Extending Dynamic Software Product Lines with Temporal Constraints

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Adaptive Cloud Environments

- Cloud computing supports construction of customized adaptable environments

> "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) **that can be rapidly provisioned and released with minimal management effort or service provider interaction**."[1]

- A cloud environment is a set of cloud services provisioned for running an application

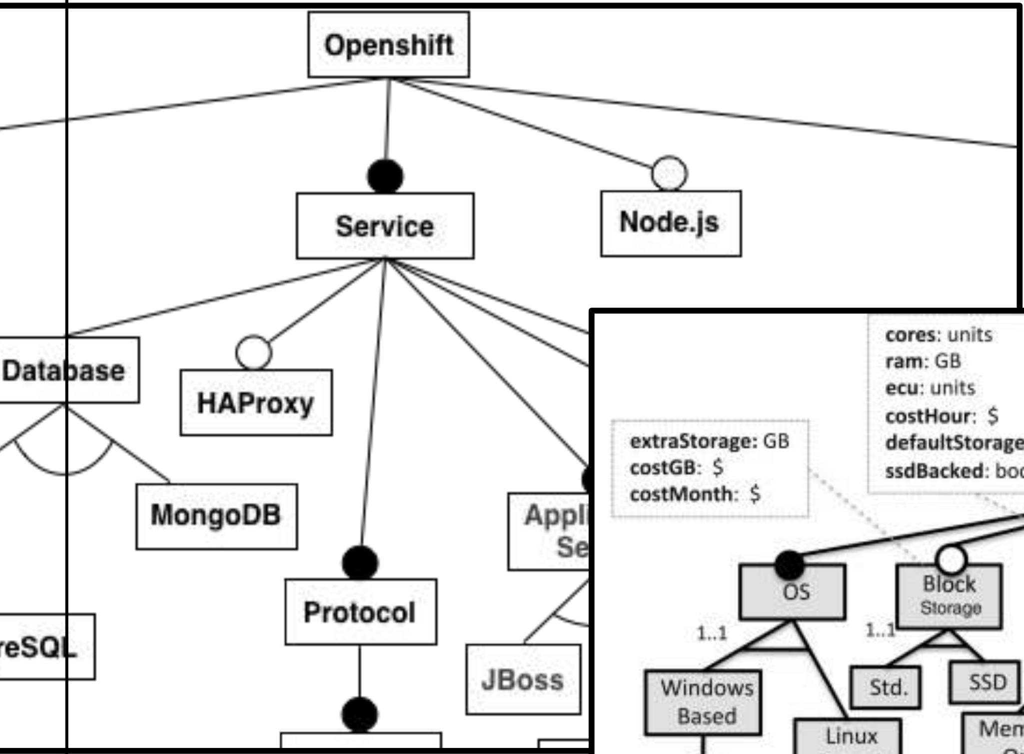
[1] P. Mell and T. Grance, "The NIST definition of cloud computing," Computer Security Division, Information Technology Laboratory, National Institute of Standards and Technology, Tech. Rep., 2011.

Cloud Providers Configuration Variability

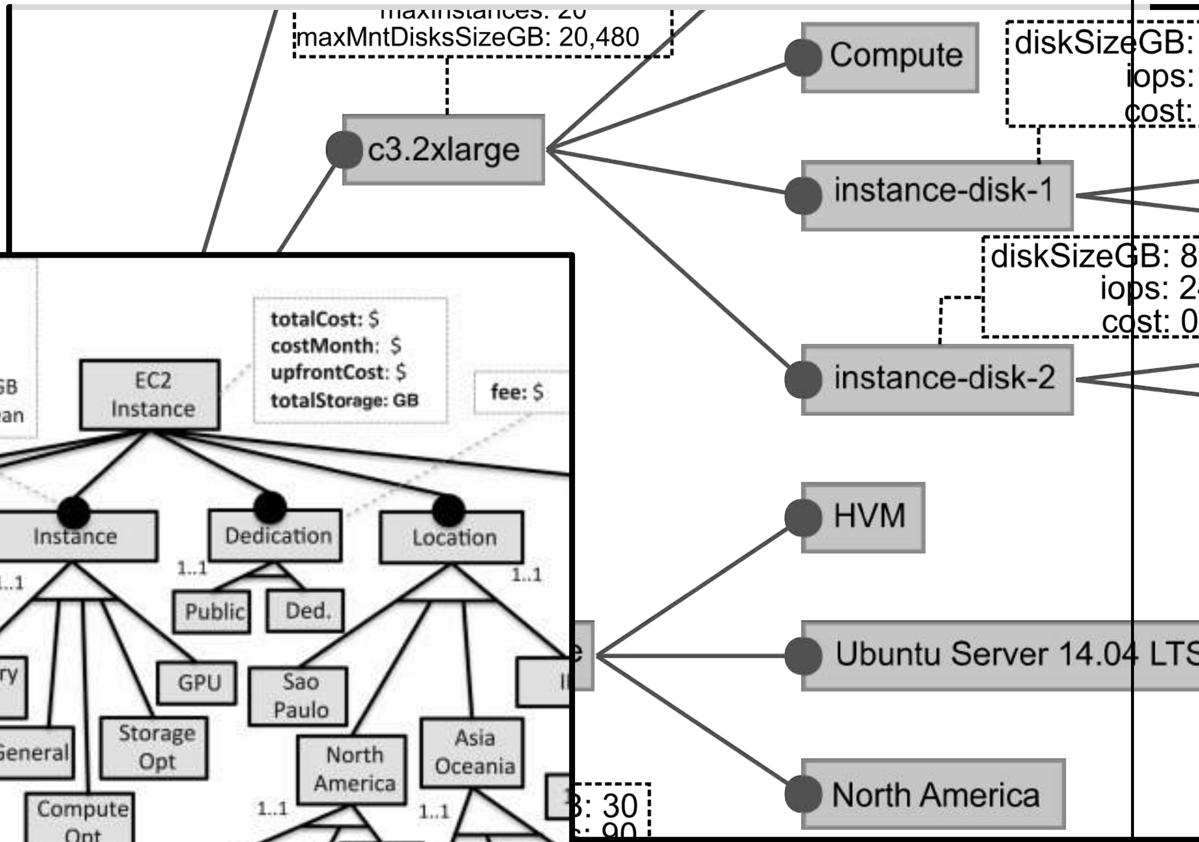
- Wide range of configurable cloud services
- Complex configuration rules and constraints

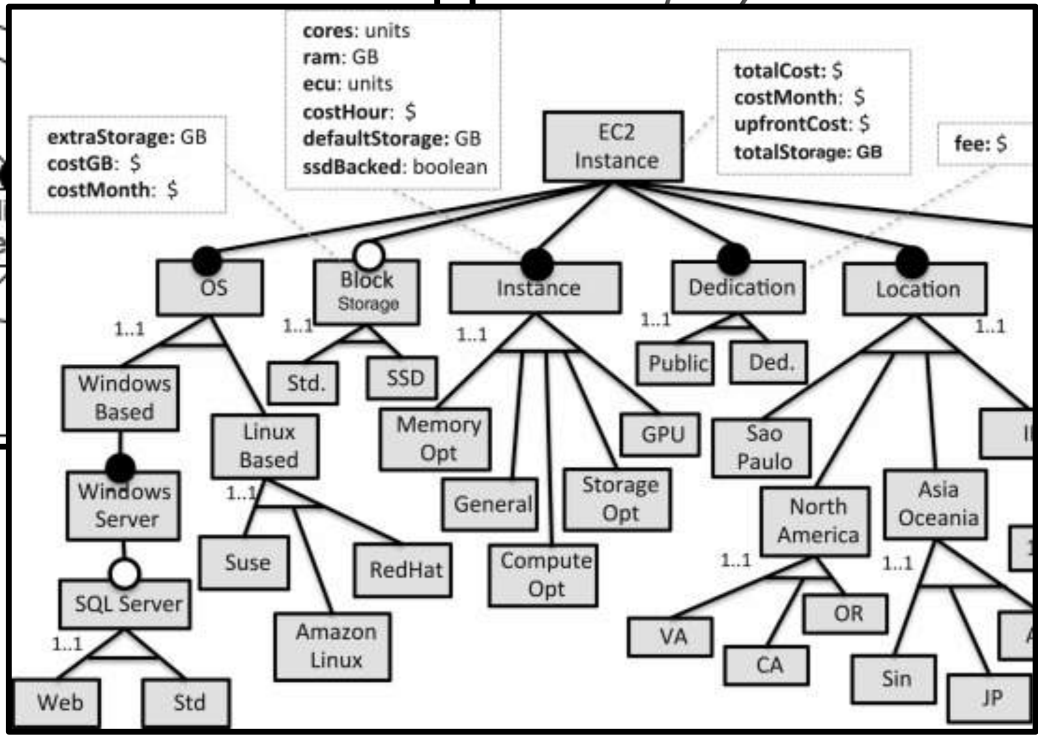
SPLs for Automated Cloud Configuration

C. Quinton et al. (2016) SALOON: a platform for selecting and configuring cloud environments.



A. Ferreira Leite et al. (2015) Automating Resource Selection and Configuration in Inter-clouds through a SPL method.





J. García-Galán et al. (2016) Automated Configuration Support for Infrastructure Migration to the Cloud.

Dynamic Software Product Lines

- **High variability** with **adaptive capabilities**

Dynamic Software Product Lines

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- DSPL vs SPL
  - Features can be (re)bound at runtime
  - Adaptive system vs systems family
  - Variability model central to both

