High-Confidence Ubiquitous Computing Systems

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Some Facts

Google Android Market

- The average price of the top 50 *paid* applications is US$3.79 [modymi.com]
- 79.3% of paid applications have been downloaded *less than 100 times* [Distimo]
- Only 0.1% of paid applications have been downloaded 50,000 times or more [Distimo]

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There are many simplistic, low-quality apps!

CAAAs

Context-Aware Adaptive Applications

CAAAs

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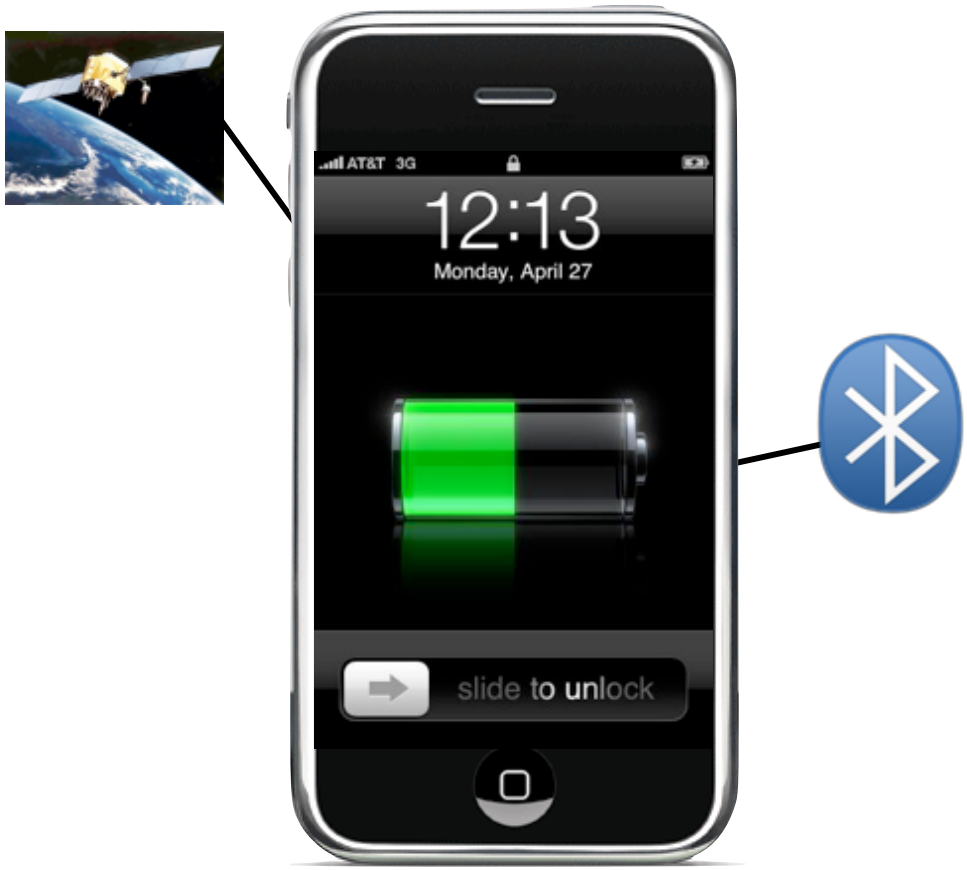
Context-Aware Adaptive Applications



CAAAs

Context-Aware **Adaptive** Applications

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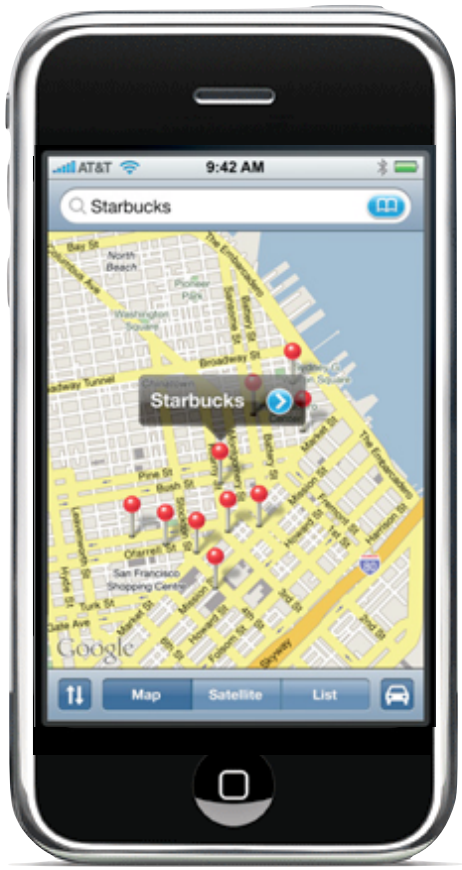
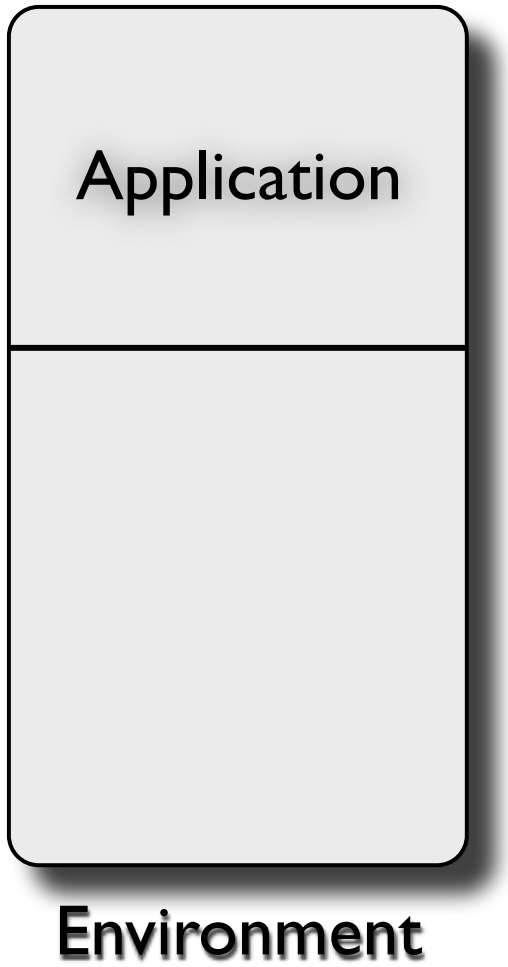


Adaptation in CAAAs



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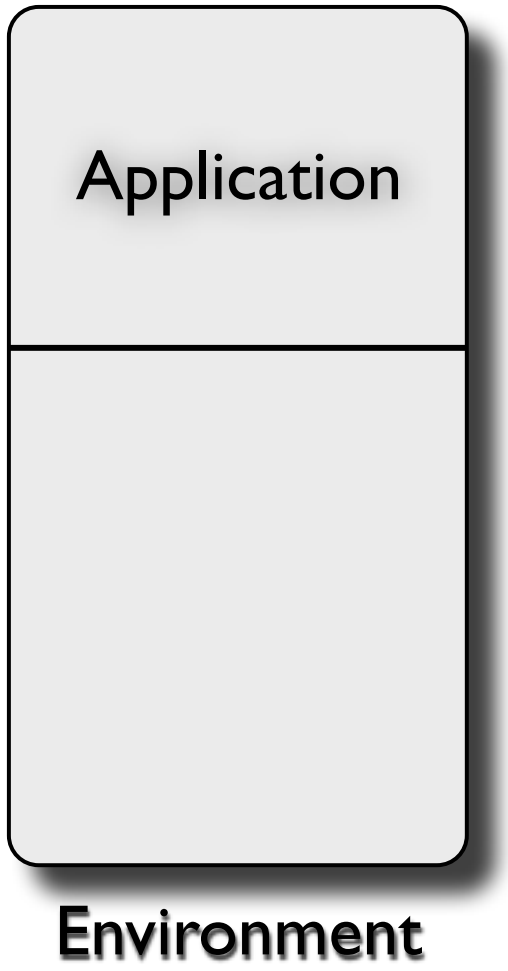

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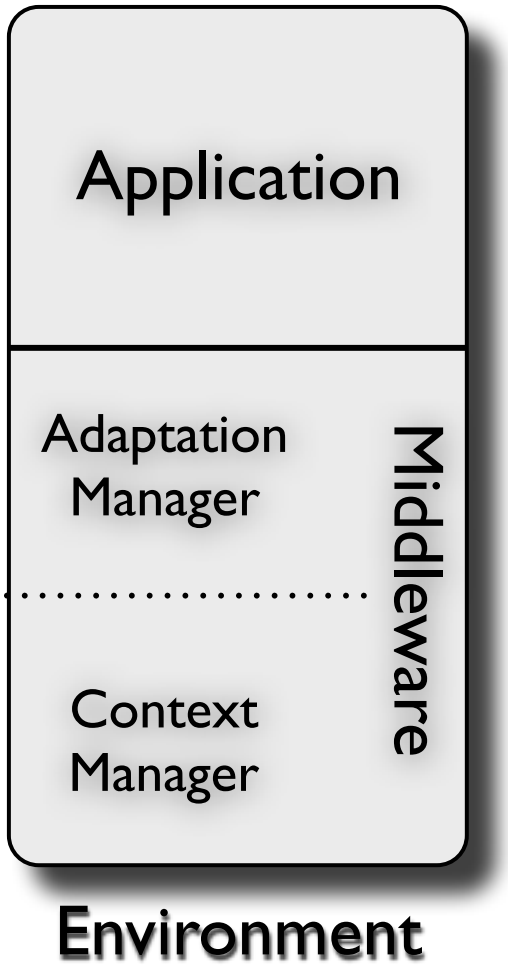

