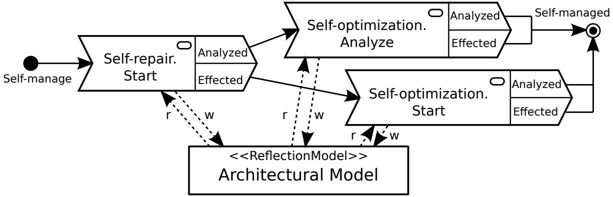

One solution: Linearizing Complete Feedback Loops

Modeling Interacting Feedback Loops

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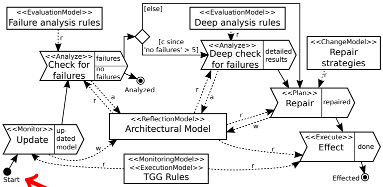

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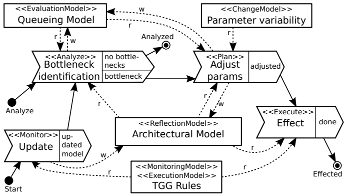
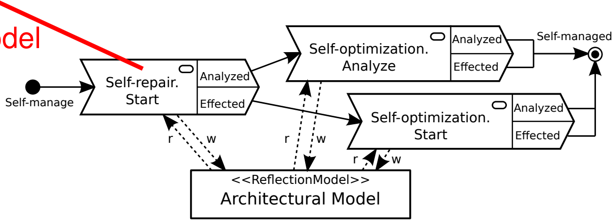


Complex model operations



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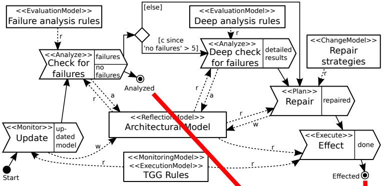

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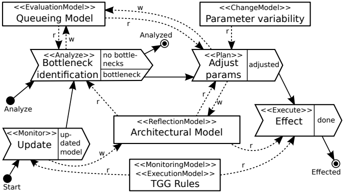

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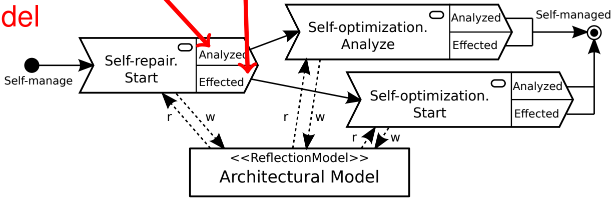

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Modeling Interacting Feedback Loops

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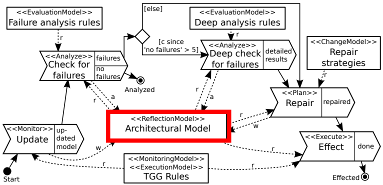

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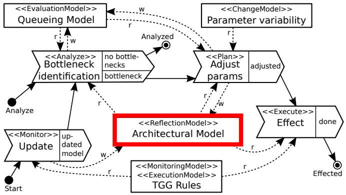
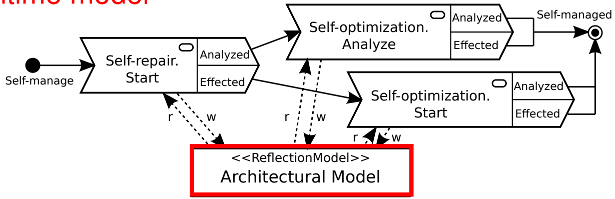


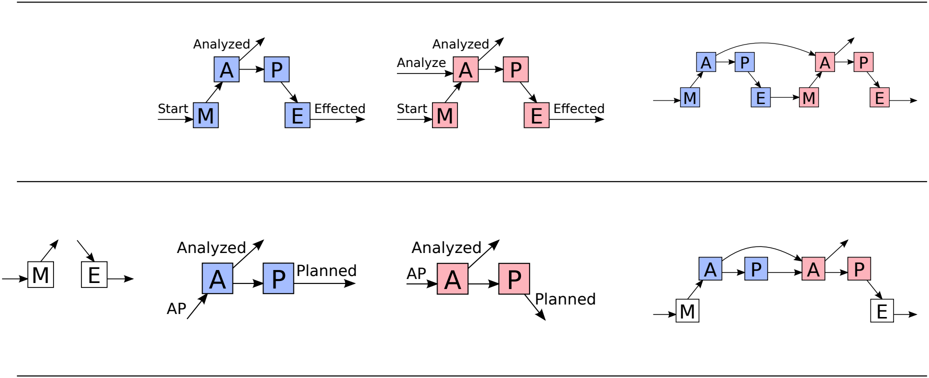
Shared runtime model



One solution: Linearizing Complete Feedback Loops

Other Solutions. . .