Dynamic Software Product Lines

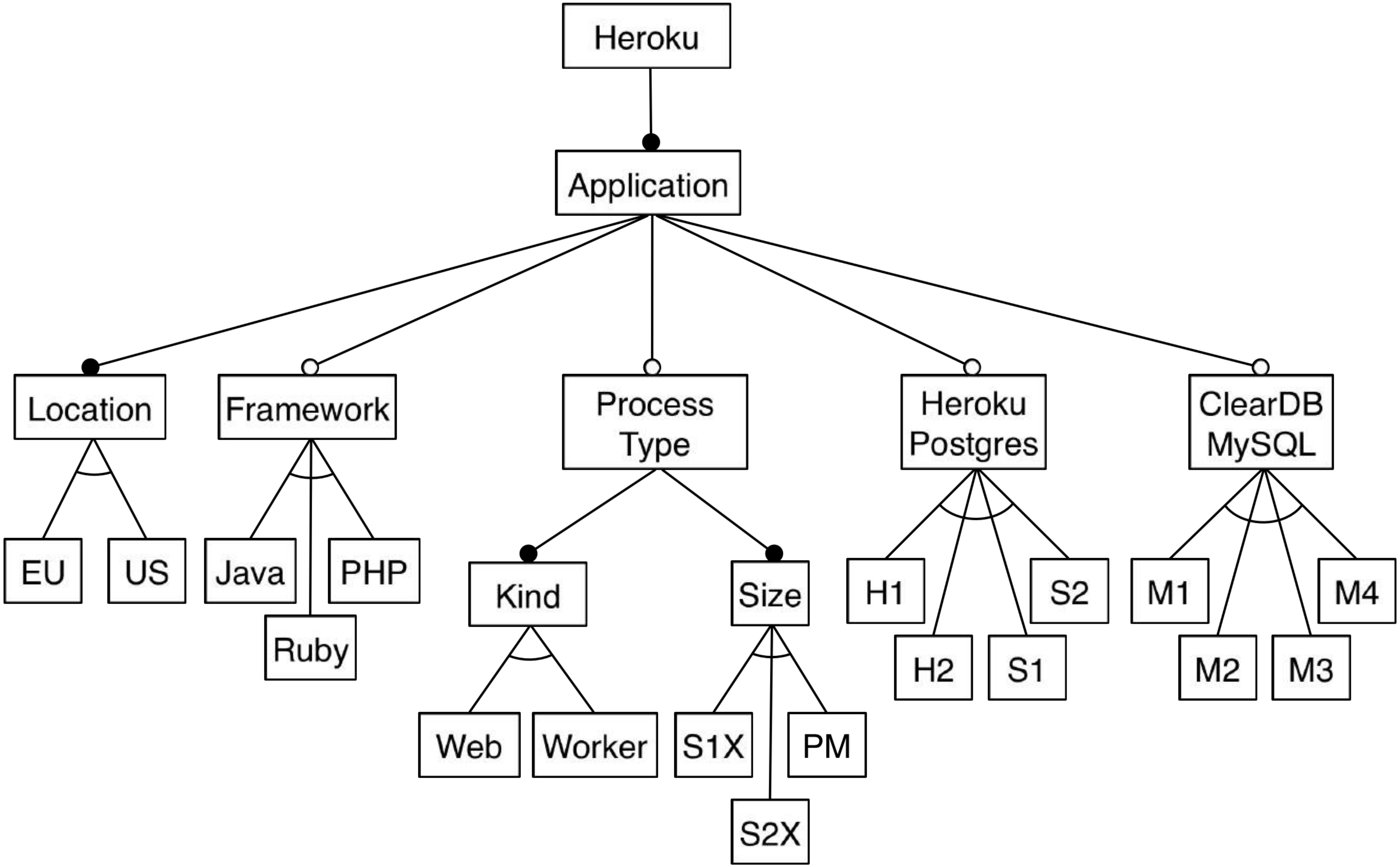
- **High variability** with **adaptive capabilities**
- DSPL vs SPL
  - Features can be (re)bound at runtime
  - Adaptive system vs systems family
  - Variability model central to both
- Adaptation in DSPLs
  - A context change is mapped to a request to include or exclude a set of features from the current configuration
  - SPL analysis is used to derive valid configurations

Cloud Computing Environment

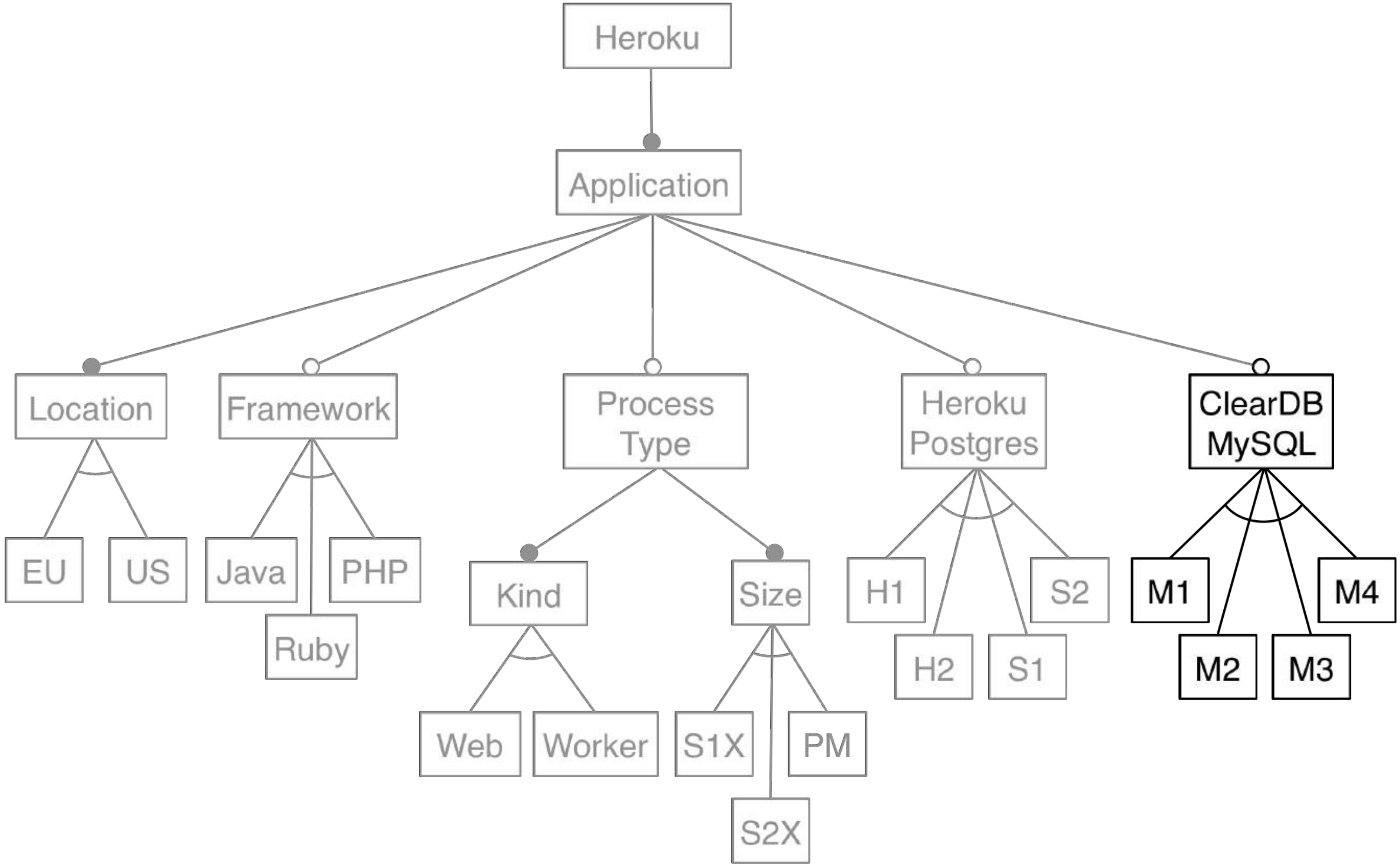
- Reconfiguration mechanisms are provider-dependent and heterogeneous
  - May depend on initial or previous configurations
  - Alternative ways to reconfigure

- Compliance to variability model is not enough
  - Does not ensure valid and safe reconfigurations