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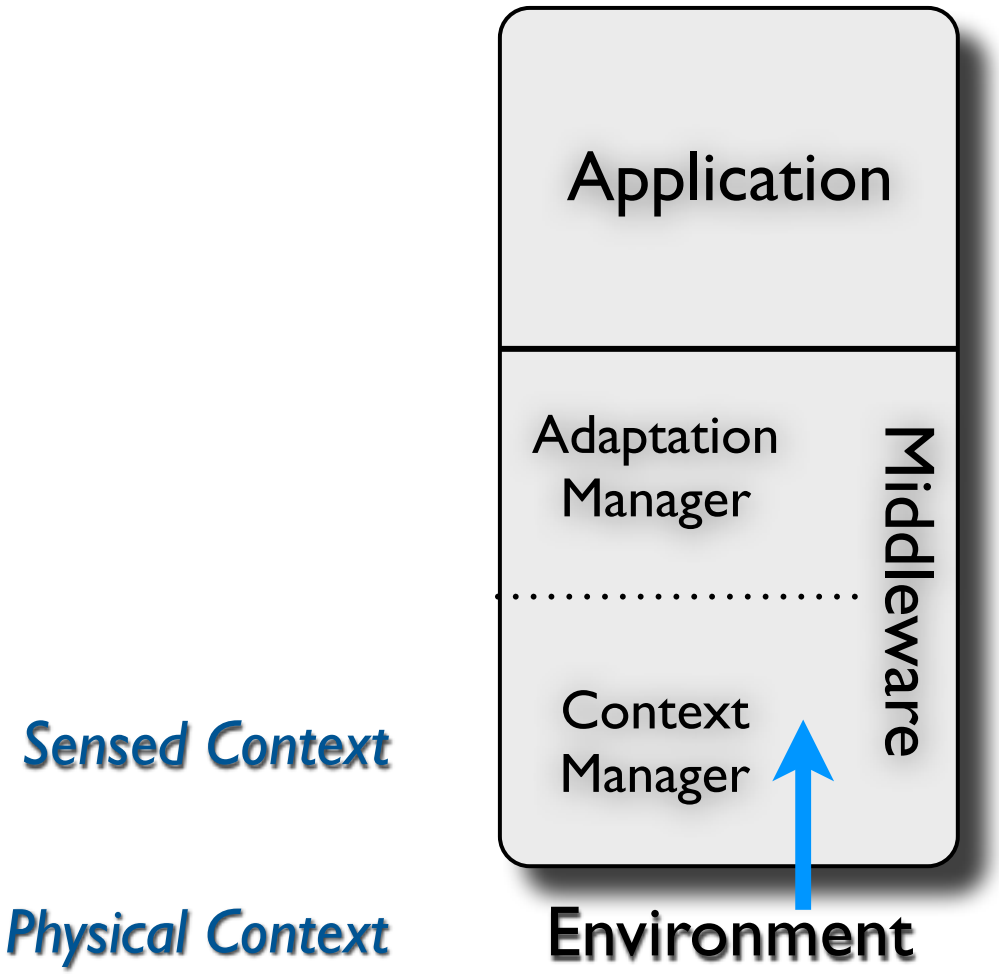

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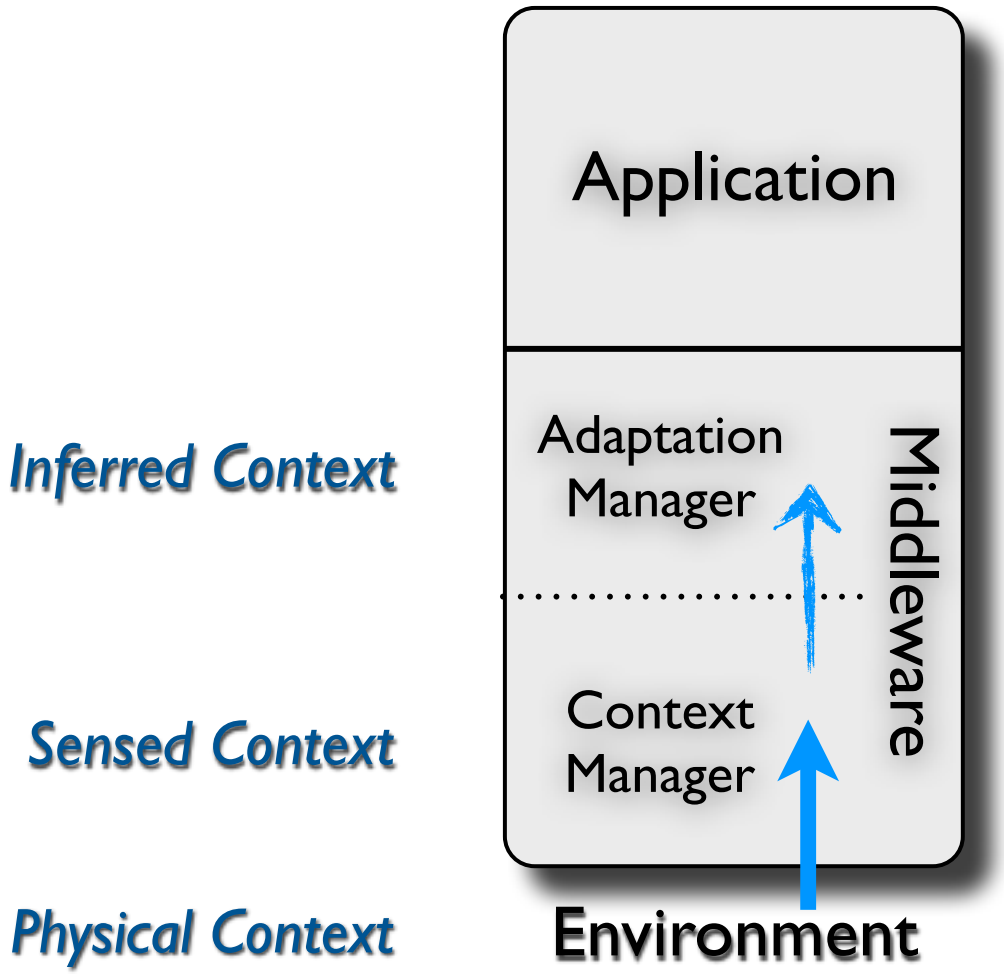

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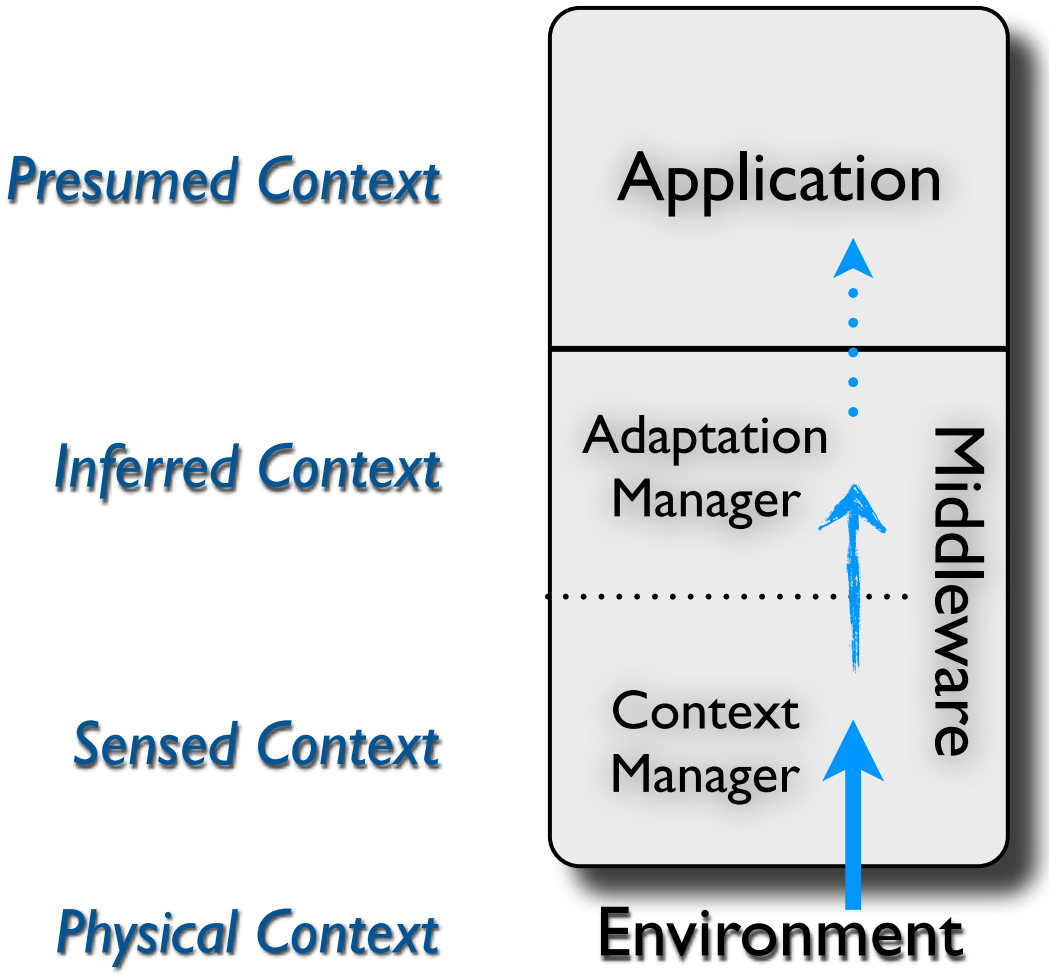