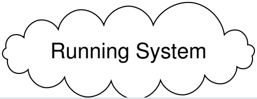
Generic Self-repair Self-optimization Composition



⇝ Patterns for control in self-adaptive systems [Weyns et al., 2012]

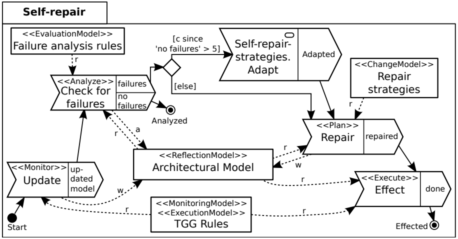
Modeling Hierarchies of Feedback Loops

Layer$_0$

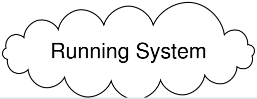


Modeling Hierarchies of Feedback Loops

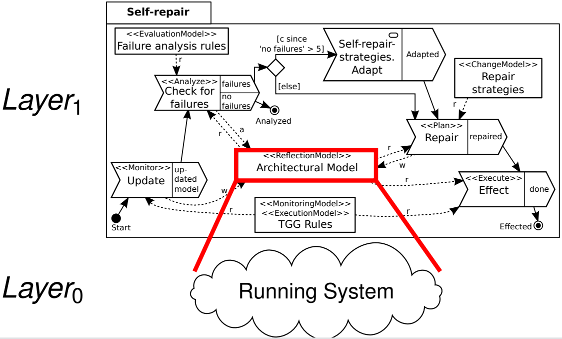
Layer$_1$



Layer$_0$



Modeling Hierarchies of Feedback Loops



Causal connection

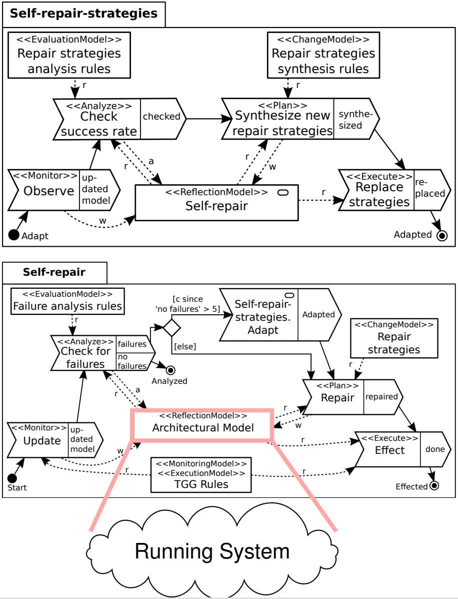
- sensors + effectors required
- implementation efforts!

Modeling Hierarchies of Feedback Loops

$Layer_2$

$Layer_1$

$Layer_0$


Self-repair-strategies
<<EvaluationModel>> Repair strategies analysis rules
<<ChangeModel>> Repair strategies synthesis rules
r
r
<<Analyze>> Check success rate
checked
<<Plan>> Synthesize new repair strategies
synthe-sized
r
a
r
w
<<Monitor>> Observe
up-dated model
<<ReflectionModel>> Self-repair
r
<<Execute>> Replace strategies
re-placed
w
Adapt
Adapted
Self-repair
<<EvaluationModel>> Failure analysis rules
r
[c since 'no failures' > 5]
Self-repair-strategies. Adapt
Adapted
<<ChangeModel>> Repair strategies
<<Analyze>> Check for failures
failures
no failures
[else]
Analyzed
r
a
r
<<Plan>> Repair
repaired
r
w
<<ReflectionModel>> Architectural Model
<<Monitor>> Update
up-dated model
<<Execute>> Effect
done
w
r
r
r
<<MonitoringModel>> <<ExecutionModel>> TGG Rules
Start
Effected
Running System

Causal connection

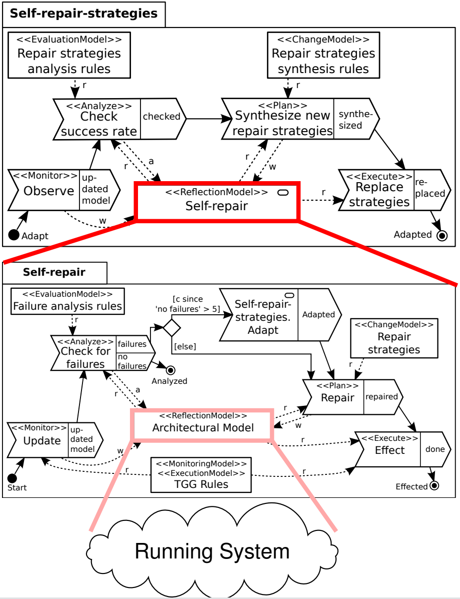
- sensors + effectors required
- implementation efforts!

Modeling Hierarchies of Feedback Loops

$Layer_2$

$Layer_1$

$Layer_0$



Layer$_2$ **directly uses the megamodel of** *Layer*$_1$

- no specific sensors and effectors required
- adapts the models or control flow of the *Layer*$_1$ megamodel
- interpreter (flexibility)!

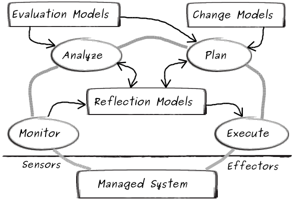
Causal connection

- sensors + effectors required
- implementation efforts!

Conclusion

Models at runtime

- Adaptation steps and knowledge
- Single and multiple feedback loops



Discussion

(1) Cost-effective development

(2) Reflection capabilities

(3) Making feedback loops explicit

(4) Flexible (runtime) solutions

. . . while being runtime efficient (incremental, on-line techniques)

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