Motivating Example



Motivating Example



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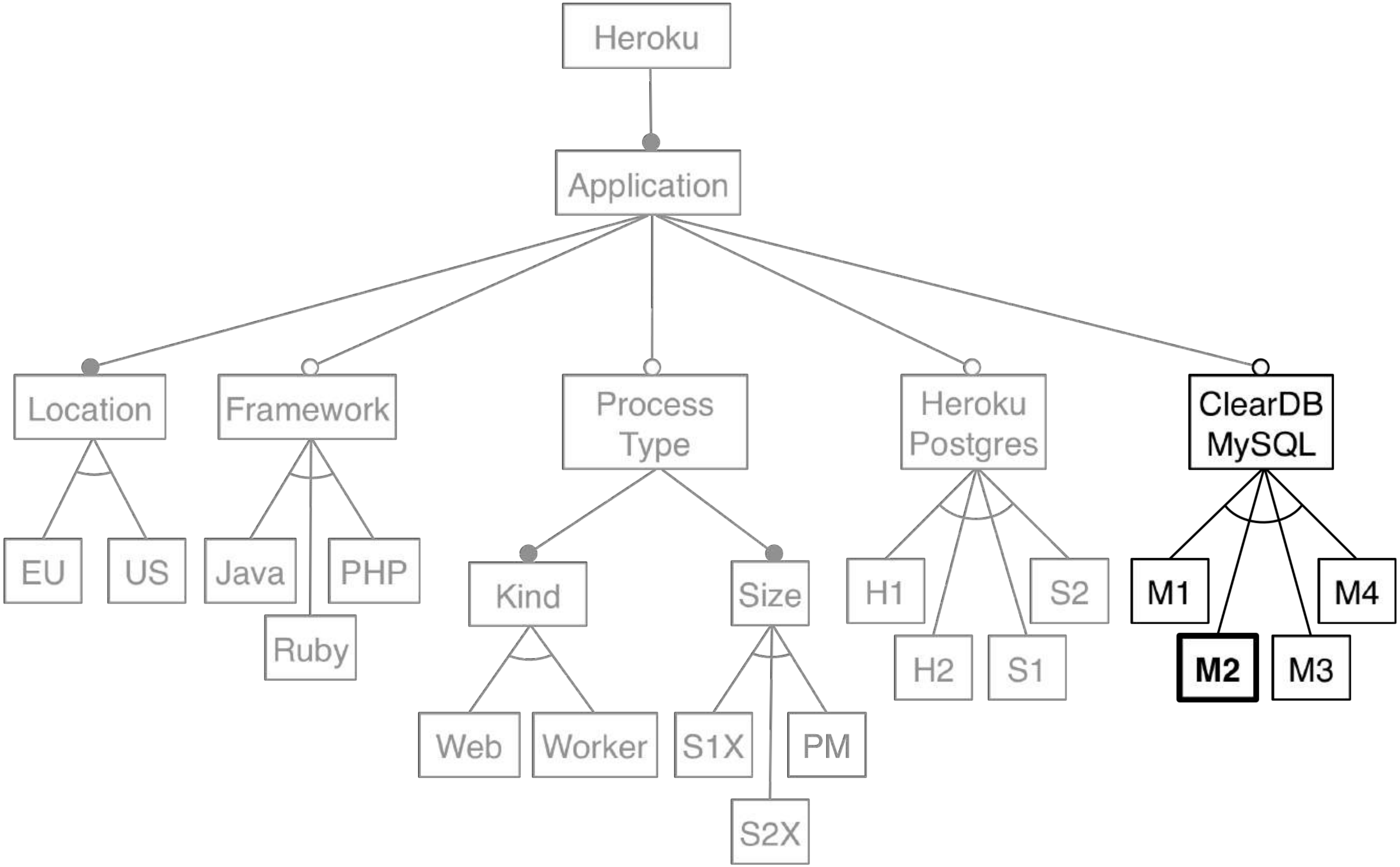

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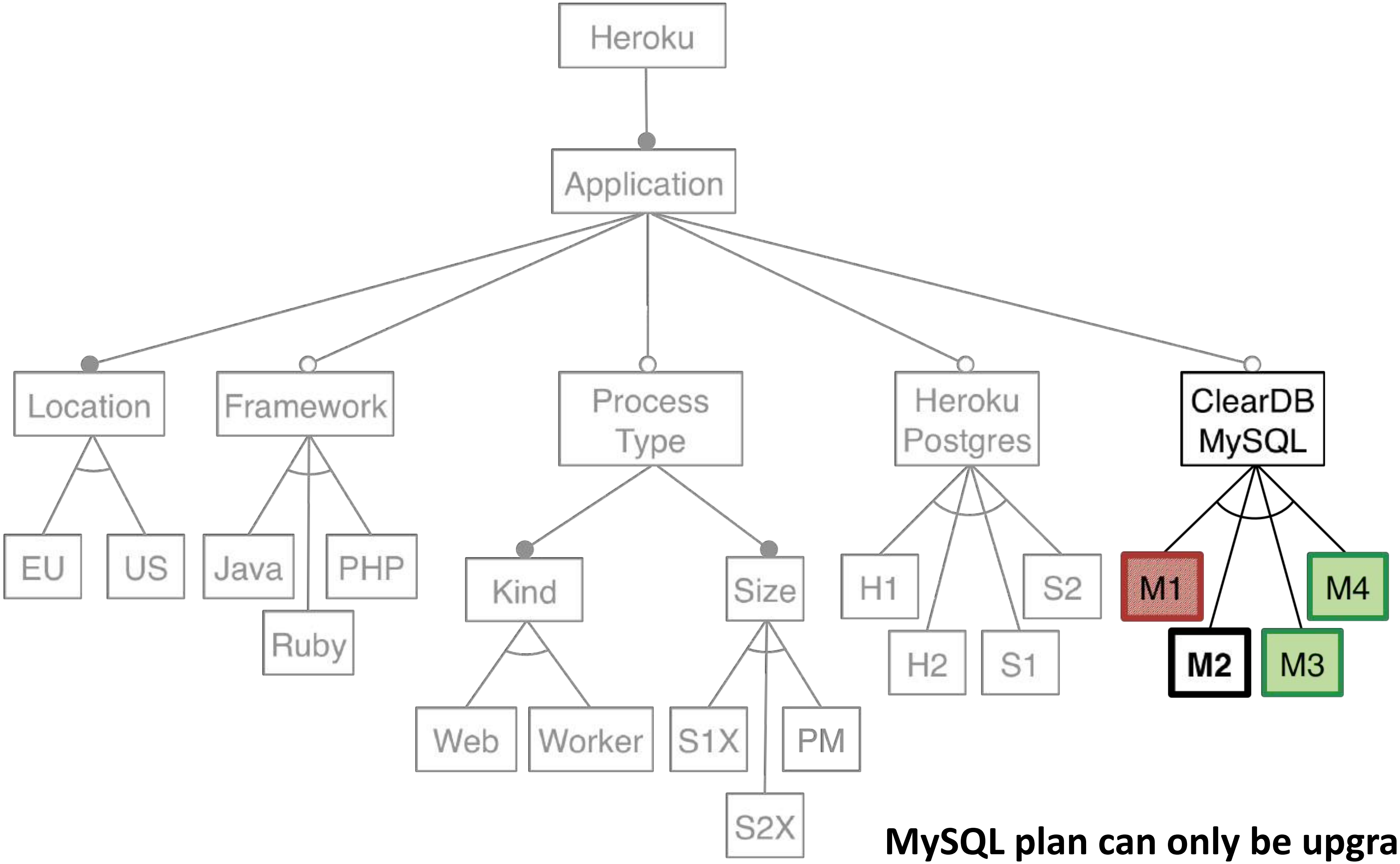
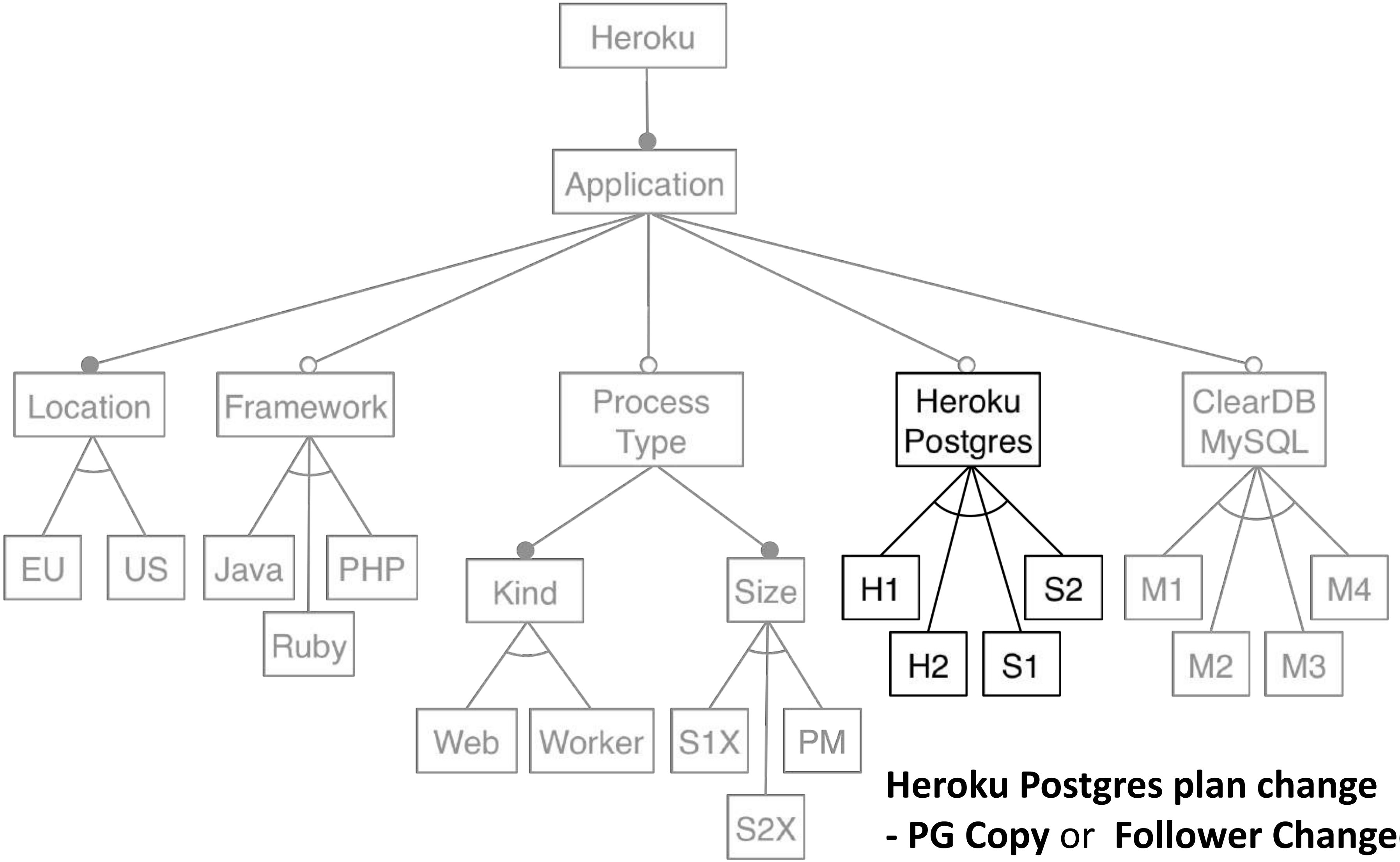