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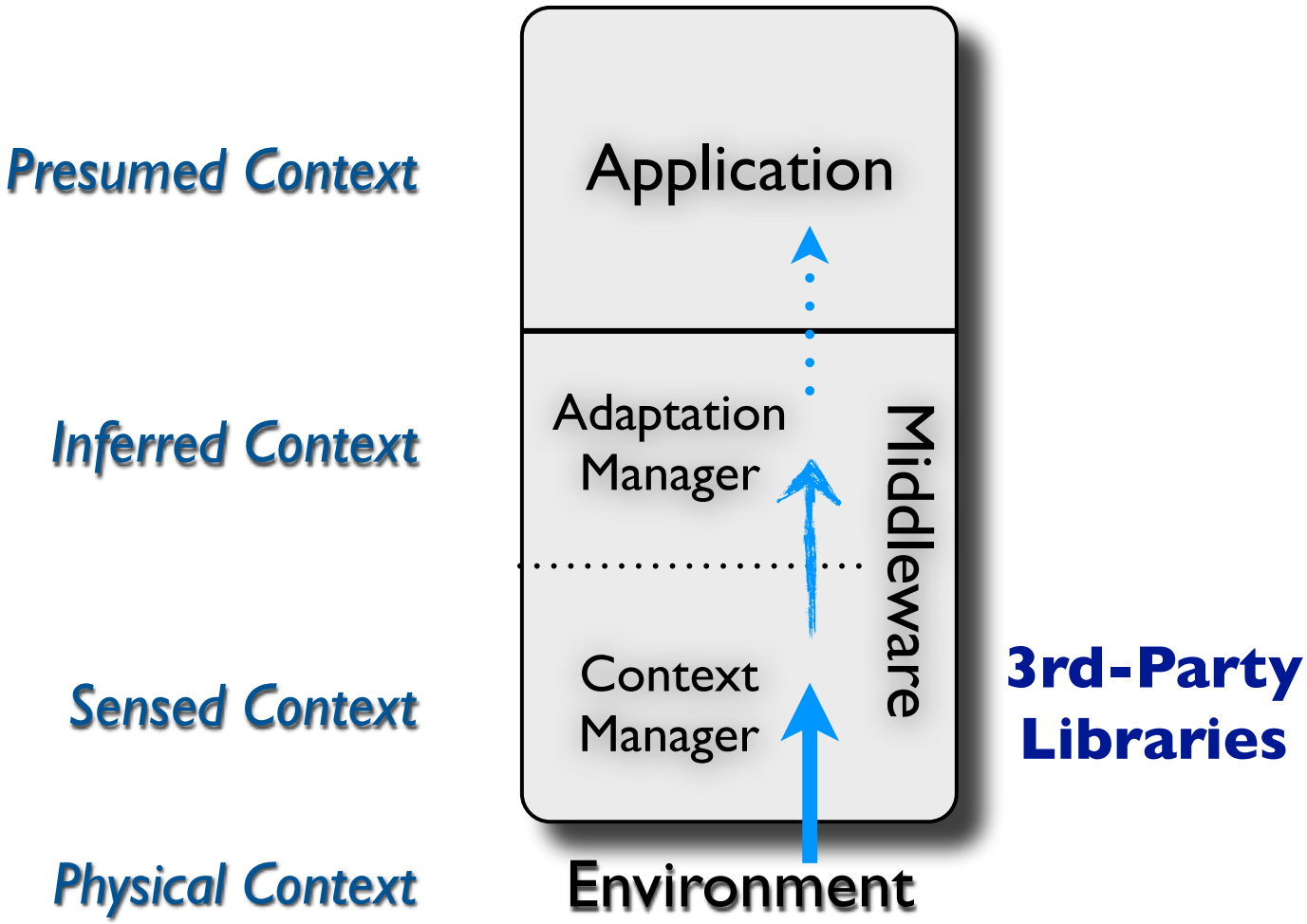

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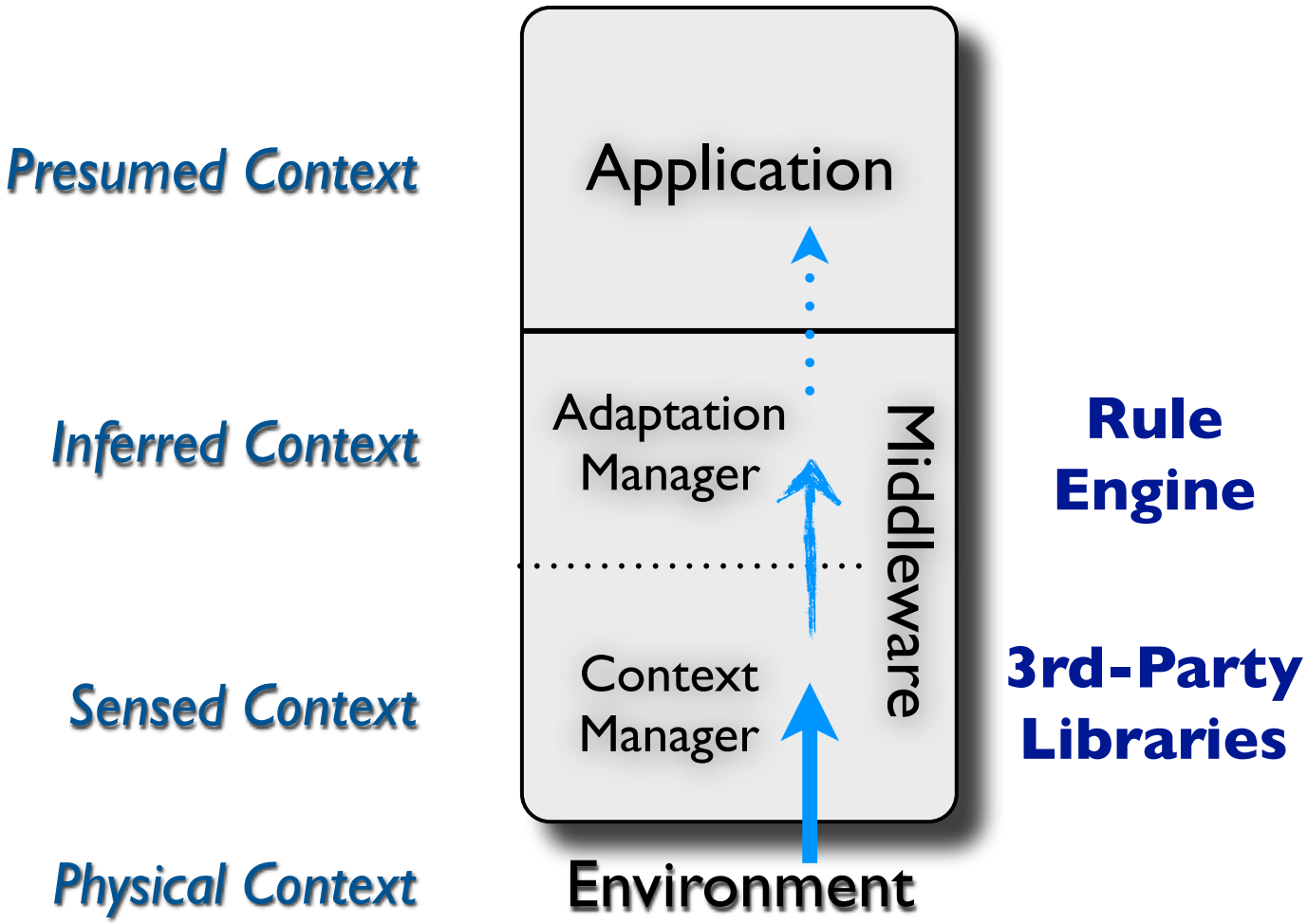
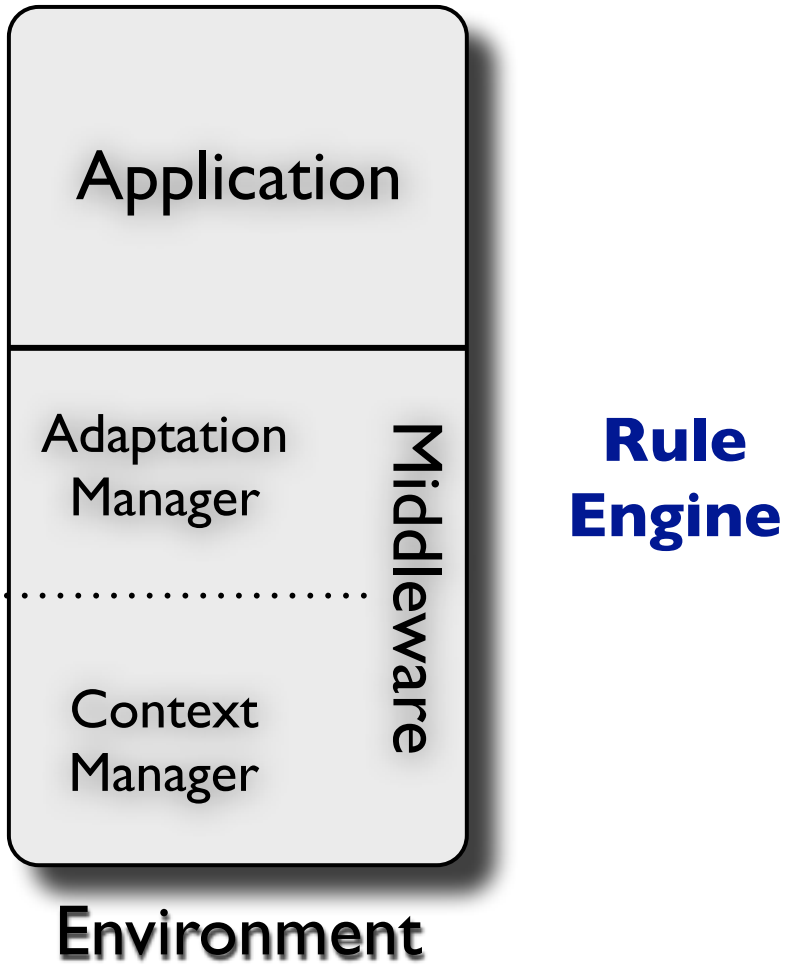


