Building Dependable Concurrent Systems through Probabilistic Inference, Predictive Monitoring and Self-Adaptation

Gul Agha

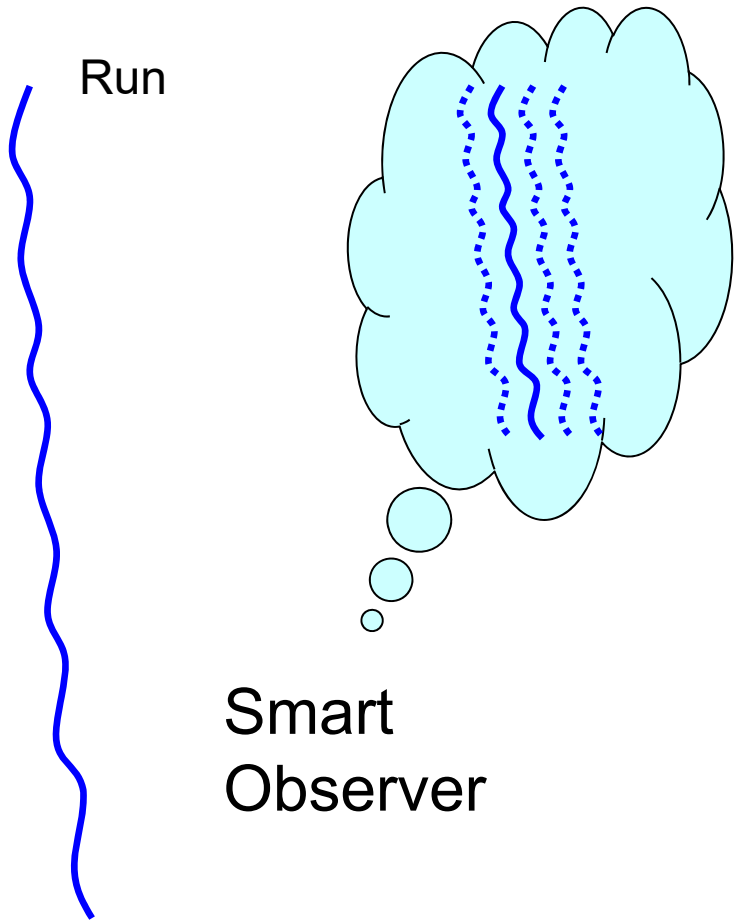
University of Illinois at Urbana-Champaign

Predictive Monitoring

Joint work with Koushik Sen and Grigore Rosu

Smart Observer

- Monitoring is limited to what is observed.
- In real world, we learn from near misses
- A single execution trace contains more information than appears at first sight
- Extract other possible runs from a single execution
- Analyze *all* these runs



Smart Observers

- *"Smartness"* obtained by capturing causality
- Possible global states generated dynamically $\rightarrow$ form a *lattice*
- Analysis is performed on a level-by-level basis in the lattice of global states

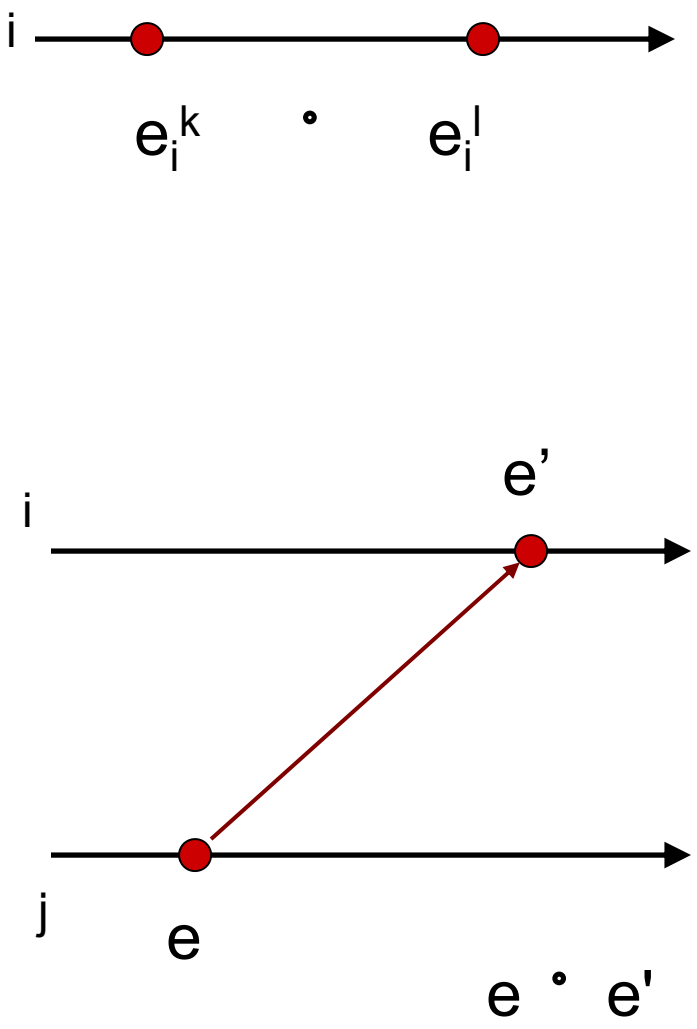
Causality

Define the partial order $\prec$ on the set of events:

1. $e_i^k \prec e_i^l$ if $k < l$;
2. $e \prec e'$ if
   $\exists x \in S \; e <_x e'$

and at least one of e, e' changes state.

- e $\prec$ e'' if
  e $\prec$ e' and e' $\prec$ e''.



Vector Clocks and Relevant Events

- Consider a subset R of relevant events.
- R-relevant causality is a relation $\lhd \subseteq \prec$
  - $\lhd$ is a projection of $\prec$ on $R \times R$.
- We used a technique based on vector clocks to implements the relevant causality relation.

Causality and Vector Clocks

Theorem: If $< e, i, V >$ and $< e', j, V' >$ are messages sent then $e \lhd e'$ iff $V[i] \leq V'[j]$

If *i* and *j* are not given, then

$e \lhd e'$ iff $V < V'$

Actor Creation

- A newly created actor inherits the "vector clock" from its parent at creation time.
- Vector Clock is not really a vector but an *association list* of actor names and its current estimated local time.

An Example

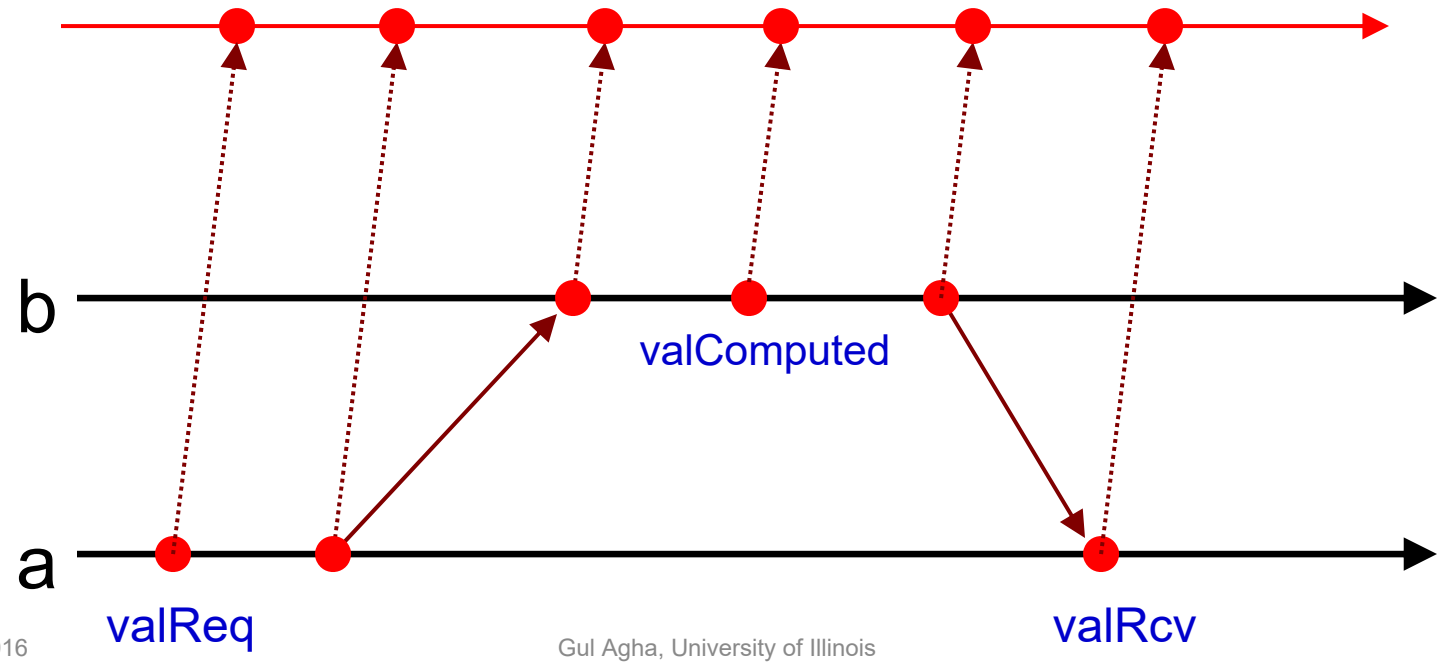
- Actor a requests certain value from node b
- b computes the value and sends it to a
- Property: no node receives a value from another node to which it had not sent a request

Centralized Monitoring Example

"If a receives a value from b then b calculated the value after receiving request from a"

valRcv → ⟐(valComputed ∧ ⟐valReq)

valRe ⟐valRe valCc ⟐(valComputed ∧ ⟐valReq) lReq)