MySQL plan can only be upgraded

https://devcenter.heroku.com/articles/cleardb#upgrading-your-cleardb-database

Motivating Example

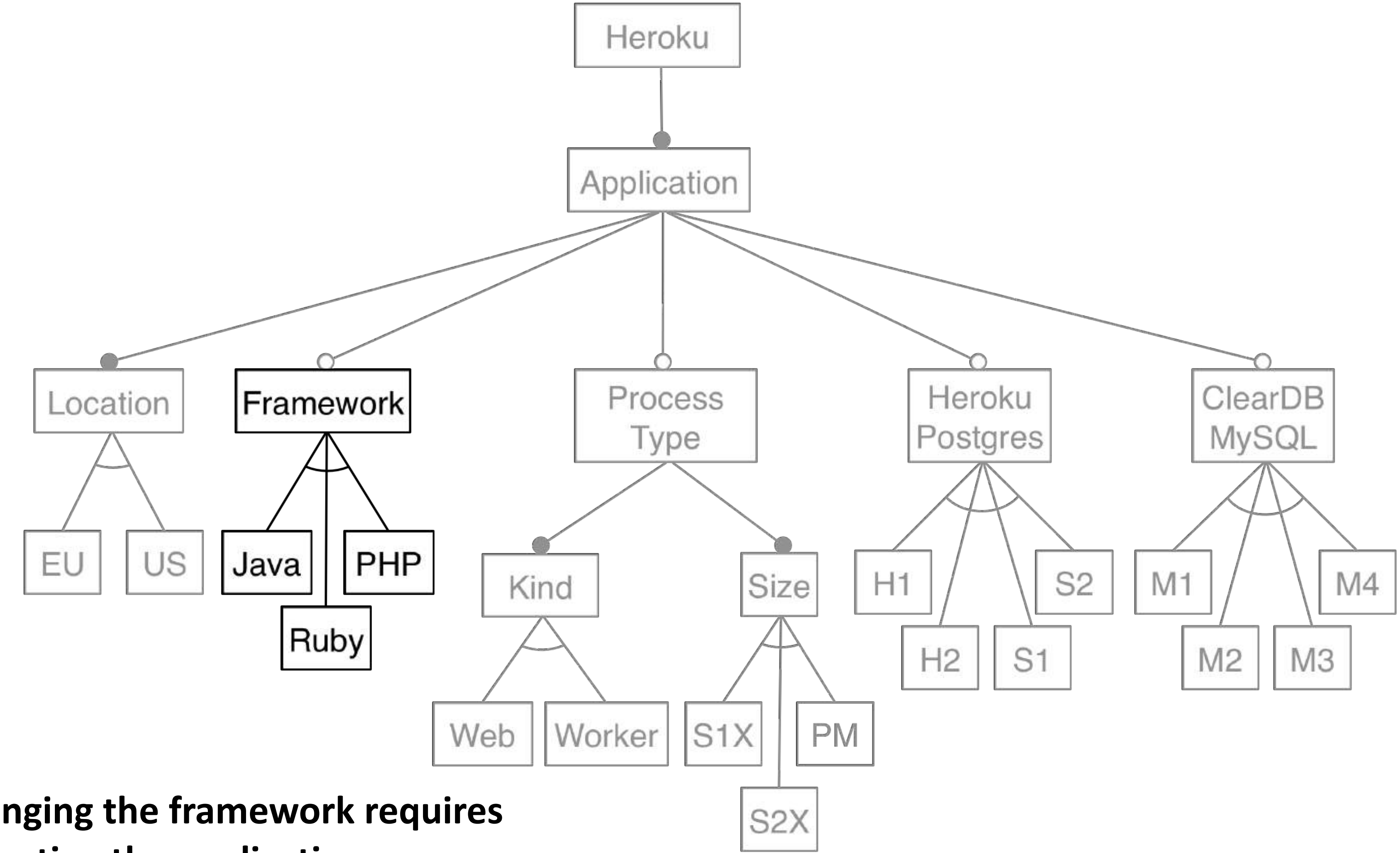


Heroku Postgres plan change

- PG Copy or **Follower Changeover**

https://devcenter.heroku.com/articles/upgrading-heroku-postgres-databases

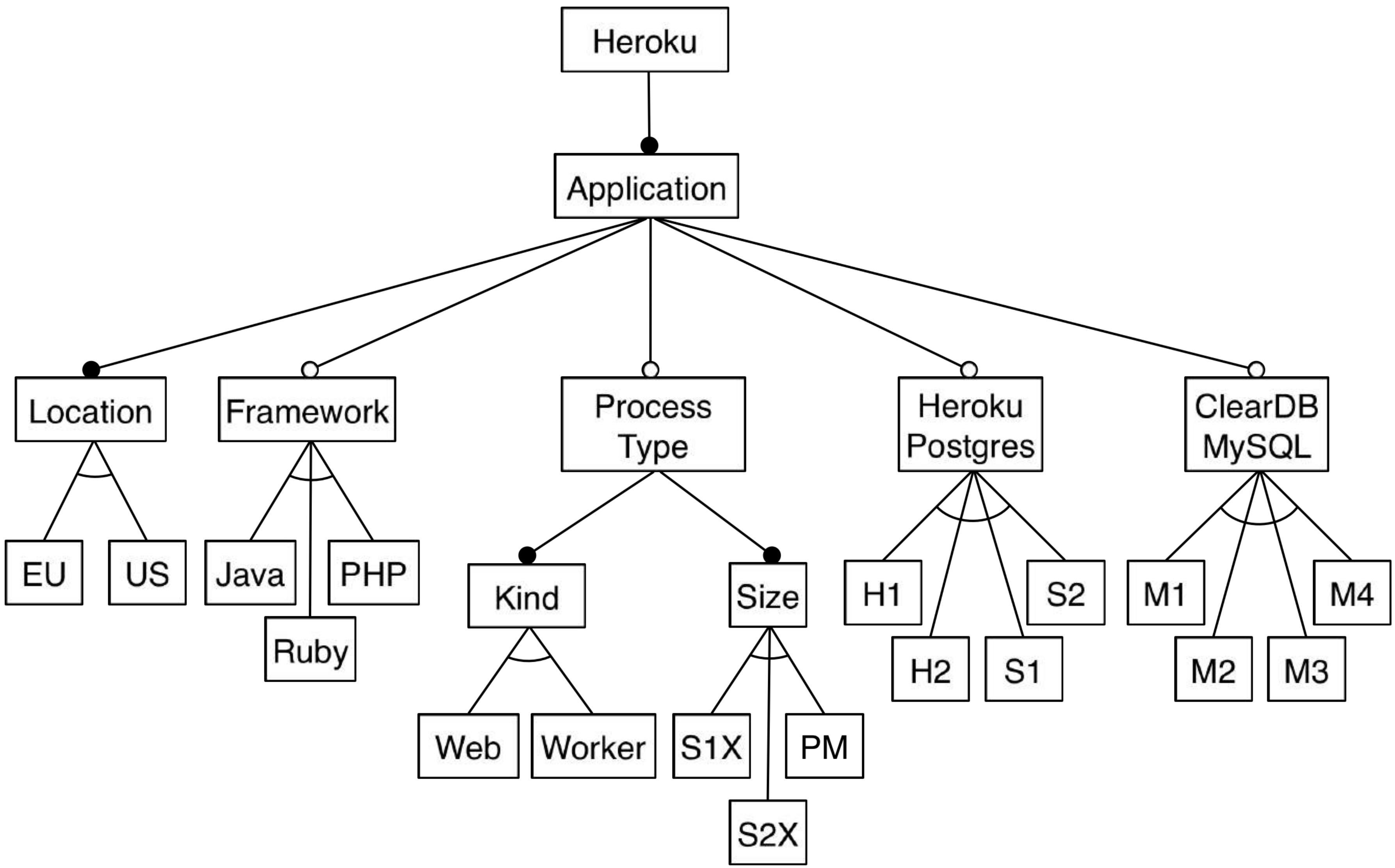
Motivating Example



Changing the framework requires restarting the application

https://devcenter.heroku.com/articles/buildpacks#setting-a-buildpack-on-an-application

Motivating Example



Limitations in DSPLs

- Seminal works on DSPLs highlight the need for validating transitions between system configurations
  - systems should evolve through safe migration paths[6]
  - dynamic constraints on allowed transitions must be considered[7]

- Validation is mostly limited to compliance to a variability model

[6] B. Morin, O. Barais, J. M. Jezequel, F. Fleurey, and A. Solberg, "Models@run.time to support dynamic adaptation," Computer, vol. 42, no. 10, pp. 44–51, Oct 2009.

[7] A. Hubaux and P. Heymans, "On the evaluation and improvement of feature-based configuration techniques in software product lines," in Proc. 31st Int. Conf. Software Engineering (ICSE'09), Vancouver, Canada, May 2009, pp. 367–370.