Validation of CAAAs

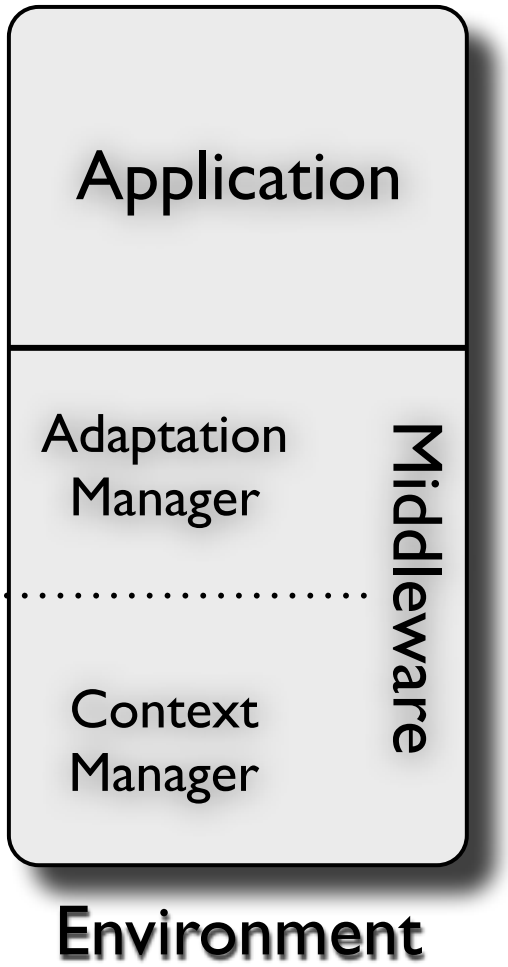


Validation of CAAAs

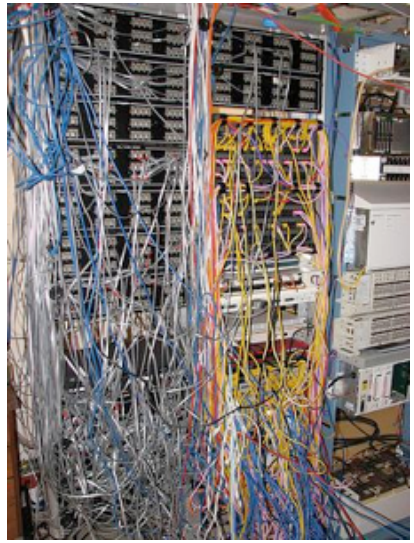
Rules are strongly interdependent

and have multiple priorities

making reasoning difficult even for a small number of rules



Rule Engine



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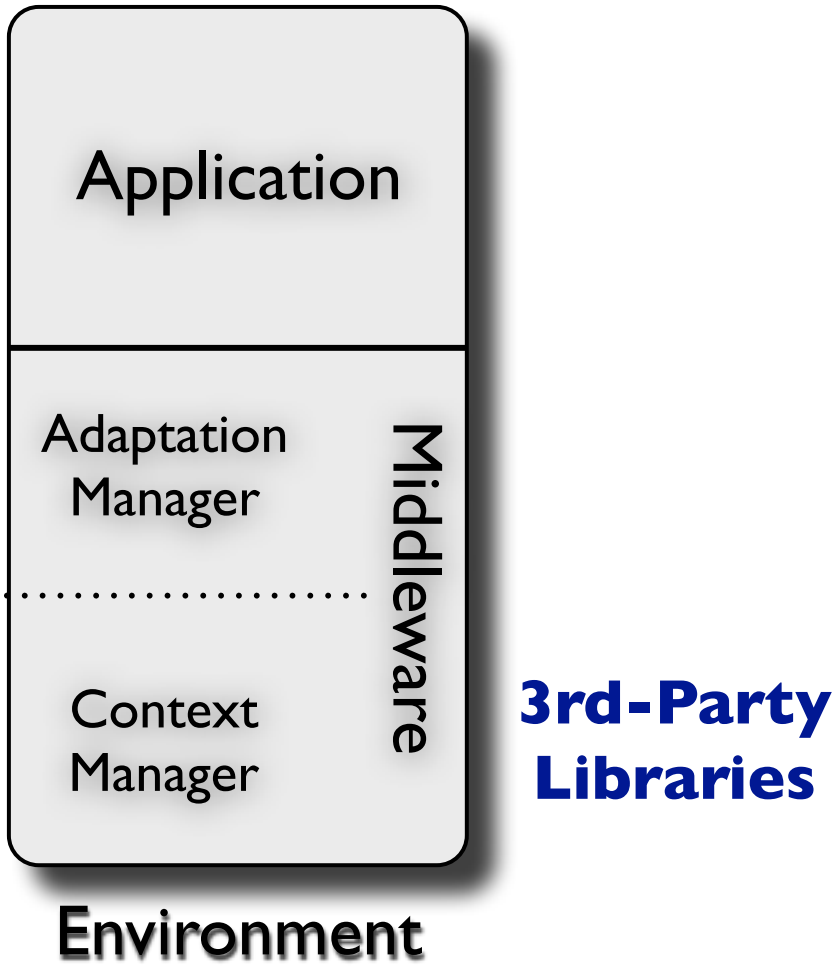
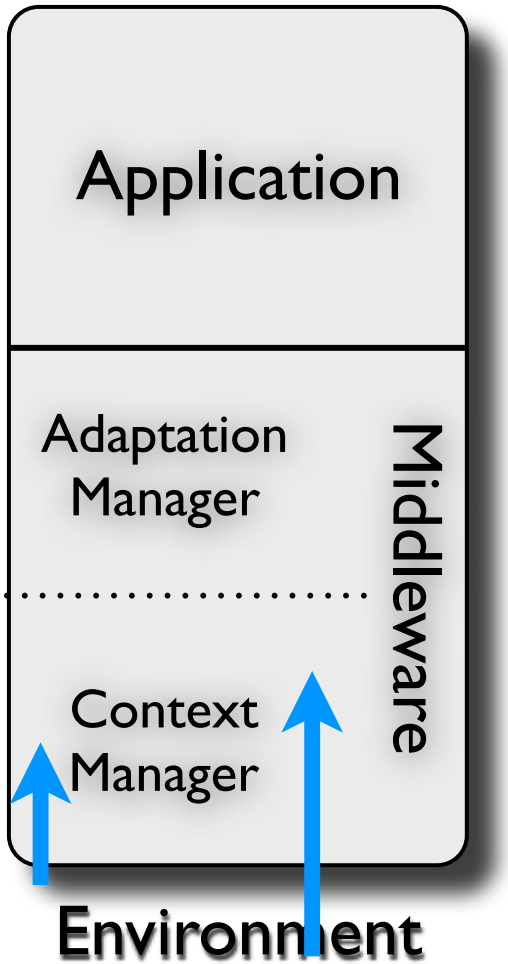