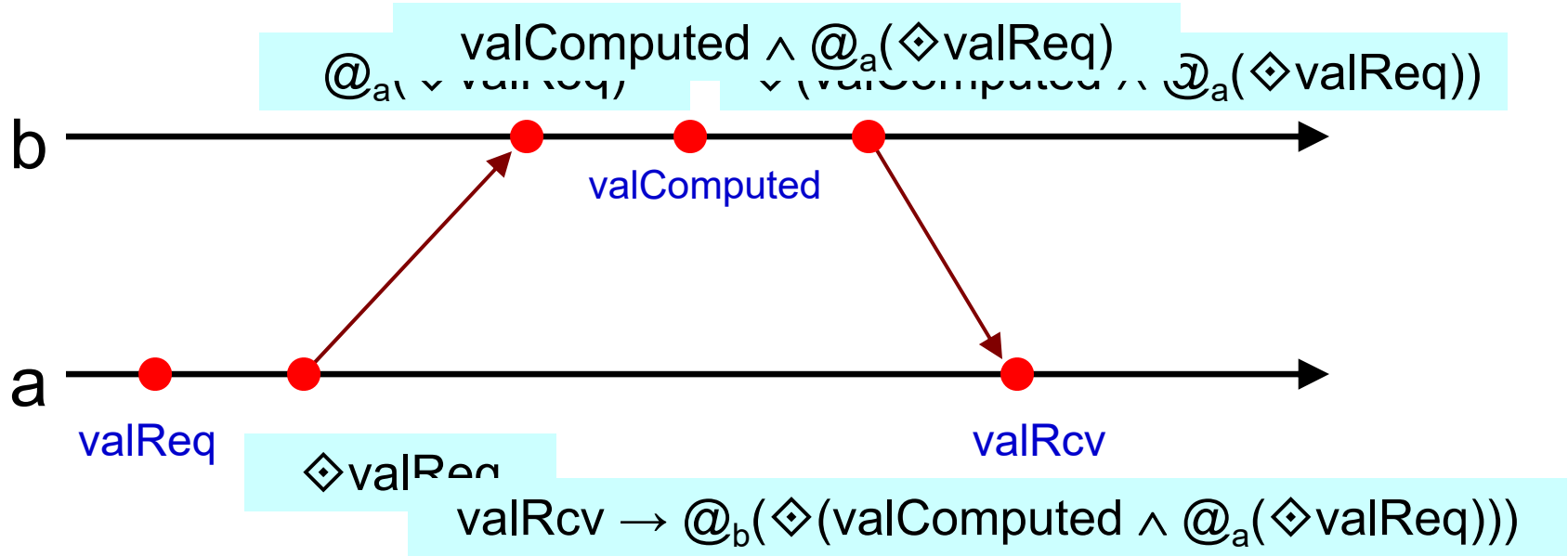
Decentralized Approach

- Distribute property
  - Properties expressed with respect to a process
  - Local properties at every process
- Decentralize Monitoring
  - Maintain knowledge of global state at each process
  - Update knowledge with incoming messages
  - Attach knowledge with outgoing messages
  - At each process check safety property against local knowledge

Decentralized Monitoring Example

"If a receives a value from b then b calculated the value after receiving request from a"

$valRcv \rightarrow @_b(\diamond(valComputed \wedge @_a(\diamond valReq)))$



Past time Distributed Temporal Logic

- Based on epistemic logic
- Properties with respect to a process, say p
- Interpreted over a sequence of global states that the actor p is aware of
  - Each actor monitors the properties local to it
  - No need for extra messages to create a *relevant* portion of global state
  - KnowledgeVector keeps track of relevant global state that can effect a property.

Remote Expressions in pt-DTL

- Remote expressions – arbitrary expressions related to the state of another actor
- Propositions constructed from remote and local expressions

"If my alarm is set then eventually in past difference between my temperature and temperature at process b exceeded the allowed value"

$$alarm \rightarrow \diamondsuit((myTemp - @_b temp) > allowed)$$

Safety in Airplane Landing

" If my airplane is landing then the runway that the airport has allocated matches the one that I am planning to use"

landing $\longrightarrow$ (runway = $@_{airport}$allocRunway)

Leader Election Example

"If a leader is elected then if the current process is a leader then, at its knowledge, none of the other processes is a leader"

$$elected \rightarrow (state=leader \rightarrow \bigwedge_{i \neq j}(@_j(state \neq leader)))$$

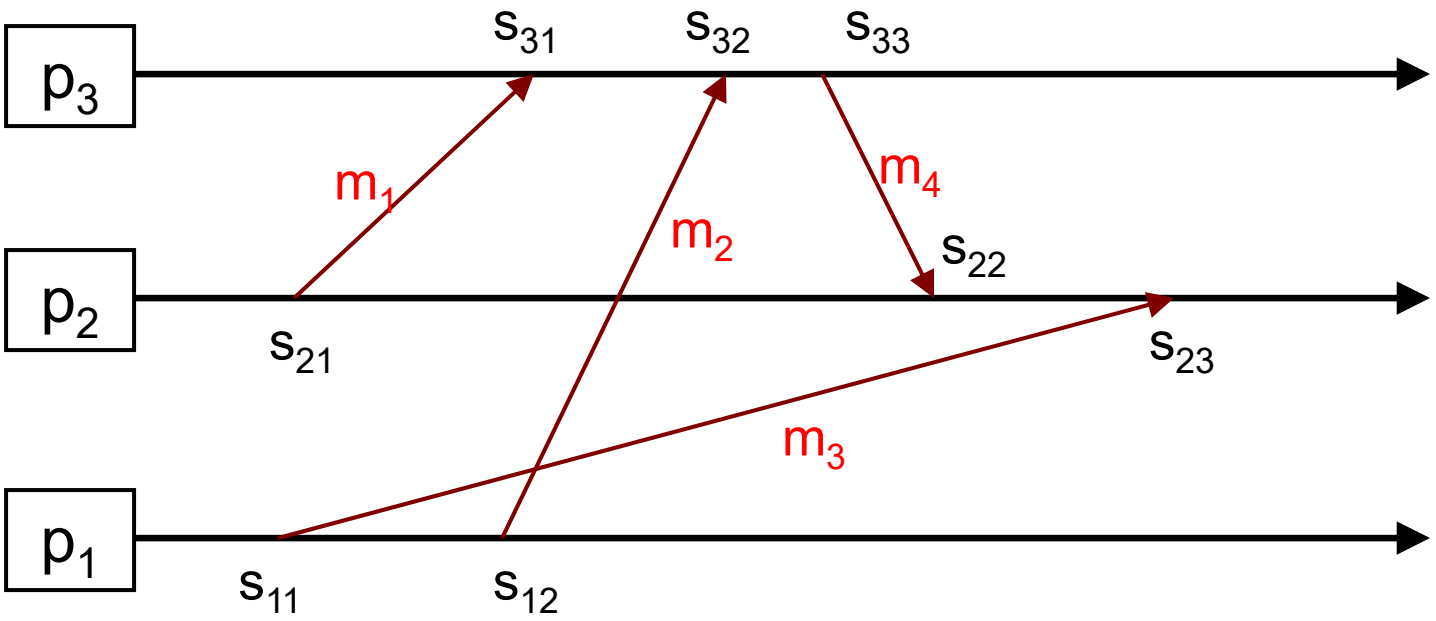
pt-DTL syntax and semantics

- F_i ::= true | false | $P(E_i)$ | = F_i | F_i a F_i — propositional
  - | · F_i | ¥ F_i | ◈F_i | F_i S F_i — temporal
  - | $@_jF_j$ — epistemic
- E_i ::= c | v_i 5 V_i | $f(E_i)$ — functional
  - | $@_jE_j$ — epistemic

- · F_i : previously F_i
- ¥ F_i : always in past F_i
- ◈Fi : eventually in past F_i
- F_i S F'_i : F_i since F'_i
- $@_jF_j$: F_j at process j

- c : constant
- v_i : variable at process I
- $P(E_i)$: predicate on E_i
- $f(E_i)$: function f applied to E_i
- $@_jE_j$: expression E_j at process j