Problem statement

- How to model constraints over the adaptation behavior?
  - Temporal dependencies between features and reconfiguration operations
- How to reason over a variability model with reconfiguration constraints to find reconfigurations that meet a given criteria?
  - e.g. reduced downtime or costs

Proposed approach

- Combine **variability models** with **temporal constraints** and **reconfiguration operations**
  - Leverage concepts and solutions from model checking

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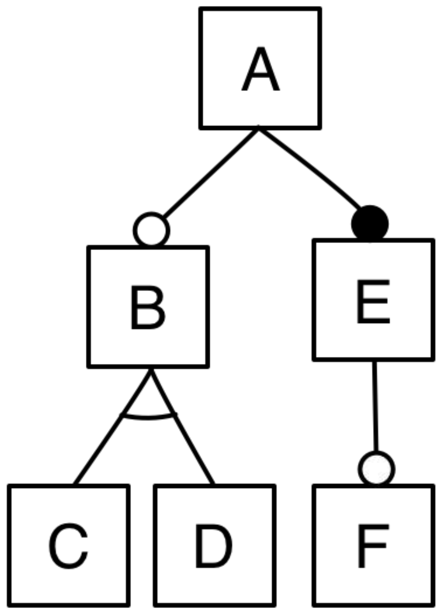
Feature Models and Transition Systems

- Feature model $M = (F, C)$
  - F is the set of features
  - $C \subseteq \mathcal{P}(F)$



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C2 = {A, E, F}
C3 = {A, B, C, E}
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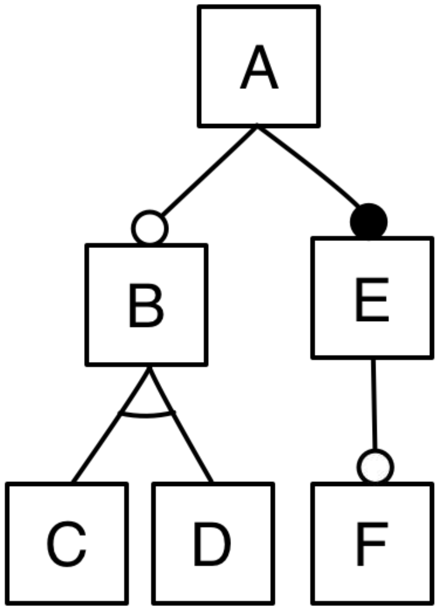
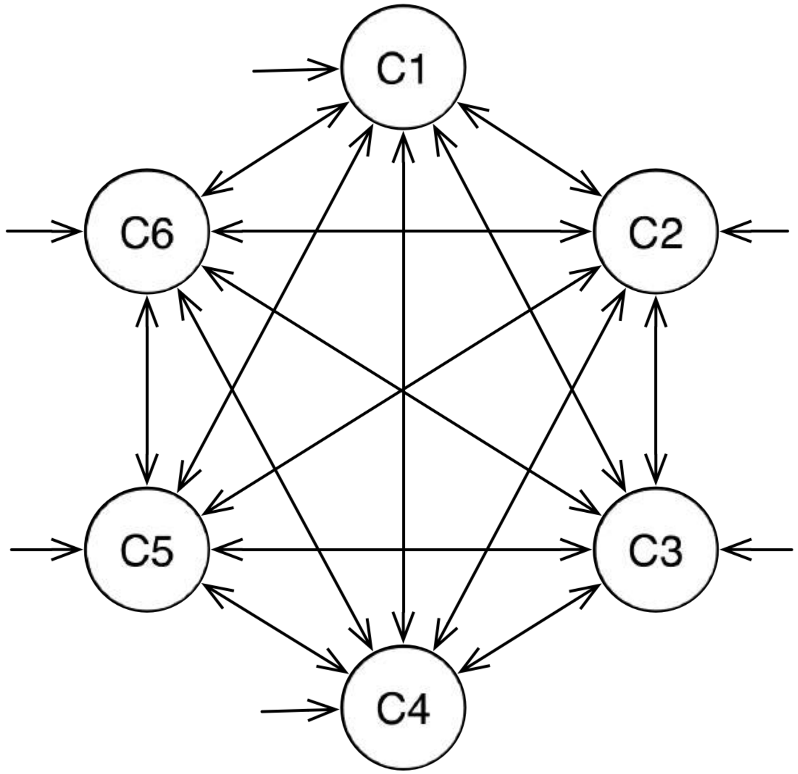
DSPLs as Transition Systems





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"A DSPL's execution can be abstracted as a highly connected state machine where the states are the possible system configurations and the transitions the migration paths."[6]

[6] B. Morin, O. Barais, J. M. Jezequel, F. Fleurey, and A. Solberg, "Models@run.time to support dynamic adaptation," Computer, vol. 42, no. 10, pp. 44–51, Oct 2009.

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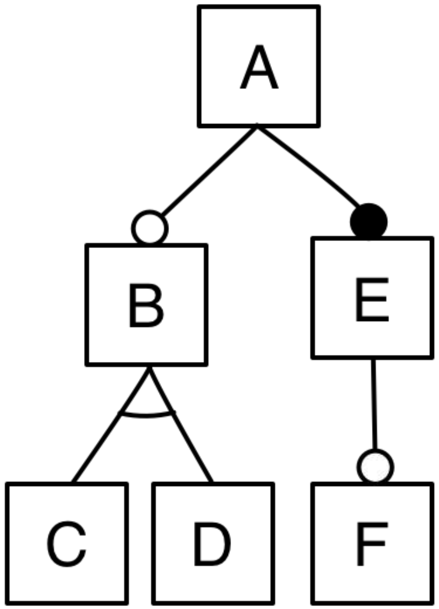

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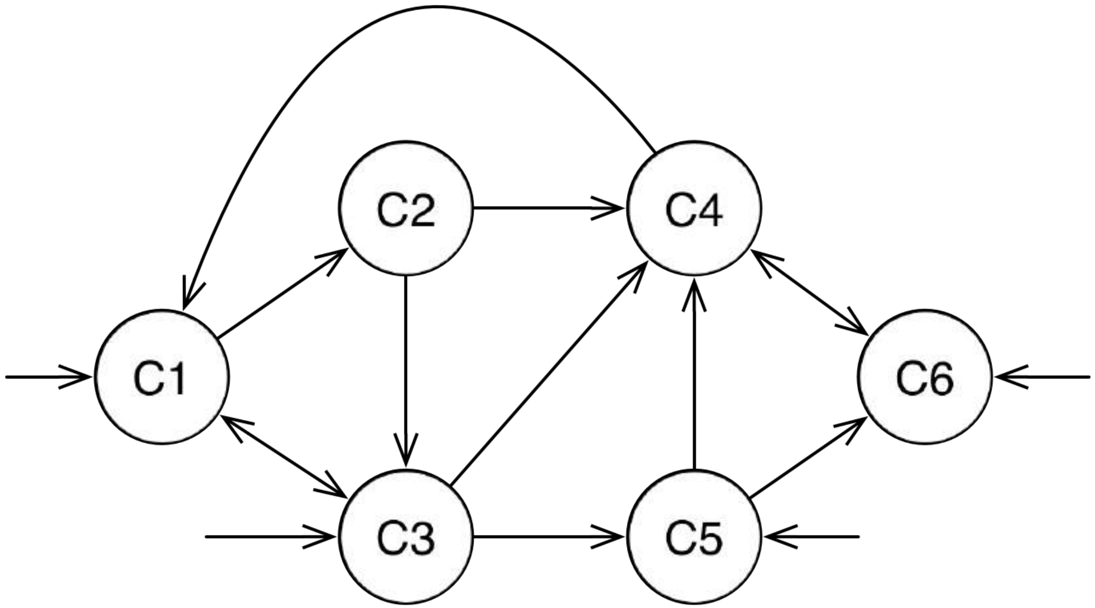


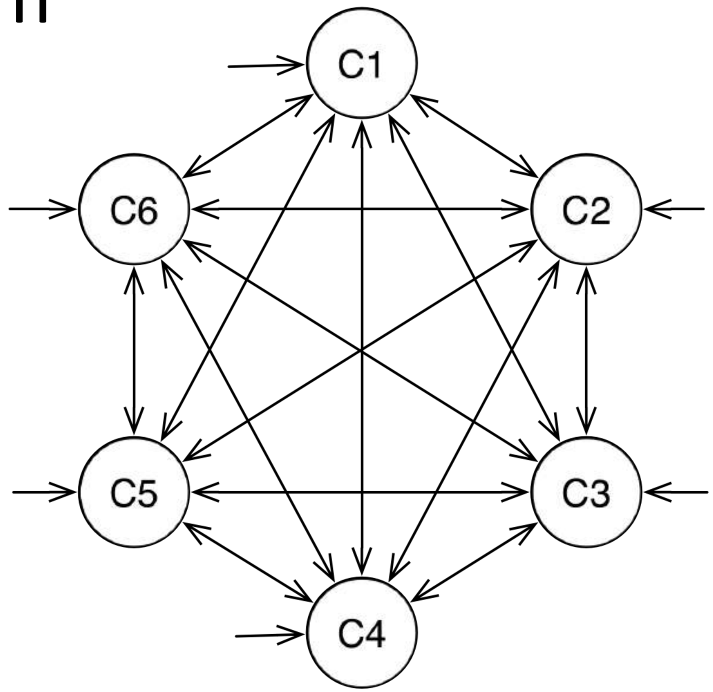
Temporal properties

- A temporal property defines a condition over the executions of a transition system
  - Execution:

    $\rho = s_0 s_1 s_2 s_3 s_4 \ldots$

    $s_i \rightarrow s_{i+1}$ is a transition

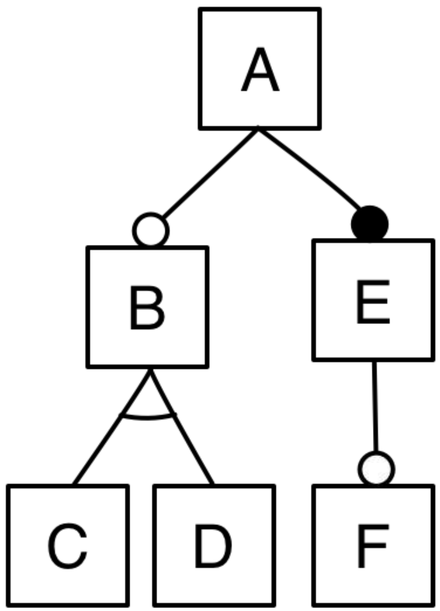
  - A property is a set executions



  - A system exhibits a property if all its executions are part of the property set