Validation of CAAAs

Context is sensed periodically

from multiple sources

at varying rates



3rd-Party Libraries

Approach

1. Derive *Adaptation Finite-State Machine* (A-FSM) from rule logic
2. Explore state space of A-FSM to discover potential faults
   - ✓ *Enumerative algorithms*
   - ✓ *Symbolic algorithms*
   - ✓ *Planner-based counterexample generation*
3. (Confirm existence of discovered faults)

PhoneAdapter

PhoneAdapter

silent, vibrate

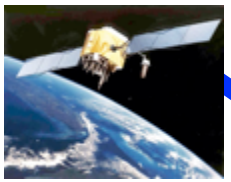
normal, vibrate

loud, divert to hands-free

silent, divert to voicemail

loud, vibrate

PhoneAdapter



silent, vibrate

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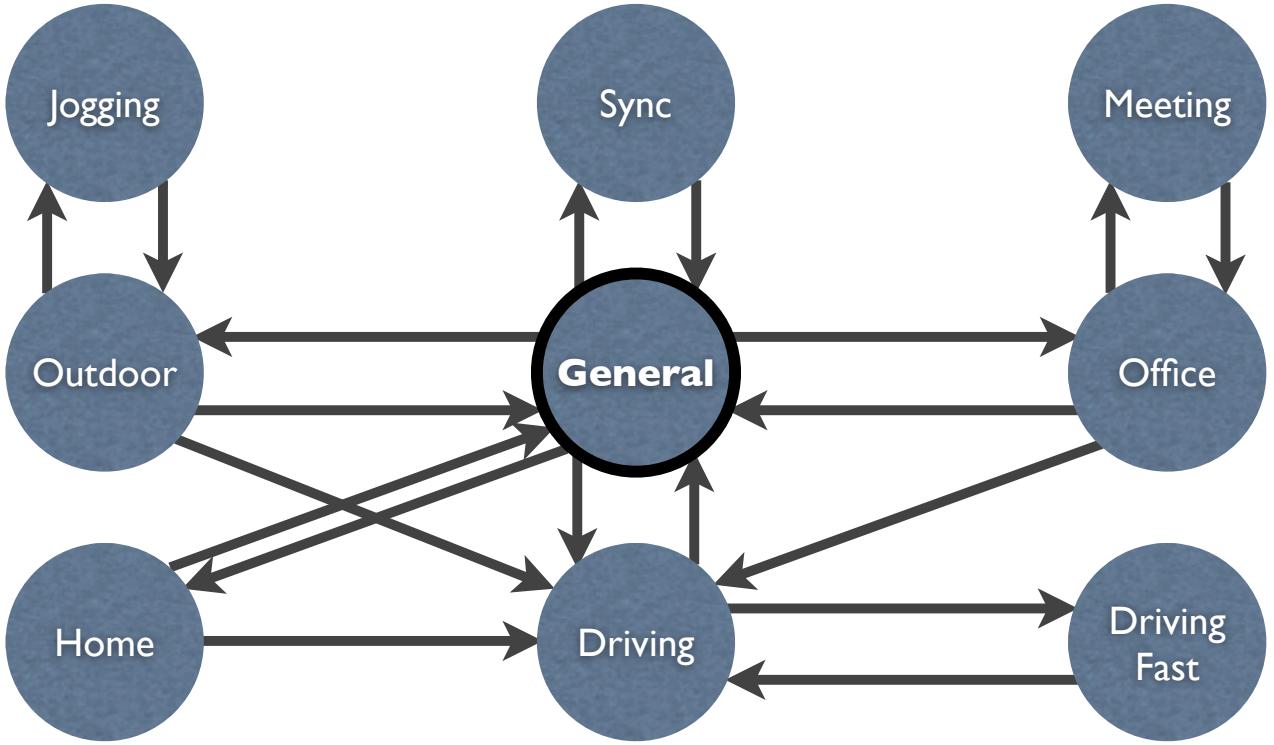
loud, vibrate

PhoneAdapter A-FSM



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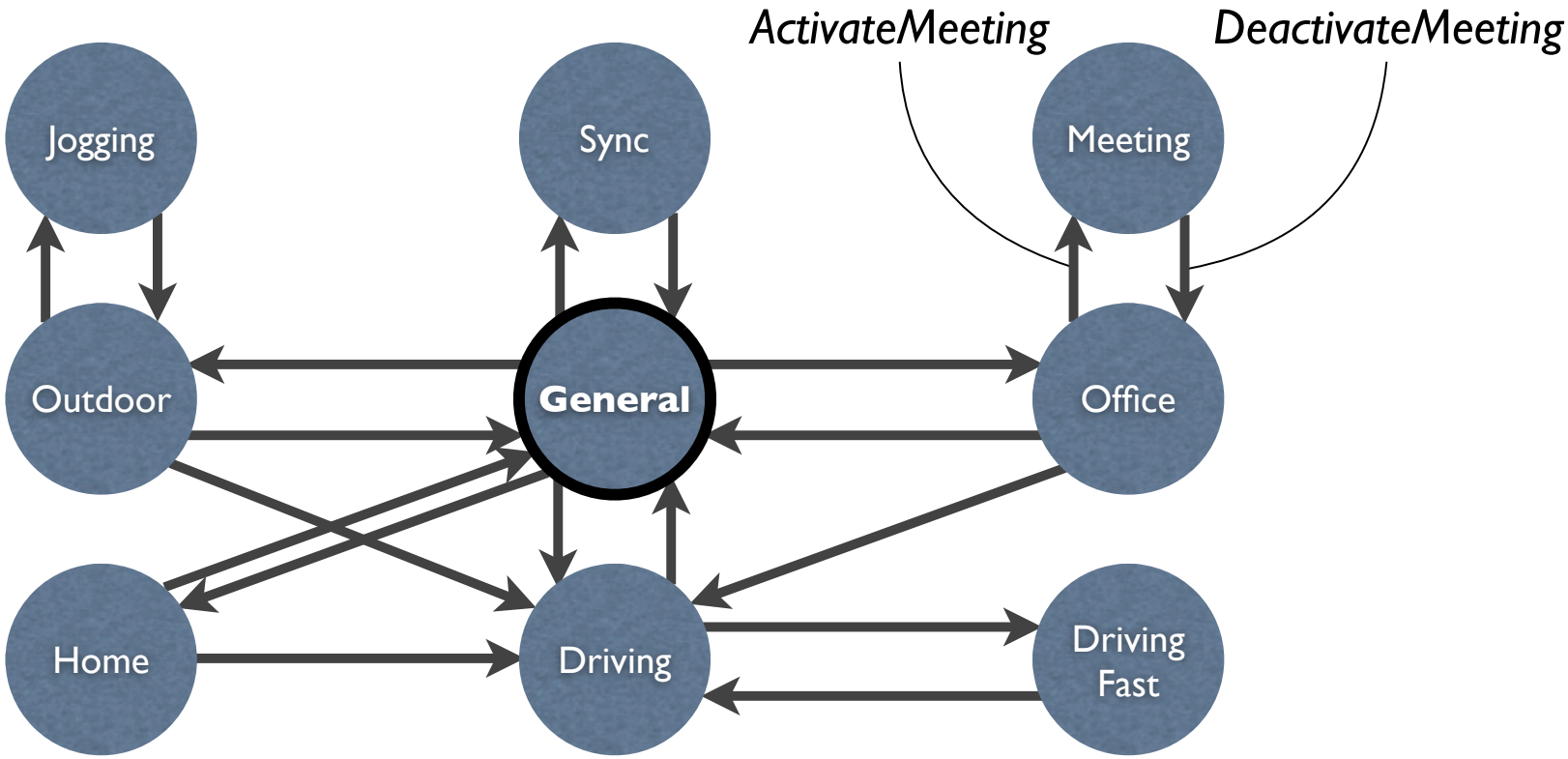
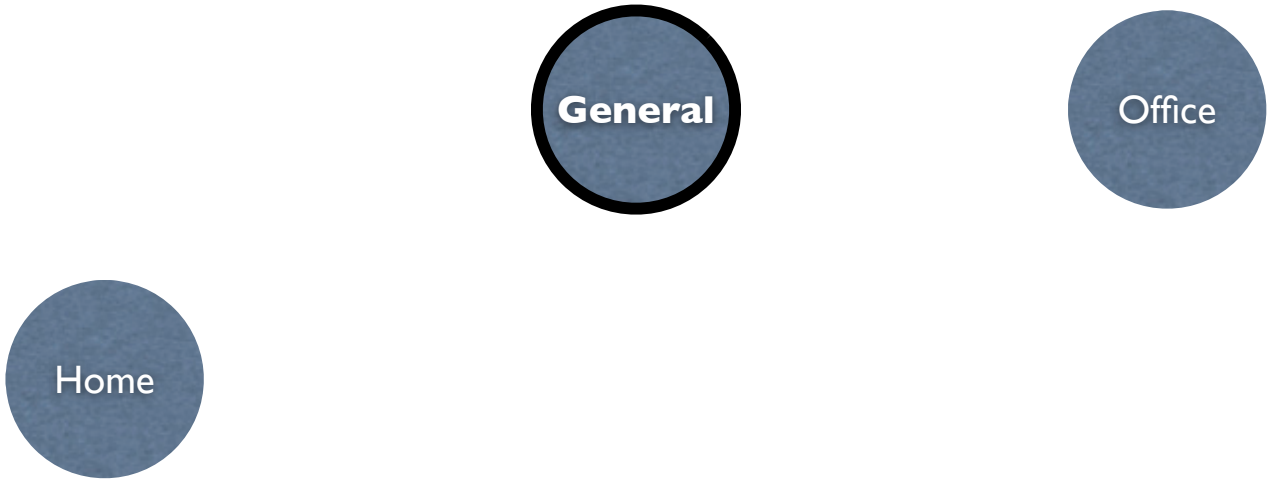