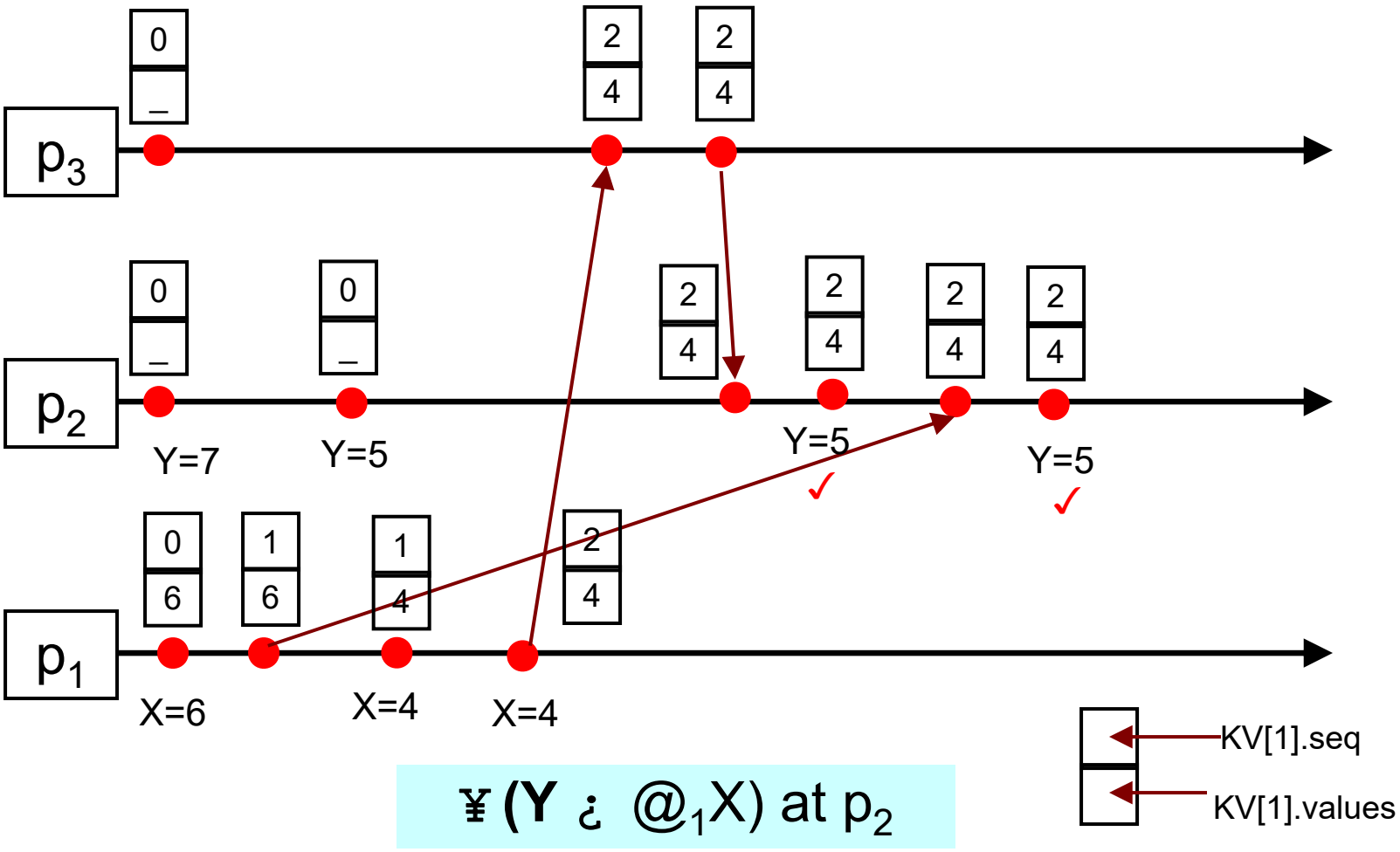
Interpretation of $@_jE_j$ at process i



Since, at s_{23} p_2 is aware of s_{12} of p_1

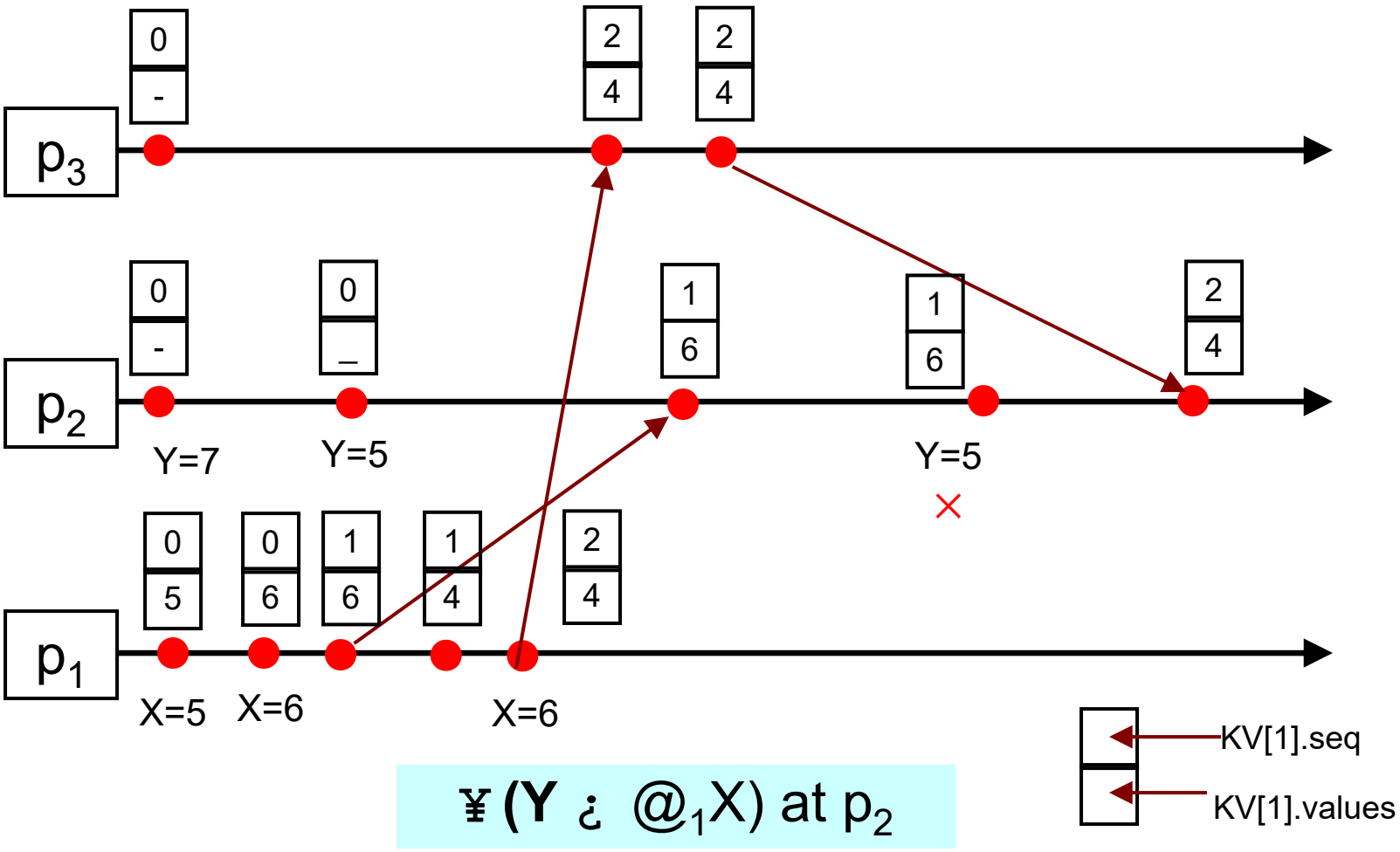
value of $@_1E$ in s_{23} at p_2 = value of E in s_{12} at p_1