Feature Models and Transition Systems

- Feature model $M = (F, C)$
- Transition system $TS_M = (S, I, R, AP, L)$
  - $S = I = C$, $R = S \times S$, $AP = F$, $L(x) = x$



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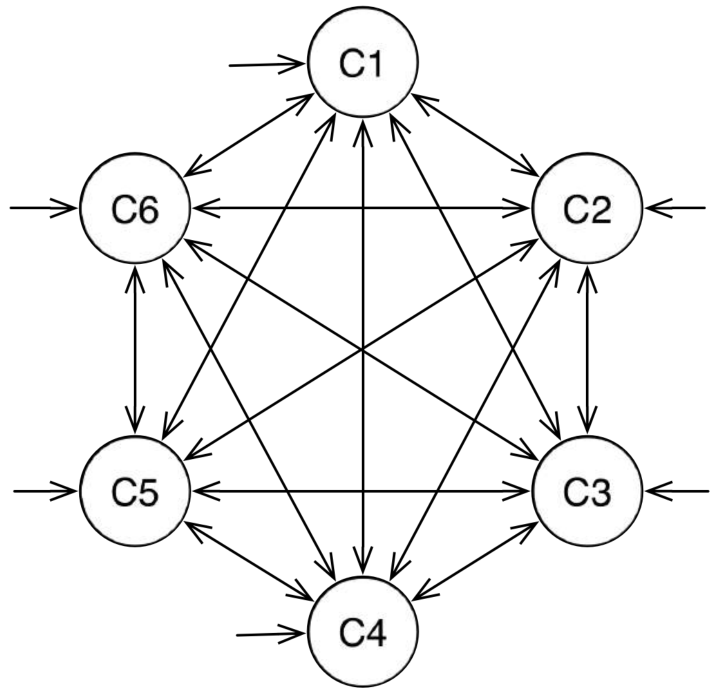

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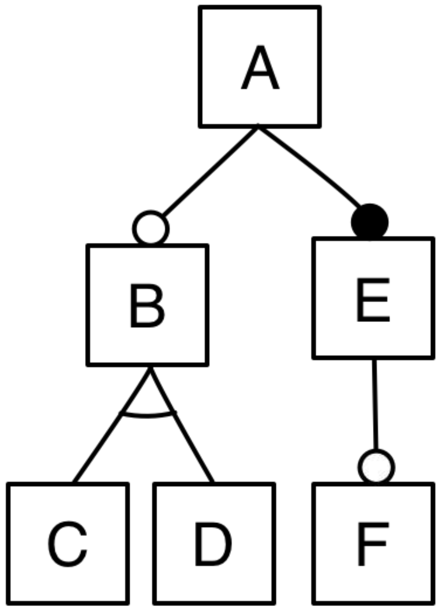

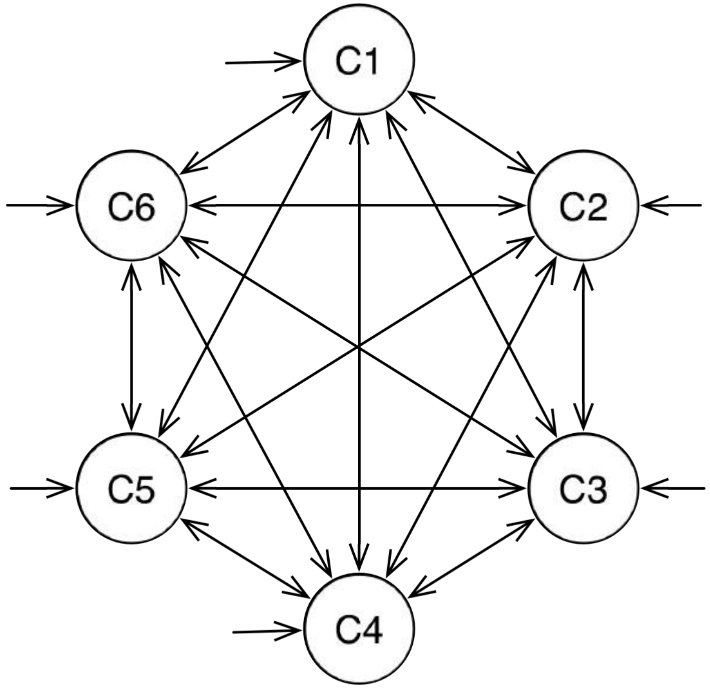

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$$P = \{s_0 s_1 s_2 s_3 \ldots \mid C \in L(s_i) \leftrightarrow D \notin L(s_{i+1})\}$$

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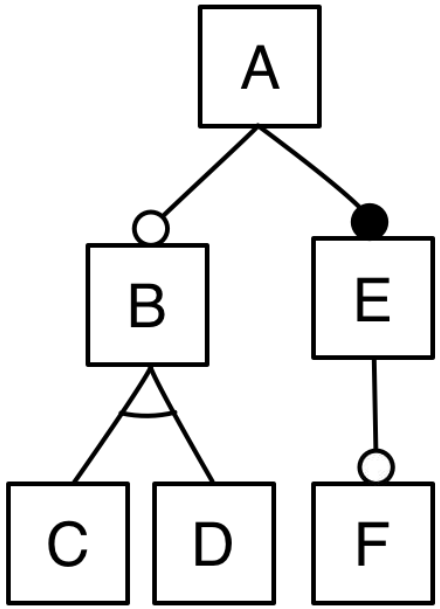

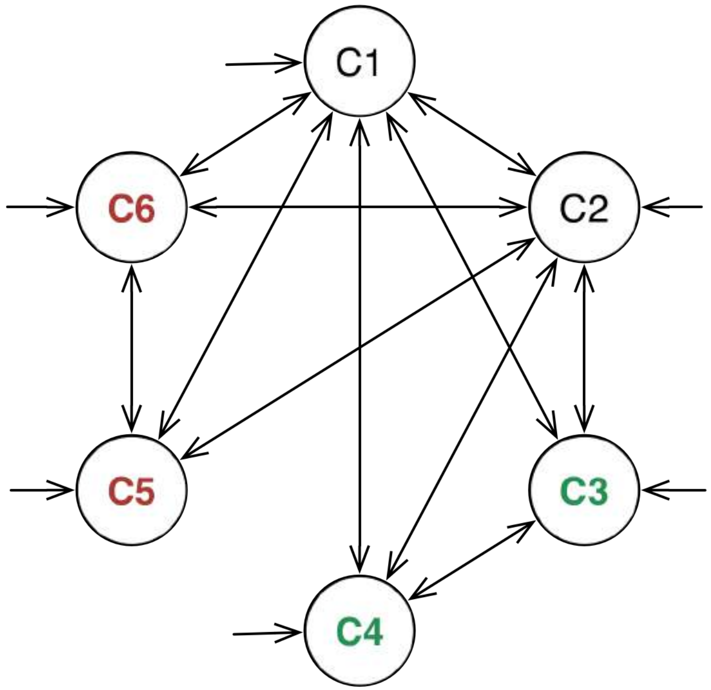

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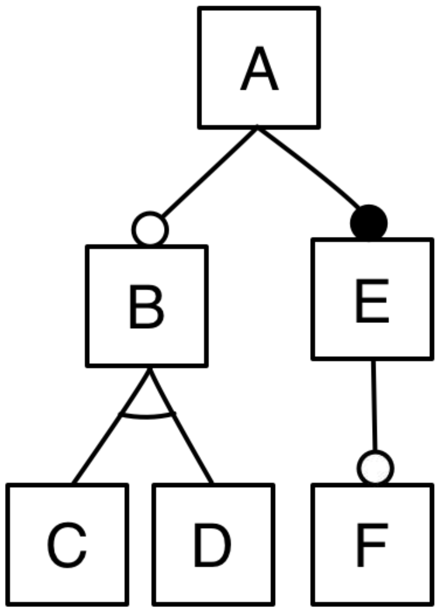
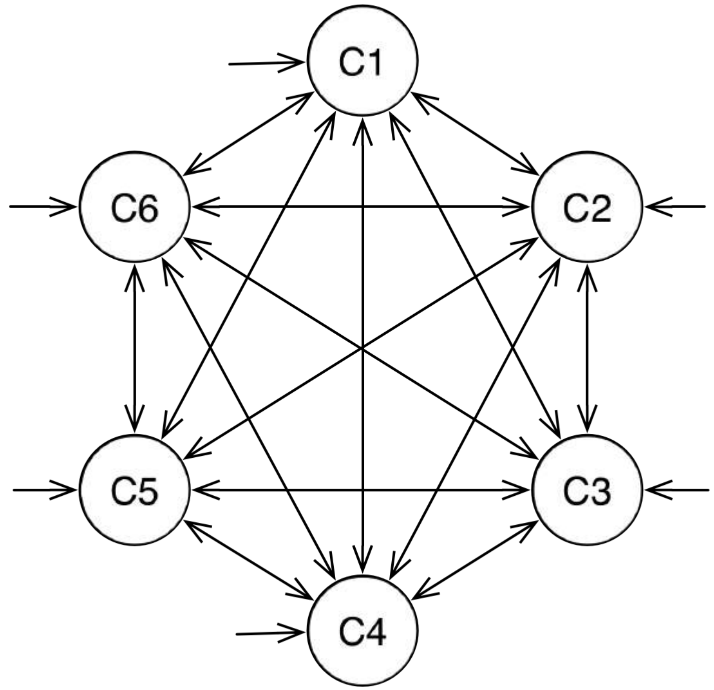
$$P = \{s_0 s_1 s_2 s_3 \ldots \mid C \in L(s_i) \leftrightarrow D \notin L(s_{i+1})\}$$

Linear Temporal Logic (LTL)