Example Faults in PhoneAdapter



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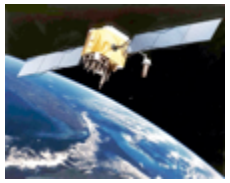


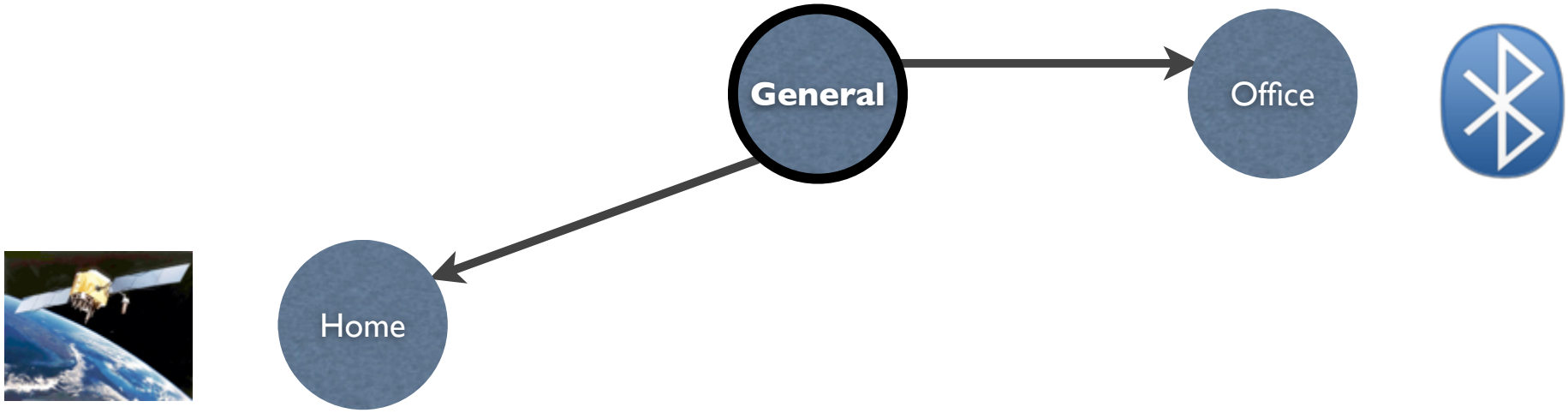
Home

General

Office

User's phone discovers office PC at home (or vice versa)

Example Faults in PhoneAdapter



Nondeterminism!

Example Faults in PhoneAdapter

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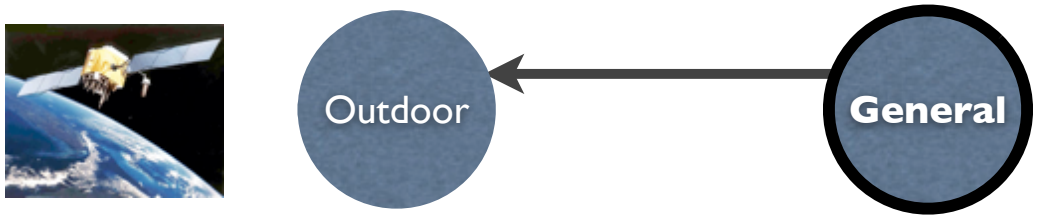
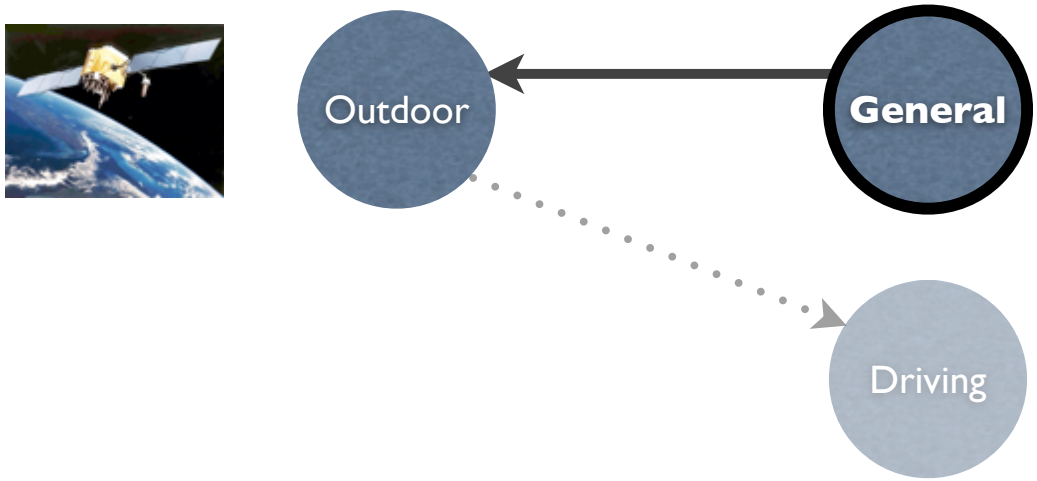


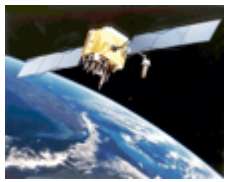
User leaves home

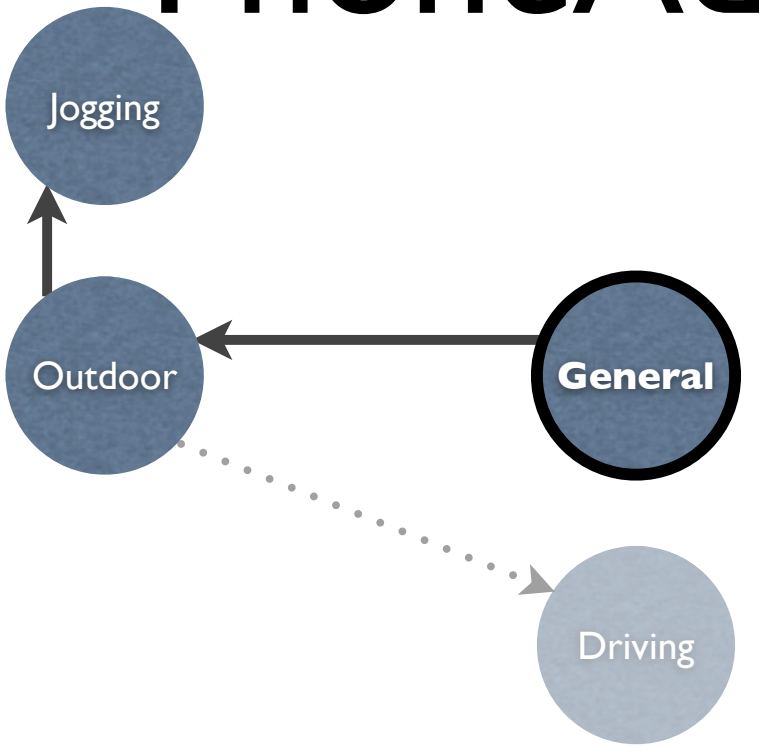
Example Faults in PhoneAdapter



User starts driving before Bluetooth detects hands-free system

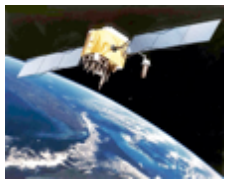
Example Faults in PhoneAdapter

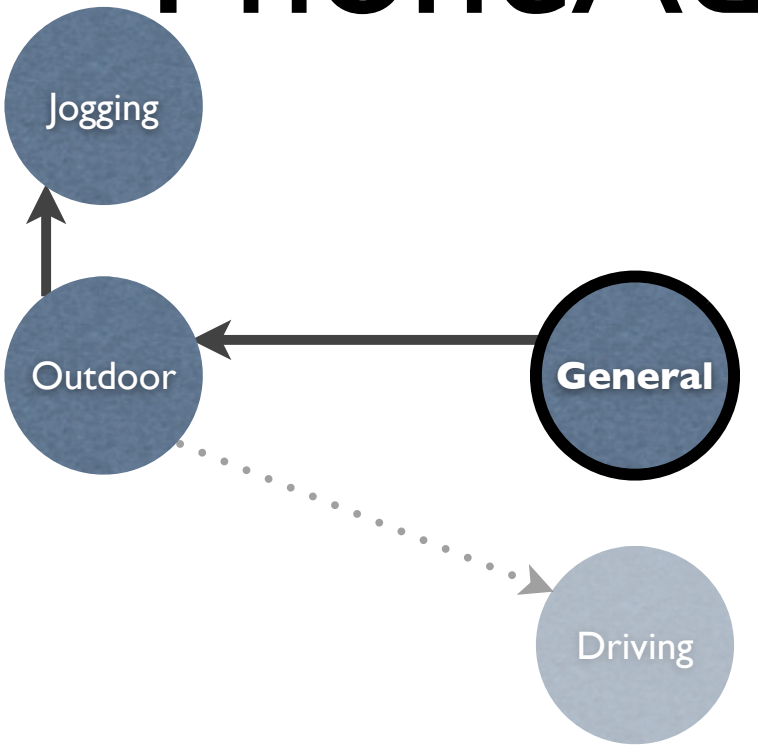




Activation hazard!