Example



¥(Y ¿ @$_1$X) at p_2

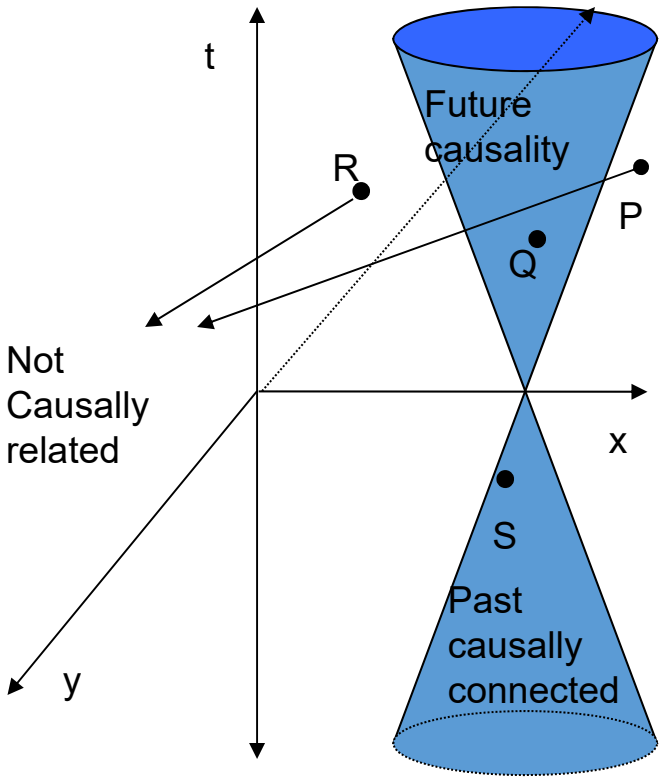
Example

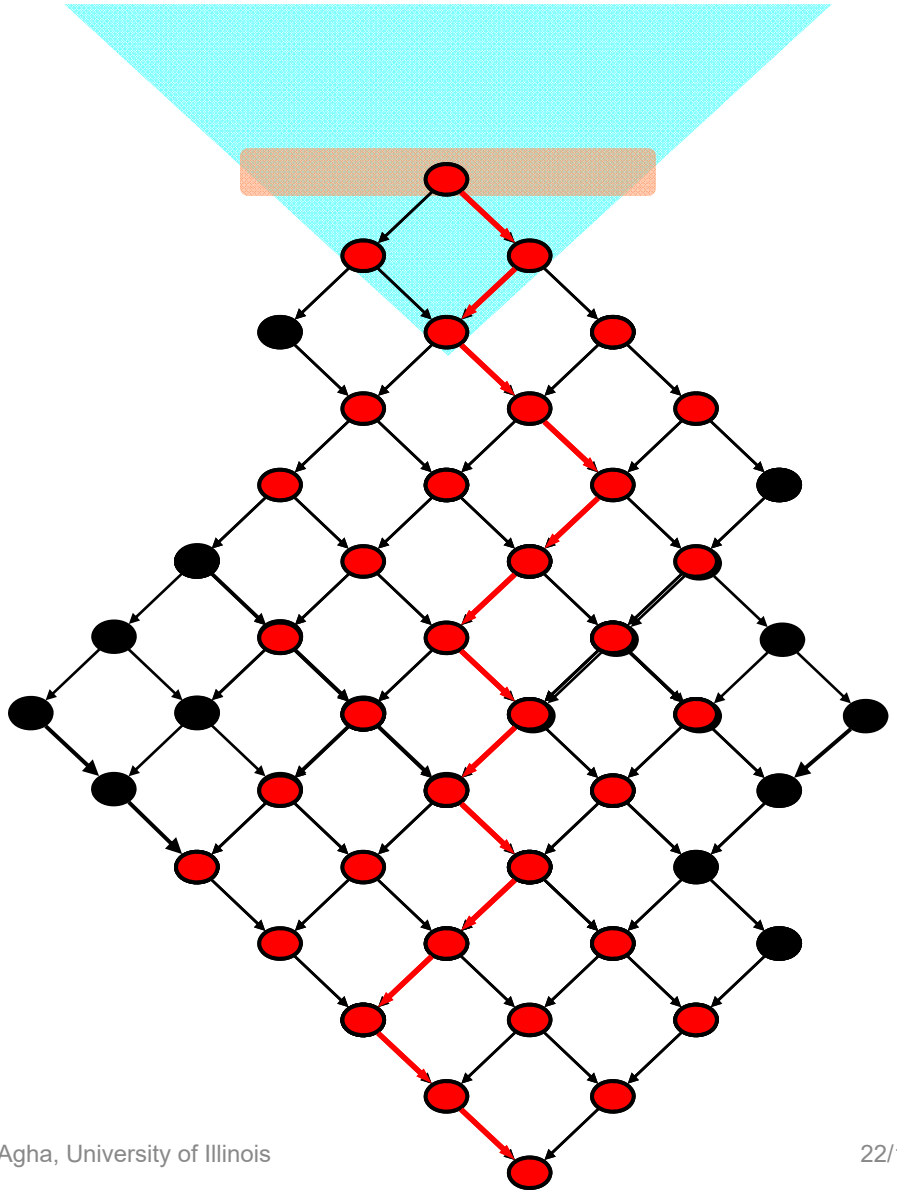

0
-
2
4
2
4
p_3
0
-
0
_
1
6
1
6
2
4
p_2
Y=7
Y=5
Y=5
0
5
0
6
1
6
1
4
2
4
p_1
X=5
X=6
X=6
KV[1].seq
KV[1].values
¥(Y ¿ @1X) at p2

Predictive Monitoring

- Can predict the violation from the run that did not have the violation.
- Cannot detect a violation if there is no direct communication of intermediate value from p1 to p2
  - *Need time-outs or alarms*
  - *Have to be designed into the system*

Causality Cone Heuristics



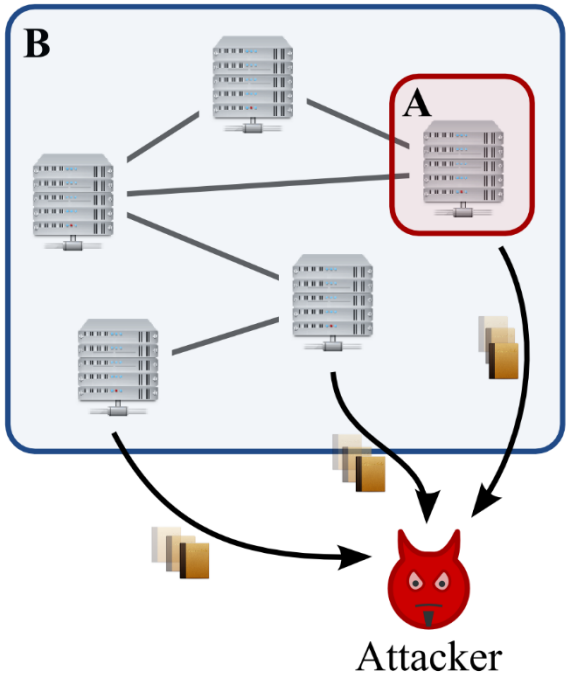


- Theory of relativity
  - Speed of light
- Space-time: causality cone

Aggregate Properties

Example:

- A cluster has information distributed across thousands of nodes
- An attacker wants to steal confidential information from the cluster
- Each node sees only a few file transfers per hour, a common usage pattern



Scalable Monitoring

- Local monitoring doesn't help:

$$\text{downloads}(f, C) < \text{limit}$$

Is not violated at any node.

- Want to monitor for:

$$\sum_{n \in \text{Nodes}} @_n \, \text{downloads}(f, C) < \text{limit}$$

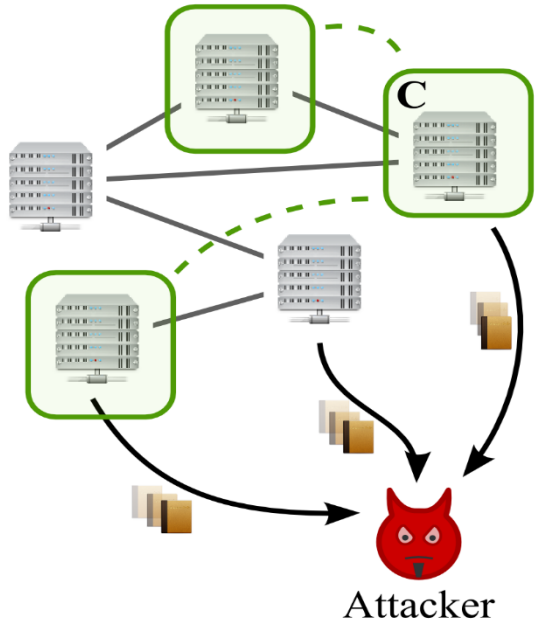
But monitoring thousands of nodes for millions of events is too expensive!

Statistical Runtime Monitoring

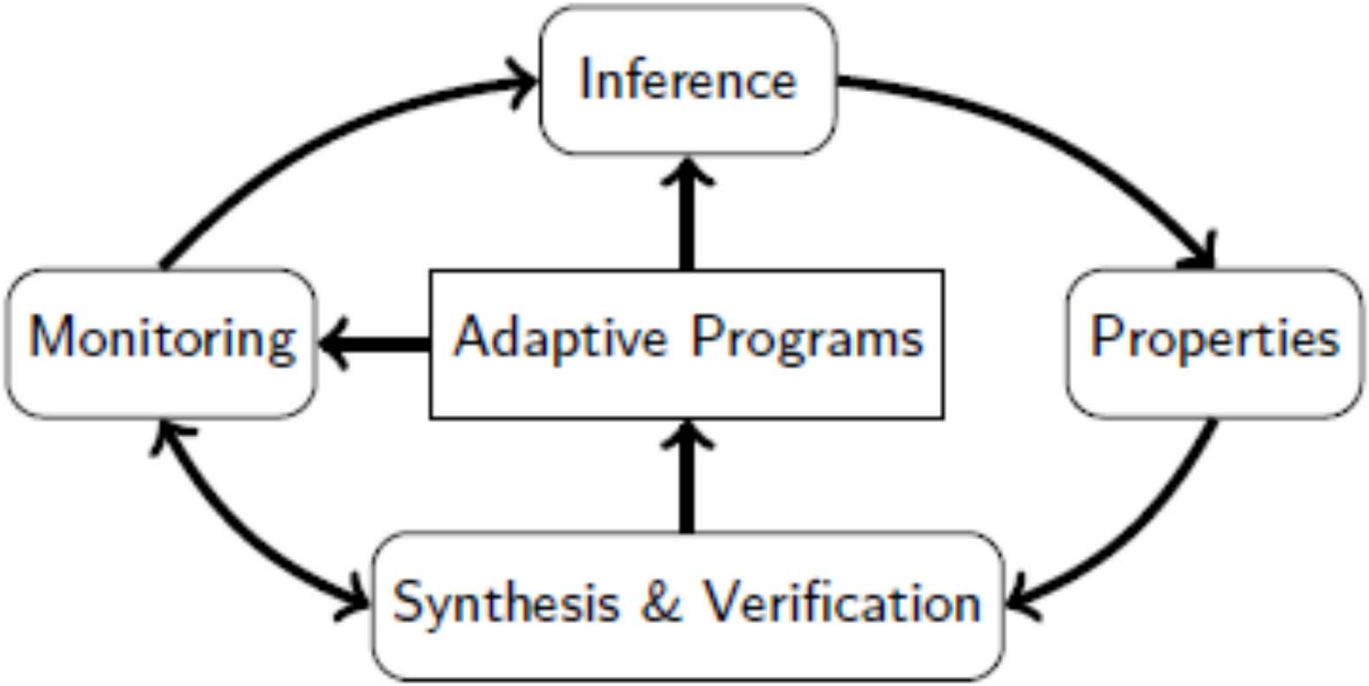
Efficient and effective to monitor probabilistic properties:

$$\Pr\left(\sum_{n \in \text{Nodes}} @_n \, \text{downloads}(f, C) < \text{limit}\right) > 0.999$$

- Monitoring against spatial and temporal variations.
- *cf: Statistical Model Checking*

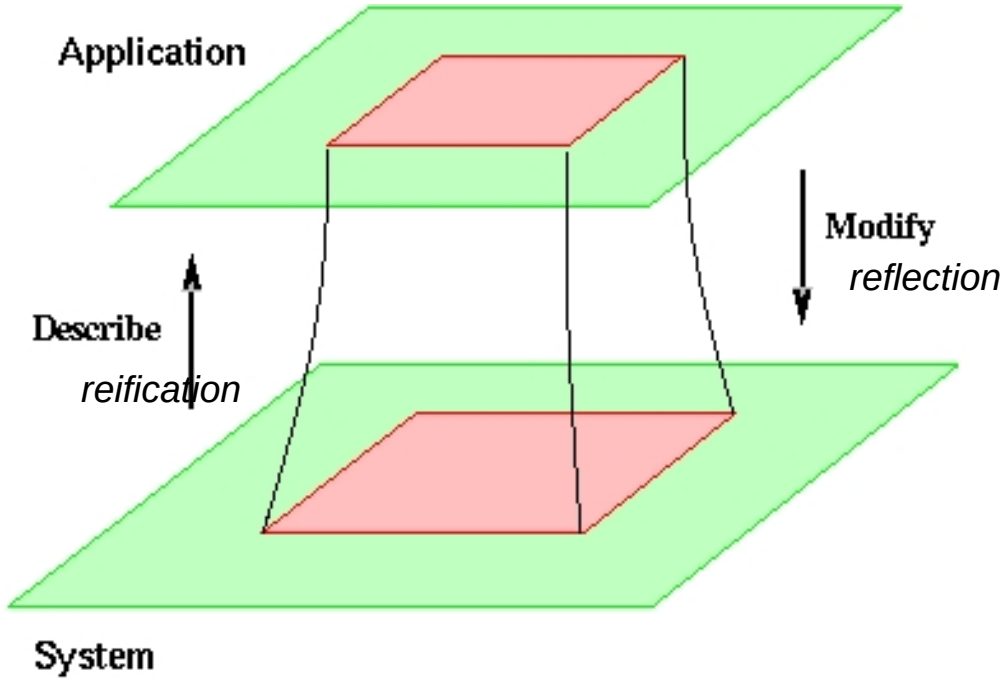


Adaptive Programs



Computational Reflection

- A meta-level actor describes functionality of actor.
- To change the application's behavior, modify the relevant meta-actor.