- Defines temporal properties over transition systems
- Combines propositional logic with temporal operators (always, eventually, until)
  - $\Box A$ // always A
  - $\Box(M2 \rightarrow \neg \bigcirc M1)$ // always (M2 is not followed by M1)
  - $\Box(M2 \rightarrow \neg \diamond M1)$ // after M2, M1 is not allowed

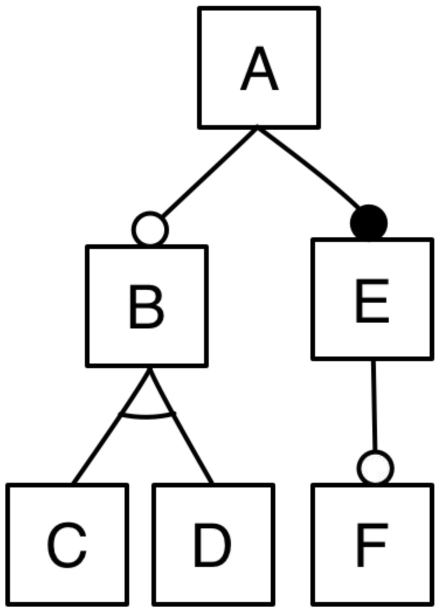
DSPL with temporal properties





$$\square(C \rightarrow \neg \bigcirc D)$$
$$\square(D \rightarrow \neg \bigcirc C)$$

DSPL with temporal properties



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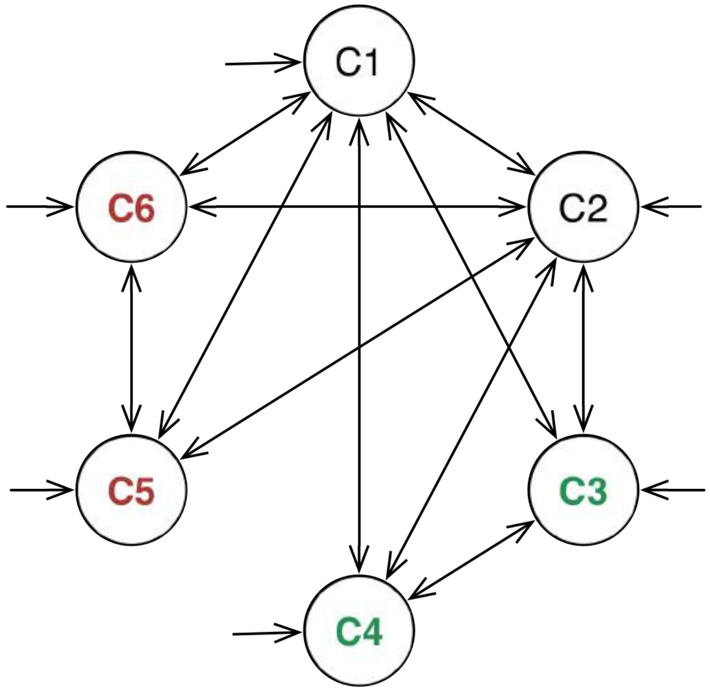
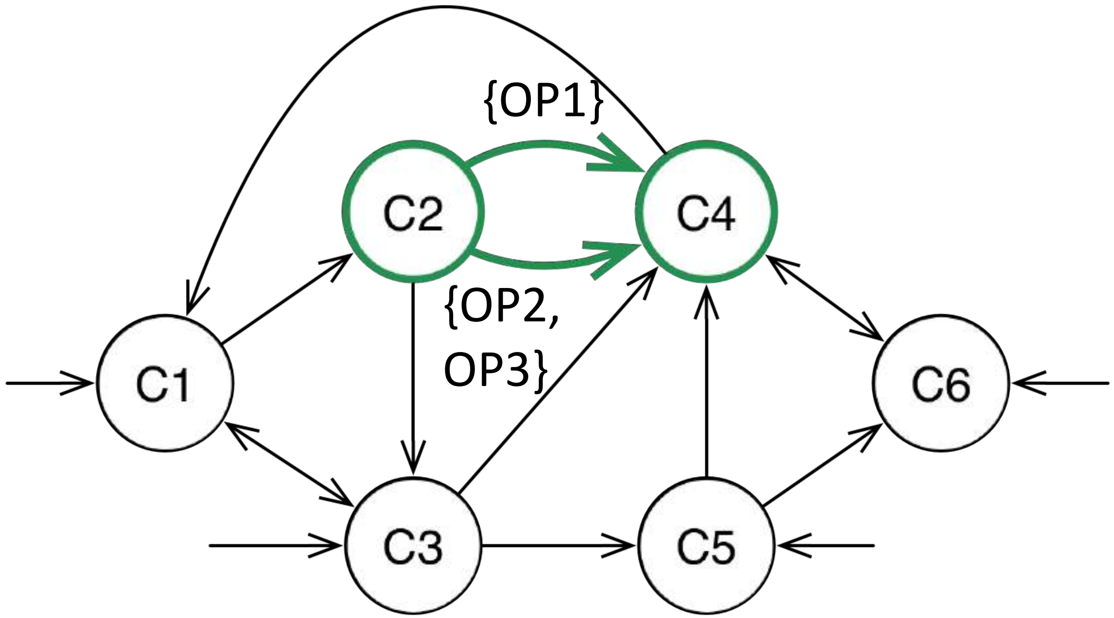


Reconfiguration operations

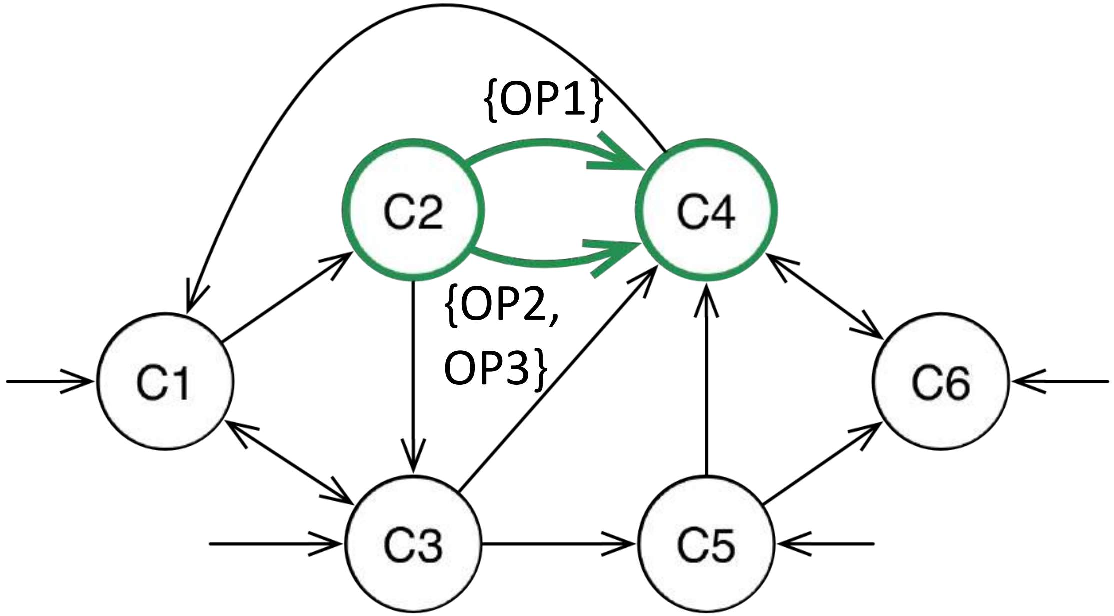
- Doubly labeled transition systems[22]



[22] M. H. ter Beek et al., "An Action/State-Based Model-Checking Approach for the Analysis of Communication Protocols for Service-Oriented Applications," in Proc. 12th Int. Workshop Formal Methods for Industrial Critical Systems (FMICS'07), Berlin, Germany, Jul. 2008, pp. 133–148.

Reconfiguration operations

- Doubly labeled transition systems[22]
  - $TS = (S, I, \boldsymbol{OP}, R, AP, L)$
  - OP is the set of reconfiguration operations in the DSPL
  - $R \subseteq S \times 2^{OP} \times S$



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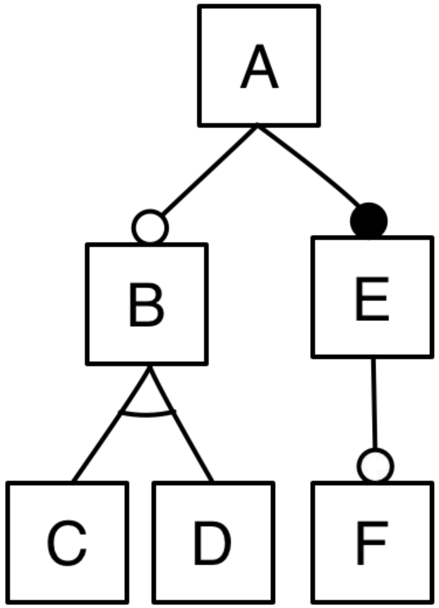
State/Event LTL

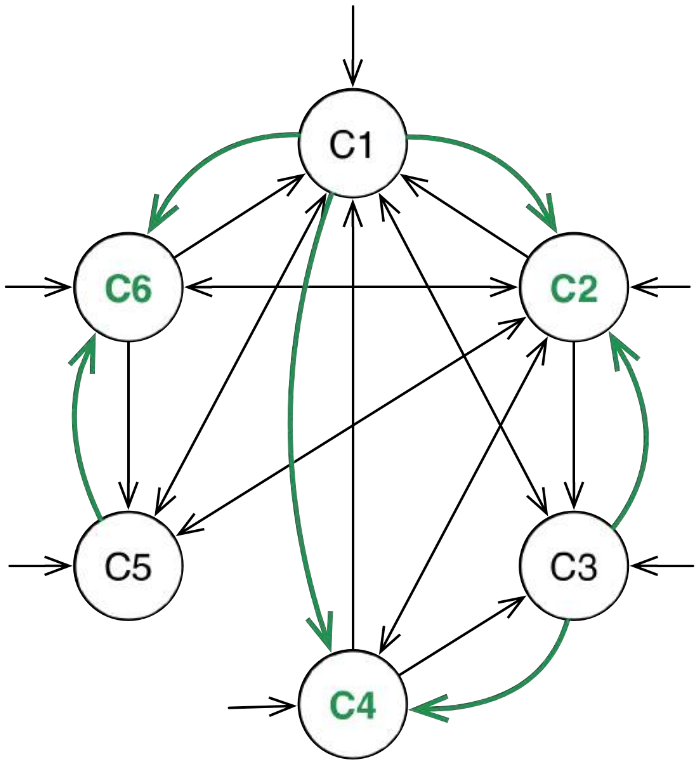
- SE-LTL can express temporal expressions over state and transition labels[23]
  - Can combine reconfiguration operations and features in temporal constraints

[23] S. Chaki et al. “State/Event-Based Software Model Checking,” in Proc. 4th Int. Conf. Integrated Formal Methods (IFM’04), Canterbury, UK, Apr. 2004, pp. 128–147.