Example Faults in PhoneAdapter





Activation hazard!

Faults in CAAAs

- Behavioral Faults
  - *Nondeterminism*
  - *Dead rule*
  - *Dead state*
  - *Unreachable state*
  - *Activation race*
  - *Activation cycle*

Faults in CAAAs

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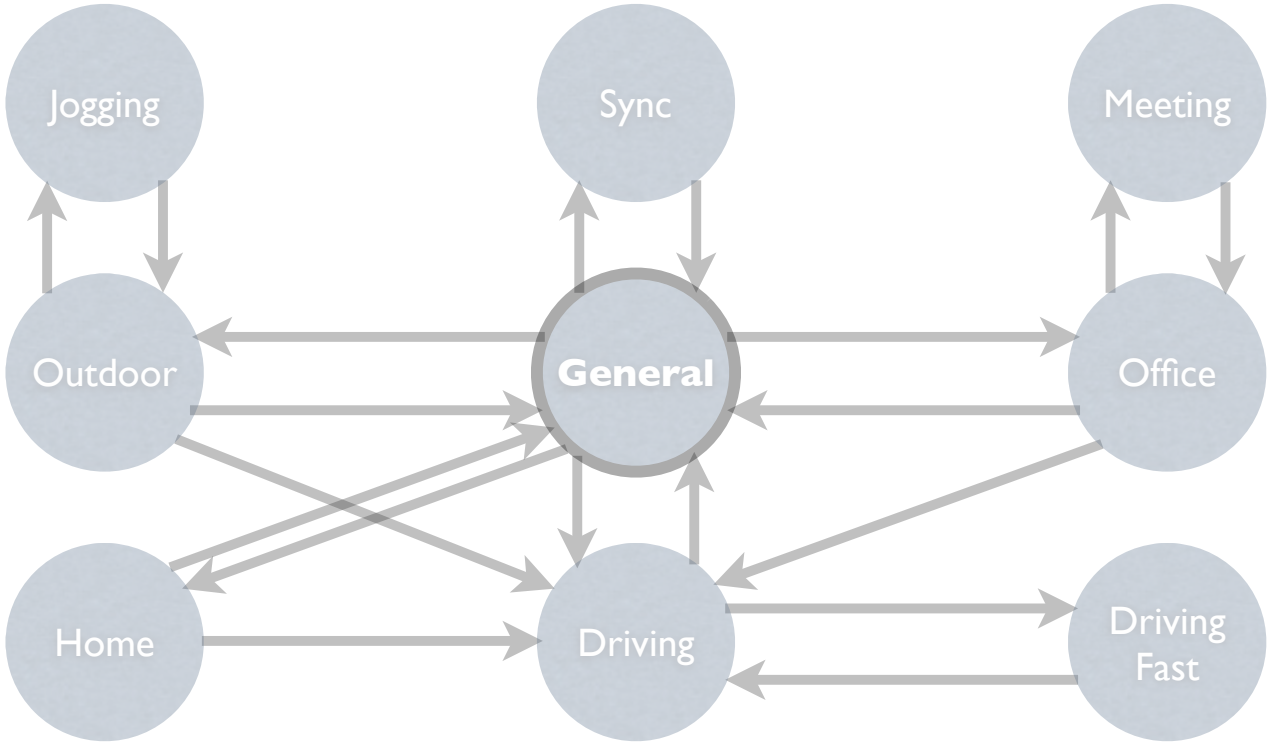
  - *Unreachable state*
  - *Activation race*
  - *Activation cycle*
- Hazards
  - *Hold hazard*
  - *Activation hazard*
  - *Priority inversion hazard*

Why Not Use Model Checkers?

- Difficult to encode fault patterns as temporal logic formulae
  - ✳ *Bisimilar models may fail differently*
- Difficult to encode rule logic as models in common model checkers
  - ✳ *Predicates and actions label the transitions*
- Difficult to interpret counterexamples as faults in adaptation behavior

Algorithms

Basic Operation

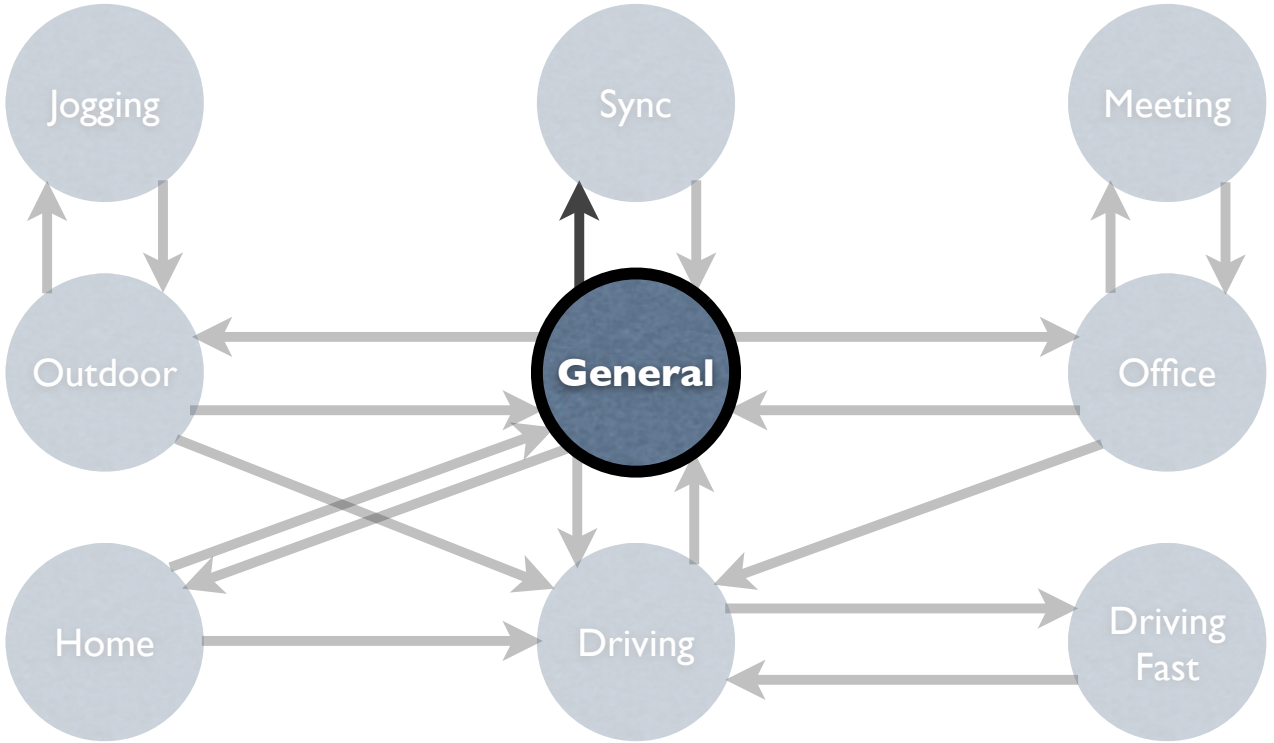


For each state

Analyze rules & inputs, and search along transitions for instances of fault patterns