Use Runtime Monitoring to Infer Specifications

- Assume violations are rare events
- Infer concurrency patterns by monitoring traces
- Use Bayesian methods for robustness against outlier observations
  - Incorporate new evidence in a structured way
  - Rare spurious behavior weighed against preponderance of contrary evidence and ignored
- Enforce or monitor for extended specification
- *Example: figure out the intended concurrency patterns and use it to transform to a safer actor program*

Goal: Moving Legacy Concurrent Programs to Clouds

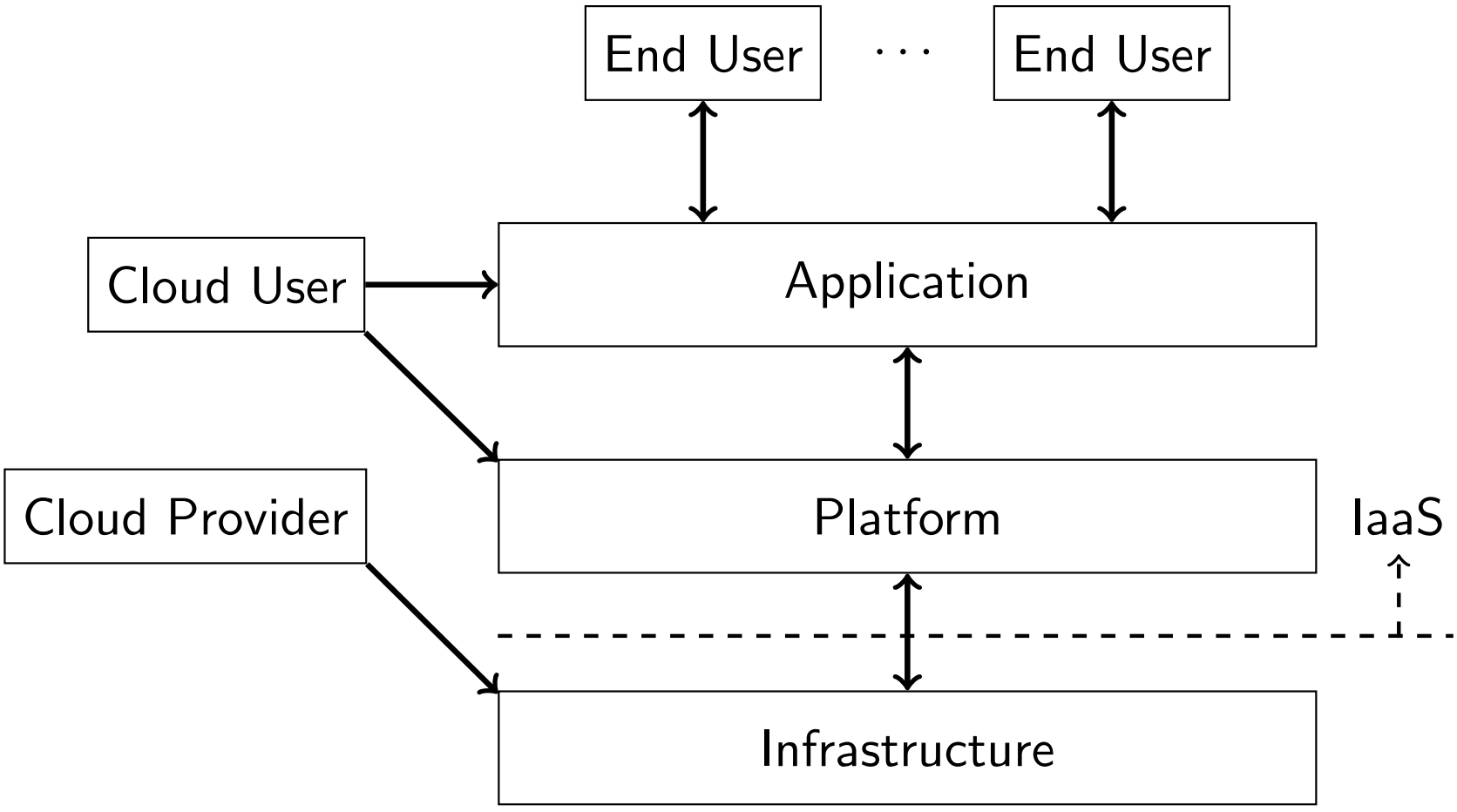
Benefits of moving legacy programs to clouds

- Lower maintenance costs
- Easier and less costly redundancy
- Scalability

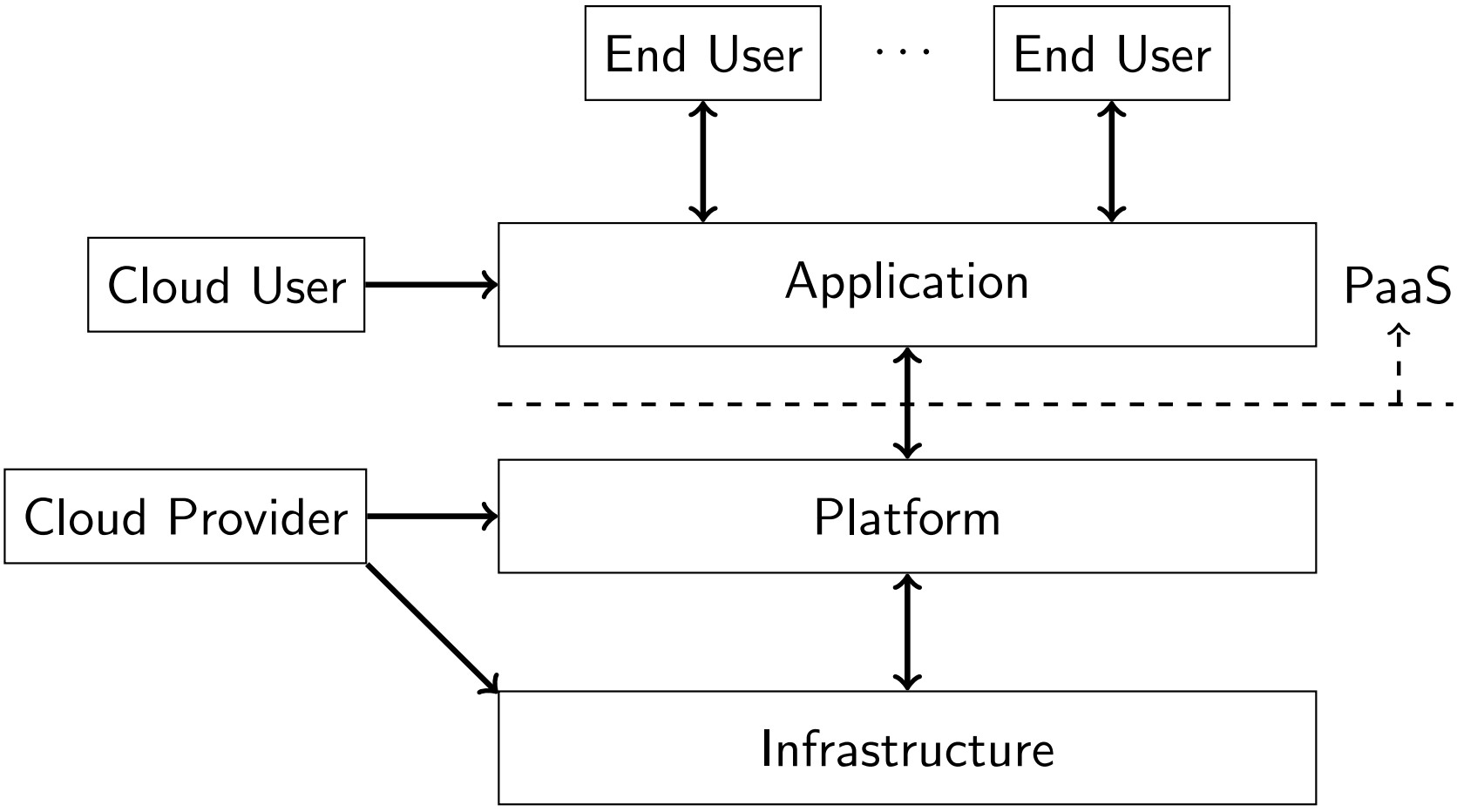
Some cloud migration problems

- Most legacy concurrent programs use *shared memory*
- Running on single virtual machine gives few advantages
- Difficult to simulate shared memory in distributed setting

Infrastructure-as-a-Service



Platform-as-a-Service



Scalability: Actor Model of Computation

An actor is an autonomous, concurrent agent which responds to messages.