Reconfiguration operations

$$OP = \{ActivateF\}$$





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$$\Box(C \rightarrow \neg \bigcirc D)$$
$$\Box(D \rightarrow \neg \bigcirc C)$$

$$\Box((\neg F \wedge \bigcirc F) \leftrightarrow ActivateF)$$

Examples

- Cannot downgrade MySQL plan
  - [](M2 -> !<>M1)
  - [](M3 -> !<>(M1 | M2))
  - [](M4 -> !<>(M1 | M2 | M3))
  - [](Change(ClearDBMySQL) -> UpgradeClearDB)
- Upgrade PostgreSQL
  - [](Change(HerokuPostgres) & (H1 | H2) -> PGCopy)
  - [](Change(HerokuPostgres) -> (PGCopy | FollowerChangeover))
- Change Location
  - [](Change(Location) -> MigrateApp)

Problem statement

- How to model constraints over the adaptation behavior?
  – Temporal dependencies between features and reconfiguration operations

- How to reason over a variability model with reconfiguration constraints to find reconfigurations that meet a given criteria?
  – e.g. reduced downtime or costs

Reasoning

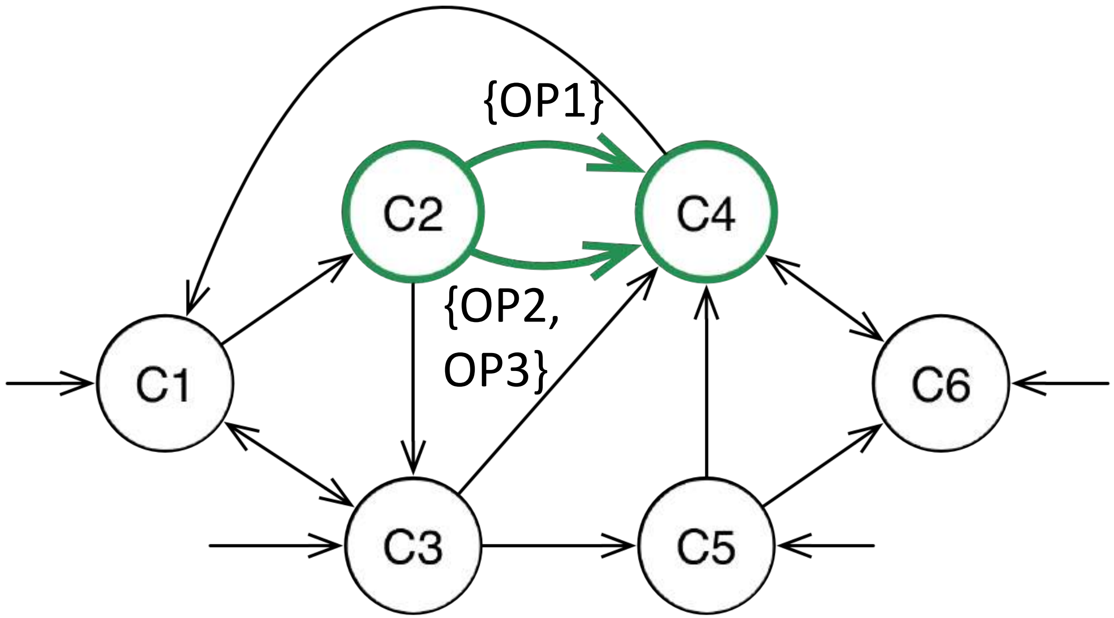
- Reconfiguration request
  - Features to be included/excluded

Reasoning

- Reconfiguration request
  - Features to be included/excluded
- Cost-based constraints
  - Reconfiguration time, downtime, financial cost, etc

Reasoning

- Reconfiguration query: $Q = (A, E, \phi)$
  - A: features to include
  - E: features to exclude
  - ϕ: constraint over costs
- Example query: $q = (\{C\}, \{D\}, \text{downtime} = 0)$



Symbolic Representation

- Building the transition system for a feature model can be unfeasible
  - State-explosion problem
- Represent a transition system as a propositional formula
  - Use SAT solver to solve reconfiguration queries

Symbolic Representation

- Feature models[25] and SE-LTL expressions[27] can be represented as propositional formulas

$$\widetilde{M} \wedge \widetilde{x} \wedge \widetilde{M}' \wedge \widetilde{s} \wedge \widetilde{q}$$

  - $\widetilde{M}$ and $\widetilde{M}'$ represent the set of possible source and target states (configurations of the feature model M)
  - $\widetilde{x}$ is the conjunction of LTL expressions
  - $\widetilde{s}$ represents the current state
  - $\widetilde{q}$ represents the reconfiguration query (pseudo-boolean encoding)

[25] D. Batory, "Feature Models, Grammars, and Propositional Formulas," in Proc. 9th Int. Conf. Software Product Lines (SPLC'05), Rennes, France, Sep. 2005, pp. 7–20.

[27] A. Cimatti, M. Pistore, M. Roveri, and R. Sebastiani, "Improving the Encoding of LTL Model Checking into SAT," in Proc. 3rd Int. Workshop Model Checking and Abstract Interpretation (VMCAI'02), Venice, Italy, Jan. 2002, pp. 196–207.

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Evaluation

Evaluation

- Case study on Heroku PaaS
  - feasibility for modeling reconfiguration constraints
  - performance of reasoning

Evaluation

- Case study on Heroku PaaS
- Feature Model extracted from documentation
  - 7 available regions, 11 programming frameworks, 6 container sizes
  - reconfiguration constraints
  - 161 addon services (data storage, networking, security, …)
  - **1036 features, 134 cross-tree constraints, 124 temporal constraints**

Evaluation

- Case study on Heroku PaaS
- Feature Model extracted from documentation
- Simulate context changes
  - 4 adaptation scenarios
  - 5 reconfiguration queries
  - 3 utilization profiles
  - 12 executions

Evaluation

- Case study on Heroku PaaS
- Feature Model extracted from documentation
- Simulate context changes
- Adaptation scenarios
  - Change in database size requires new database plan
  - Request for a new feature not available in current region
  - Change in programming framework and database
  - Scaling up application container

Evaluation

- Case study on Heroku PaaS
- Feature Model extracted from documentation
- Simulate context changes
- Adaptation scenarios
- Reconfiguration queries
  - No constraints
  - Constraints over price
  - Constraints over downtime/price
  - Optimize on price
  - Optimize on downtime/price

Evaluation

- Case study on Heroku PaaS
- Feature Model extracted from documentation
- Simulate context changes
- Adaptation scenarios
- Reconfiguration queries
- Application utilization profiles
  - Database size, application size, startup time, etc…

Evaluation

- Case study on Heroku PaaS
- Feature Model extracted from documentation
- Simulate context changes
- Adaptation scenarios
- Reconfiguration queries
- Application utilization profiles
  - DBSize: 10GB, AppSize: 100 MB, AppStartUp: 15
  - DBSize: 100GB, AppSize: 200 MB, AppStartUp: 30s
  - DBSize: 2TB, AppSize: 500 MB, AppStartUp: 60s

Results

Process step	Execution time (ms) Avg	StdDev	Min	Max	#Exec
Build Trans System	8777.31	303.71	8262	10308	720
- Process FM	244.75	28.57	191	552	
- Process LTL	8533.57	291.81	8025	10023	
All Queries	183.34	50.20	118	389	720
- Build	83.05	50.69	27	227	
- Solve	100.29	37.13	5	200	
Q wo/ Constraints	140.97	12.93	118	198	144
- Build	32.73	4.56	27	48	
- Solve	108.24	11.58	90	153	
Q w/ Constraints	224.23	55.55	128	389	288
- Build	140.41	27.65	80	227	
- Solve	83.82	53.13	5	200	
Q w/ Optimization	163.63	13.26	136	230	288
- Build	50.85	7.11	38	77	
- Solve	112.77	10.21	94	166	

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Results

- Temporal constraints enhance modeling of DSPLs
  - Compact notation for constraints over transitions
  - Support for reasoning over reconfiguration operations

- Performance is acceptable in the cloud context
  - Implementation can be improved

- Threats to validity
  - Case study is not exhaustive and considers only cloud computing

Conclusion & Perspectives

- Temporal constraints in DSPL
  - Better modeling of adaptive behavior
  - Reasoning over adaptation alternatives

Conclusion & Perspectives

- Temporal constraints in DSPL
  - Better modeling of adaptive behavior
  - Reasoning over adaptation alternatives
- Cardinality-based feature models
- Multi-cloud environment adaptation

Questions

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More information

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