Algorithms

Basic Operation



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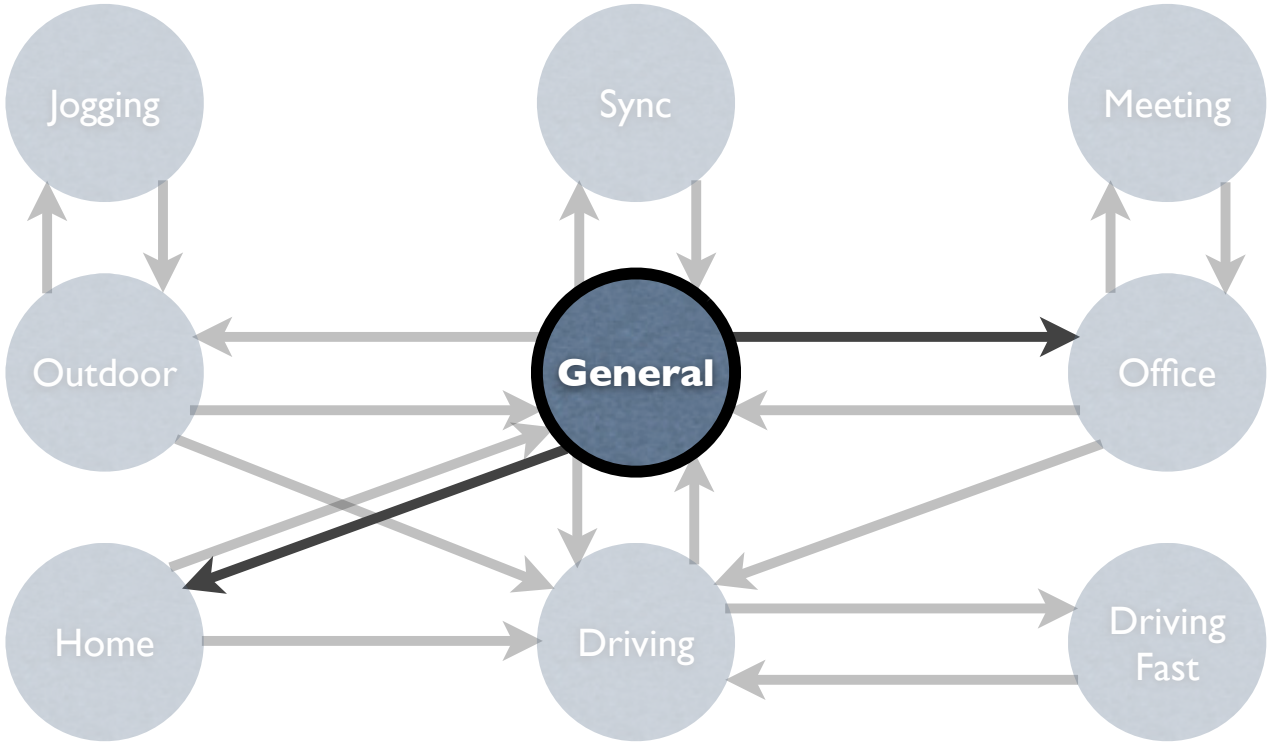

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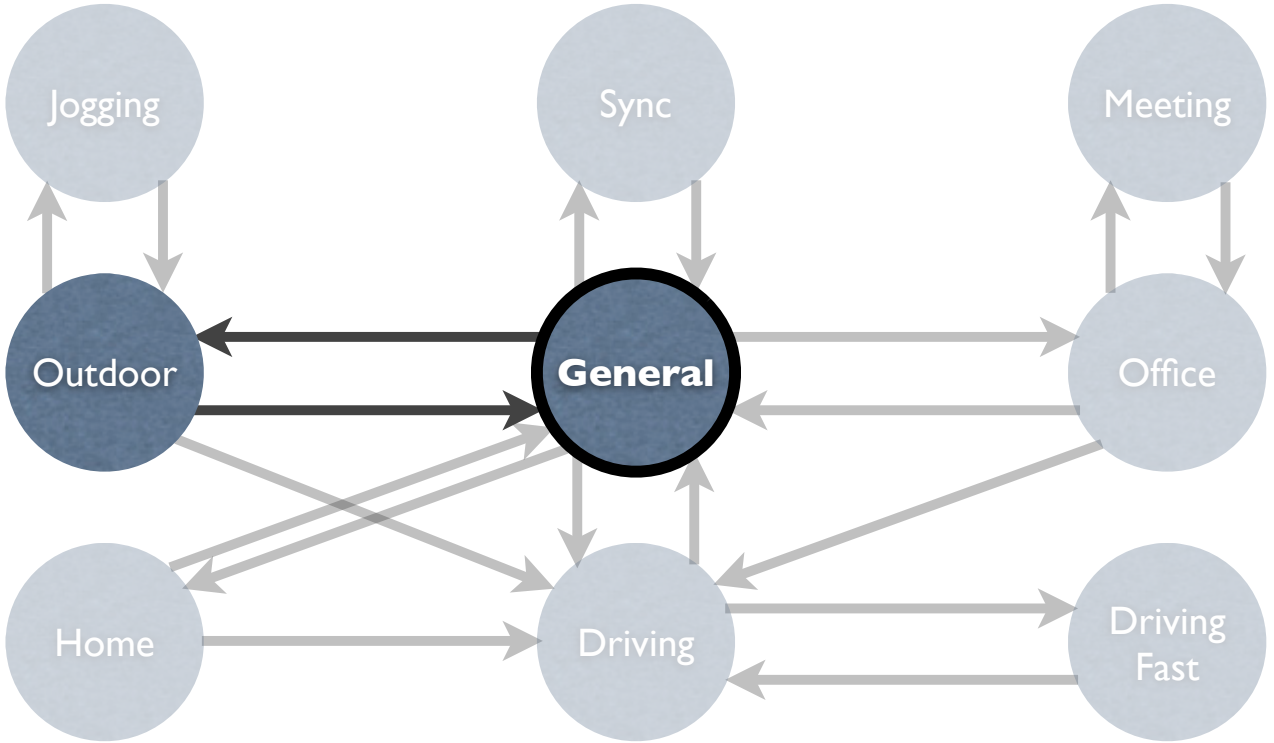

For each state

Analyze rules & inputs, and search along transitions for instances of fault patterns

PhoneAdapter Results

Behavioral Faults: Enumerative, Symbolic

State	Nondeterministic Adaptations	Dead Predicates	Adaptation		Unreachable States
			Races	Cycles	
General	37	1	45	13	0
Outdoor	3	0	135	23	0
Jogging	0	0	97	19	0
Driving	0	0	36	13	0
DrivingFast	0	0	58	19	0
Home	0	0	76	19	0
Office	0	0	29	1	0
Meeting	0	0	32	1	0
Sync	0	0	27	5	1

PhoneAdapter Results

Hazards: Enumerative

State	Context Hazards			
	Paths	Hold	Activ.	Prior.
General	14085	0	11	3182
Outdoor	161	0	0	52
Jogging	2	0	0	0
Driving	16	2	2	4
DrivingFast	2	0	0	0
Home	104	8	0	13
Office	82634	1828	368	2164
Meeting	0	0	0	0
Sync	2	2	0	0

Conclusion

Comparison of Approaches

Enumerative	Symbolic	Hybrid	Planner
Local Search	*Local Search*	*Local Search*	*Global Search*
Less Precise	*Less Precise*	*Less Precise*	*More Precise*
Concrete Counterexamples	*Symbolic Counterexamples*	*Symbolic Counterexamples*	*Concrete Counterexamples*
Handles Smaller State Spaces	*Handles Big State Spaces*	*Handles Bigger State Spaces*	*Sequential Search*
Fast	*Faster*	*Fastest*	*Slowest*

Future Work

Verification

- Continue the work on hazards and planners
- Quantitative reasoning about faults
  - Battery level, movement timings, etc.
- Online analysis of rules and faults

Future Work

Design

- *Alternatives to rule-based adaptation!*
  - Machine learning approaches to context classification and adaptation selection

Future Work

Design

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- **Felicitous Computing Institute**

Thank You!

REFERENCES

Z. Wang, S. Elbaum and D.S. Rosenblum, *Automated Generation of Context-Aware Tests*, **Proc. 2007 Int'l Conf. on Software Engineering** (ICSE 2007), Minneapolis, MN, USA, May 2007, pp. 406–415.

M. Sama, D.S. Rosenblum, Z. Wang and S. Elbaum, *Multi-Layer Faults in the Architectures of Mobile, Context-Aware Adaptive Applications: A Position Paper*, Short Paper, **Proc. ICSE 2008 Workshop on Software Architectures and Mobility** (SAM 2008), Leipzig, Germany, May 2008, pp. 47–49.

M. Sama, F. Raimondi, D. Rosenblum and W. Emmerich, *Algorithms for Efficient Symbolic Detection of Faults in Context-Aware Applications*, **Proc. 1st Int'l Workshop on Automated Engineering of Autonomous and Run-Time Evolving Systems** (ARAMIS 2008), L'Aquila, Italy, Sep. 2008, pp. 1–8.

M. Sama, D.S. Rosenblum, Z. Wang and S. Elbaum, *Model-Based Fault Detection in Context-Aware Adaptive Applications*, **Proc. 16th ACM SIGSOFT Int'l Symposium on the Foundations of Software Engineering** (FSE 2008), Atlanta, GA, USA, Nov. 2008, pp. 261–271.

J. Cubo, F. Raimondi, M. Sama and D. Rosenblum, *A Model to Design and Verify Context-Aware Adaptive Service Composition*, **Proc. IEEE Int'l Conf. on Services Computing** (SCC 2009), Bangalore, India, Sep. 2009, pp. 184–191.

M. Sama, D.S. Rosenblum, Z. Wang and S. Elbaum, *Multi-Layer Faults in the Architectures of Mobile, Context-Aware Adaptive Applications*, **Journal of Systems and Software**, invited paper for Special Issue on Software Architecture and Mobility, Vol. 83, Issue 6, Jun. 2010, pp. 906–914.

M. Sama, S. Elbaum, F. Raimondi and D.S. Rosenblum, *Context-Aware Adaptive Applications: Fault Patterns and Their Automated Identification*, **IEEE Transactions on Software Engineering**, invited paper for Special Issue on the Best Papers of FSE 2008, Vol. 36, No. 5, Sep./Oct. 2010, pp. 644–661.