- Actors operate asynchronously, potentially in parallel with each other.
- Actors do not share state
- Each actor has a unique name (address) which cannot be guessed.
- Actor names may be communicated.
- Actors interact by sending messages which are by default asynchronous (and may be delivered out-of-order).

Actor Behavior

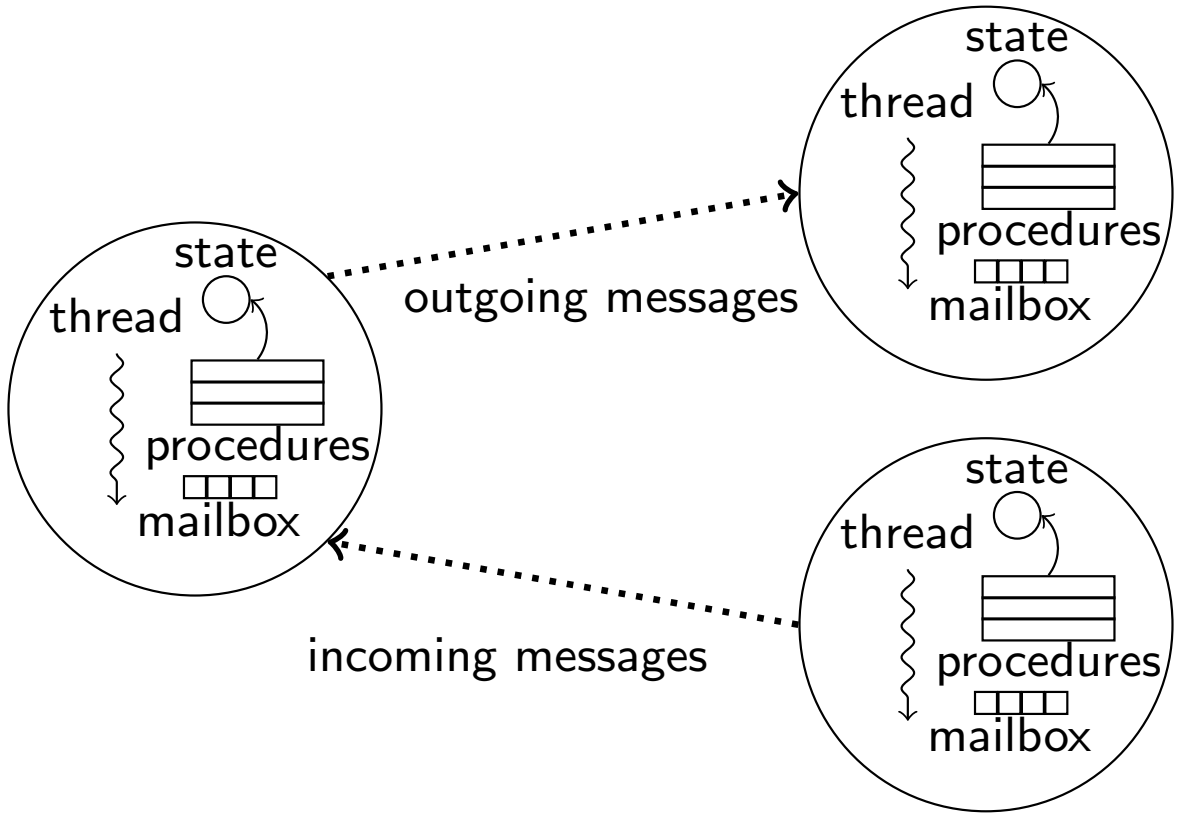
Upon receipt of a message, an actor may:

- create a new actor with a unique name (address).
- use the content of the message or perform some computation and to change state.
- send a message to another actor.

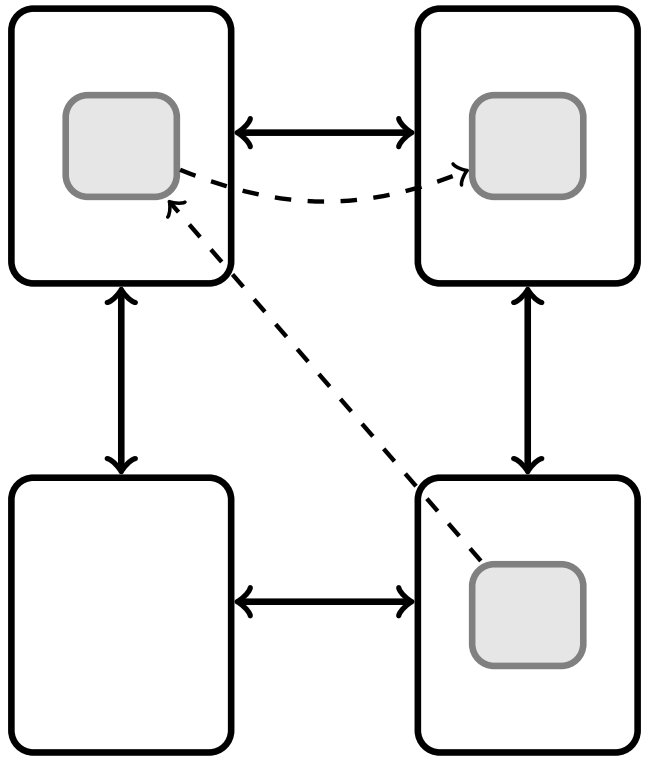
Actor Implementation in Threaded Languages

An actor may be implemented as a concurrent object. Each actor:

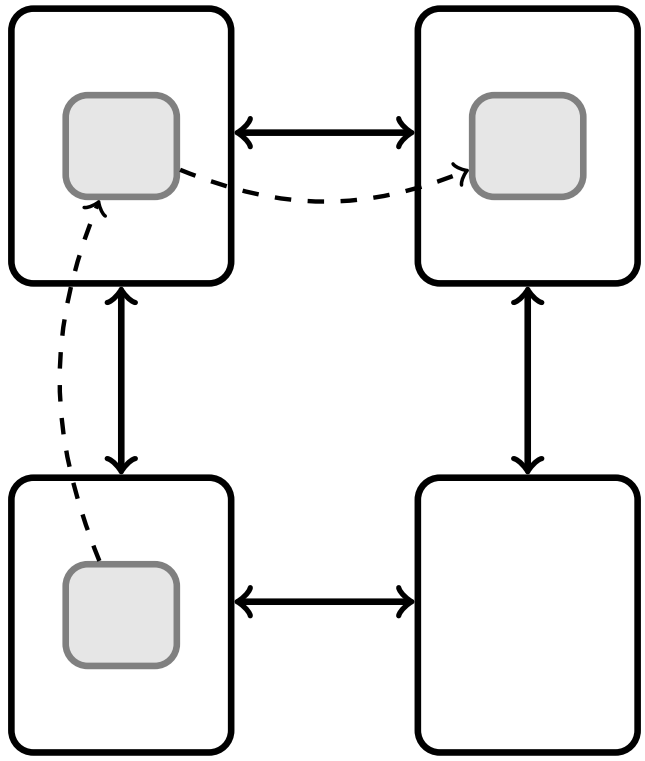
- has a system-wide unique name (mailbox address);
- has an independent thread of control; and
- has a message queue and processes **one message at a time**.



Execution of Message-Passing Programs in Networks



Execution of Message-Passing Programs in Networks



Actors: Scalable Concurrency

Large-scale concurrent systems such as Twitter, LinkedIn, Facebook Chat are written in actor languages and frameworks.

Facebook

> *"[T]he actor model has worked really well for us, and we wouldn't have been able to pull that off in C++ or Java. Several of us are big fans of Python and I personally like Haskell for a lot of tasks, but the bottom line is that, while those languages are great general purpose languages, none of them were designed with the actor model at heart." –Facebook Engineering* [1]

[1] https://www.facebook.com/notes/facebook-engineering/chat-stability-and-scalability/51412338919

Actors: Scalable Concurrency II

Large-scale concurrent systems such as Twitter, LinkedIn, Facebook Chat are written in actor languages and frameworks.

> *"When people read about Scala, it's almost always in the context of concurrency. Concurrency can be solved by a good programmer in many languages, but it's a tough problem to solve. Scala has an Actor library that is commonly used to solve concurrency problems, and it makes that problem a lot easier to solve." – Alex Payne, "How and Why Twitter Uses Scala"*[2]

[2] `http://blog.redfin.com/devblog/2010/05/how_and_why_twitter_uses_scala.html`

Some Actor Languages and Frameworks

- Erlang: web services, telecom, Cloud Computing
- E-on-Lisp, E-on-Java: P2P systems
- SALSA (UIUC/RPI), Charm++ (UIUC): scientific computing
- Ptolemy (UCB): real-time systems
- ActorNet (UIUC): sensor networks
- Scala (EPFL; Typesafe): multicore, web, banking..
- Kilim (Cambridge): multicore and network programming
- Orleans; Asynchronous Agents Library (Microsoft): multicore programming, Cloud Computing
- DART (Google): Cloud Computing

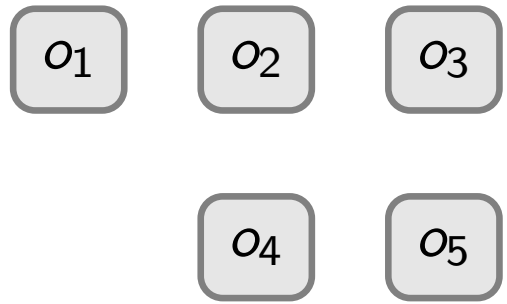
Converting Shared-Memory Programs to Message Passing

- Manual conversion to use message passing requires understanding *concurrency semantics* of programs
  - how locking is used to uphold data structure invariants
  - how thread interference is avoided
- Many different "correct" conversions are possible—but finer granularity gives more concurrency

Converting Shared-Memory Programs to Message Passing

Our approach

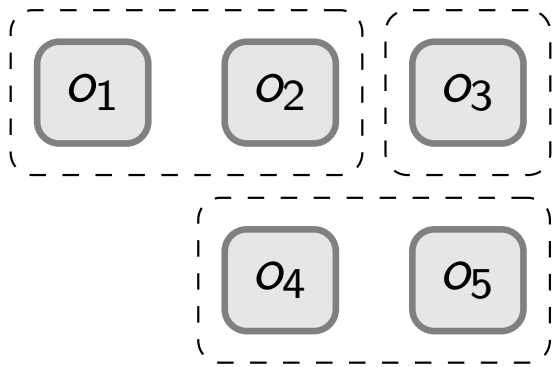
1. Use runtime monitoring to infer concurrency semantics in terms of *data-centric synchronization* requirements.
2. Encapsulate objects inside message-passing *actors* based on synchronization analysis.



Converting Shared-Memory Programs to Message Passing

Our approach

1. Use runtime monitoring to infer concurrency semantics in terms of *data-centric synchronization* requirements.
2. Encapsulate objects inside message-passing *actors* based on synchronization analysis.



Java Class With Control-Centric Synchronization

```
class ArrayList {
  int size;
  Object[] entries;

  Object get(int i) {
    synchronized(lock) {
      if (0 <= i && i < this.size) {
        return this.entries[i];
      } else {
        return null;
      }
    }
  }

  void addAll(ArrayList o) {
    synchronized(lock) {
      this.size += o.size;
    }
    /*... copy elements ...*/
  }
}
```

Java Class Annotated for Data-Centric Synchronization

```
class ArrayList {
  atomicset L;
  atomic(L) int size;
  atomic(L) Object[] entries;

  Object get(int i) {
    if (0 <= i && i < this.size) {
      return this.entries[i];
    } else {
      return null;
    }
  }

  void addAll(unitfor(L) ArrayList o) {
    this.size += o.size;
    /*... copy elements ...*/
  }
}
```

Elements of Data-Centric Synchronization

Atomic Set

Group of fields in a class connected by a consistency invariant

Unit of Work

Method that preserves the invariant when executed sequentially

Alias

Combines atomic sets

Example

In the `ArrayList` class:

- Invariant: `entries[i]` valid if `i < size`
- Atomic set $L = \{$ `size`, `entries` $\}$

Example

In the `ArrayList` class:

- Instance methods are units of work for all atomic sets of the object
- `addAll(ArrayList)` is a unit of work for the other list's atomic set L

Converting a Program to use Atomic Sets Requires Understanding its Concurrency Structure

Must *understand* old synchronization to convert it!

Conversion Experience of Dolby et al. [TOPLAS, 34(1):4, 2012]:

- Takes several hours for rather simple programs
- 2 out of 6 programs lack synchronization of some classes
- 2 out of 6 programs accidentally introduced global locks

Our Algorithm

Avoid conversion errors by automatically determining annotations from program traces using Bayesian probabilistic inference

Synopsis of our Algorithm for Probabilistically Inferring Atomic Sets, Aliases, and Units of Work

Assumptions about Input Programs

- Methods perform meaningful operations (convey *intent*)
- Data fields that a method accesses are likely connected by invariant

Algorithm Idea

- Observe which pairs of fields a method accesses atomically and their distance in terms of basic operations
  - This is (Bayesian) *evidence* that fields are connected through a semantic invariant
- Store current beliefs for all field pairs in *affinity matrices*

Analysis Supports Indirect Field Access and Access Paths

Indirect Access and Distance

- High-level semantic operations use low-level operations
- E.g., `get()` might call `getSize()` instead of accessing field `size`
- Propagate observed access to caller's scope
- Quantify directness of access as *distance*

Access Paths

- Methods traverse the object graph
- Track *access paths* instead of field names
- Example: `this.urls.size`

Bayes's Inversion Formula

Bayesian Inference Variables

H: "f and g are connected through an invariant" [Hypothesis]
e_k: "f, g accessed (non-)atomically with distance d_k" [evidence]

Consider a sequence of observations $e_1, \ldots, e_n$ w.r.t. f and g.
Want to know *probability that H holds given* $e_1, \ldots, e_n$, i.e.,

$$P(H|e_1, \ldots, e_n) = \frac{P(e_1, \ldots, e_n|H)\, P(H)}{P(e_1, \ldots, e_n)}$$

Likelihood Ratios and Belief Updating

$$\frac{P(H|e_1,\ldots,e_n)}{P(\neg H|e_1,\ldots,e_n)} = \frac{P(e_1,\ldots,e_n|H)}{P(e_1,\ldots,e_n|\neg H)} \times \frac{P(H)}{P(\neg H)}$$

$$\text{updated info} = \text{info from observations} \times \text{original info}$$

$$\text{posterior odds} = \text{likelihood ratio} \times \text{prior odds}$$

$$O(H|e_1,\ldots,e_n) = L(e_1,\ldots,e_n|H) \times O(H)$$

Conditional Independence

If $e_1, \ldots, e_n$ are conditionally independent given H, we can write

$$P(e_1, \ldots, e_n|H) = \prod_{k=1}^{n} P(e_k|H)$$

and similarly for $\neg H$, whereby

$$O(H|e_1, \ldots, e_n) = O(H) \prod_{k=1}^{n} L(e_k|H)$$

Adding one more piece of evidence e_{n+1}, we get

$$O(H|e_1, \ldots, e_n, e_{n+1}) = L(e_{n+1}|H)\, O(H|e_1, \ldots, e_n)$$

Hence, if we have independence, know $O(H)$, and can compute $L(e_k|H)$, we can update odds on-the-fly when observing!

Conditional Independence

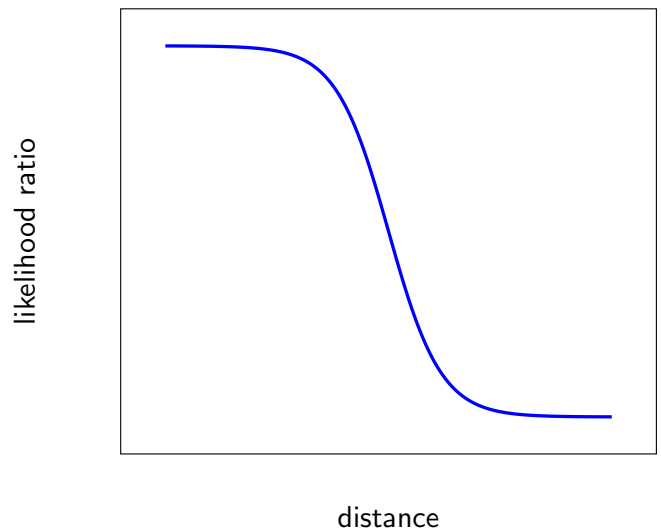
- Coarse-grained hypothesis space: $H \cup \neg H$
- With conditional independence, $e_1, \ldots, e_n$ should depend only on hypothesis, not on systematic external influence
- However, we have at least the following external factors:
  - workload
  - scheduler

Mitigating Dependencies

- Working assumption: good workload and long executions minimize external influence
- Safe to include f, g in atomic set when there is no invariant...
- ...but may result in coarser-grained concurrency

Mapping Observations to Likelihoods

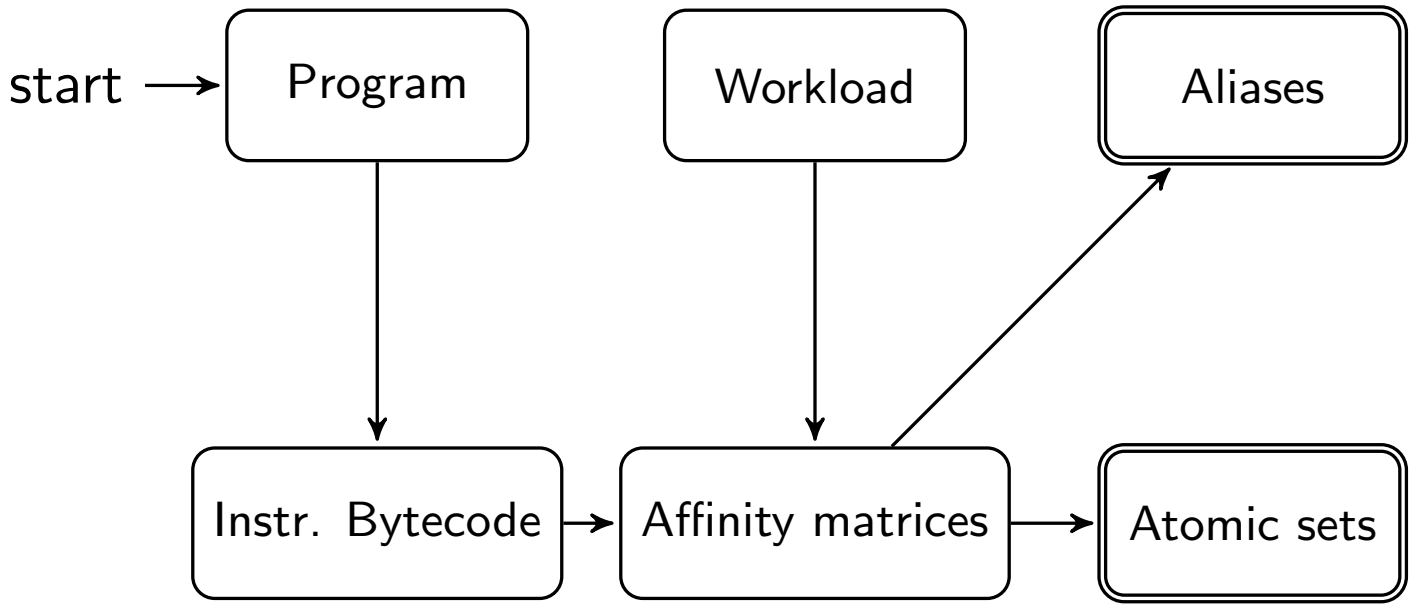
- Given access observation e_k for fields f and g with operation distance d_k, need to compute $L(e_k|H)$
- $L(e_k|H)$ should increase as d_k decreases up to some maximum, after which it is flat
- $L(e_k|H)$ should decrease as d_k increases down to some minimum, after which it is flat



Advantages of On-the-Fly Bayesian Inference

- Likelihoods incorporate scope and distance of observations
- Beliefs can be revised by new evidence, and thus improve with longer executions
- Analysis becomes robust and insensitive to outlier observations
- Size of observation data is in the size of the codebase, not size of execution
- Infers aliases similarly to atomic sets, which is hard to do statically

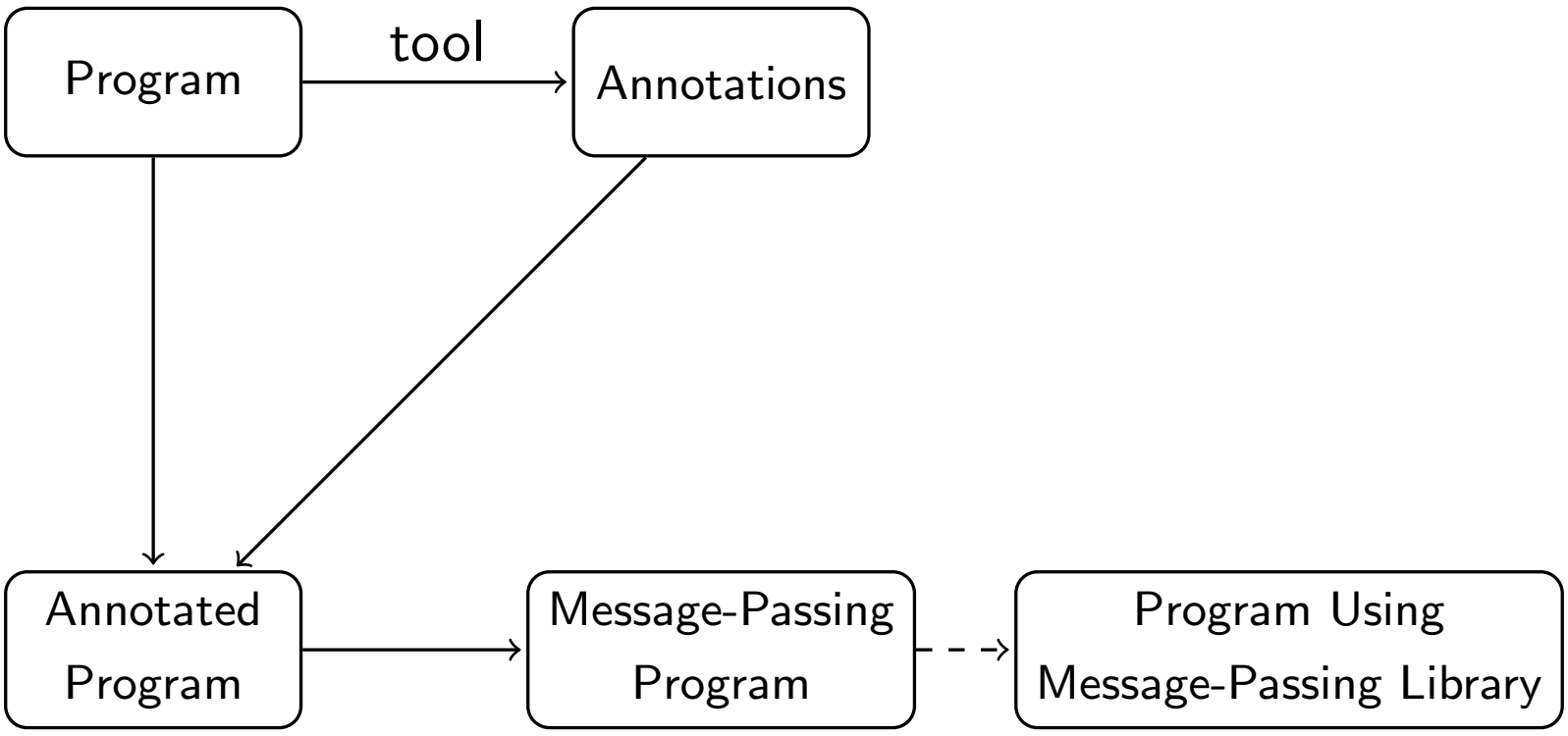
Data-Centric Synchronization Inference Toolchain



Actorizing Programs Annotated with Atomic Sets

- Key property: messages (method calls) to actors are processed *one-at-a-time*
- Fields in one atomic set *should not* span two actors at runtime
- When object instances are created:
  - instances of class `Thread` end up in separate actor
  - instances with *non-aliased* atomic sets end up in separate actor
  - instances with *aliased* atomic sets end up inside same actor
- Synchronization (two-phase commit) needed to handle some **`unitfor`** declarations!

Conversion Approach in Practice



Conversion Example

```
class DownloadManager {
  // Atomic access ensured by monitors
  ArrayList urls;
  public synchronized URL getNextURL() {
    if (this.urls.size() == 0) return null;
    URL url = (URL) this.urls.get(0);
    this.urls.remove(0);
    announceStartInGUI(url);
    return url;
  }
  /* ... */
}
class DownloadThread extends Thread {
  DownloadManager manager;
  public void run() {
    URL url;
    while((url = this.manager.getNextURL()) != null) {
      download(url); // Blocks while waiting for data
    }
  }
  /* ... */
}
```

Conversion Example, continued

```
public class Download {
  public static void main(String[] args) {
    DownloadManager manager = new DownloadManager();
    for (int i = 0; i < 31; i++) {
      manager.addURL(new URL("http://www.example.com/f" + i));
    }
    DownloadThread t1 = new DownloadThread(manager);
    DownloadThread t2 = new DownloadThread(manager);
    t1.start();
    t2.start();
  }
}
```

Conversion Example, continued

```
class DownloadManager {
  atomicset U;
  atomic(U) ArrayList urls|L=this.U|;
  public URL getNextURL() {
    if (this.urls.size() == 0) return null;
    URL url = (URL) this.urls.get(0);
    this.urls.remove(0);
    announceStartInGUI(url);
    return url;
  }
  /* ... */
}
public class DownloadThread extends Thread {
  DownloadManager manager;
  public void run() {
    URL url;
    while((url = this.manager.getNextURL()) != null) {
      download(url); // Blocks while waiting for data
    }
  }
  /* ... */
}
```

Conversion Example, continued

```
class DownloadManager implements IDownloadManager {
  ArrayList urls;
  public URL getNextURL() {
    if (this.urls.size() == 0) return null;
    URL url = (URL) this.urls.get(0);
    this.urls.remove(0);
    announceStartInGUI(url);
    return url;
  }
  /* ... */
}
public class DownloadThread extends Thread implements
     IDownloadThread {
  IDownloadManager manager;
  public void run() {
    URL url;
    while((url = this.manager.getNextURL()) != null) {
      download(url); // Blocks while waiting for data
    }
  }
  /* ... */
}
```

Conversion Example, continued

```
public class Download {
  public static void main(String[] args) {
    // Actorized initializations
    IDownloadManager manager = new actor DownloadManager();
    for (int i = 0; i < 31; i++) {
      manager.addURL(new URL("http://www.example.com/f" + i));
    }
    IDownloadThread t1 = new actor DownloadThread(manager);
    IDownloadThread t2 = new actor DownloadThread(manager);
    t1.start();
    t2.start();
  }
}
```

Future Work

- Runtime monitoring to detect specification of process/session types.
- Use runtime verification to detect violations of specifications.
- Enforcement of session types through a meta-actors.
- How to update specifications? Adaptation problem...

References I: Actor Languages, Computational Reflection and Runtime Verification

- Gul Agha, Ian A. Mason, Scott F. Smith, and Carolyn L. Talcott. A Foundation for Actor Computation. J. Funct. Program, 7(1):1–72, 1997.
- Svend Frolund and Gul Agha. "A Language Framework for Multi-Object Coordination". In: *ECOOP'93 - Object-Oriented Programming, 7th European Conference*, Kaiserslautern, Germany, July 26-30, 1993, Proceedings. Ed. by Oscar Nierstrasz. Vol. 707. Lecture Notes in Computer Science. Springer, 1993, pp. 346–360.
- Gul Agha, Svend Frolund, WooYoung Kim, Rajendra Panwar, Anna Patterson, and Daniel C. Sturman. "Abstraction and modularity mechanisms for concurrent computing". In: *IEEE Parallel and Distributed Technology* 1.2 (1993), pp. 3–14.
- Koushik Sen, Abhay Vardhan, Gul Agha, and Grigore Rosu. 2004. Efficient decentralized monitoring of safety in distributed systems. In *Proceedings of the 26th International Conference on Software Engineering* (ICSE '04). IEEE Computer Society, Washington, DC, USA, 418-427.
- Sen, Koushik, Grigore Roşu, and Gul Agha. Online efficient predictive safety analysis of multithreaded programs.. *International Conference on Tools and Algorithms for the Construction and Analysis of Systems*. Springer Berlin Heidelberg, 2004. STTT, 8(3):248–260, 2006.
- Bill Donkervoet and Gul Agha. Reflecting on adaptive distributed monitoring. In Formal Methods for Components and Objects. 2007.
- Gul Agha, Minas Charalambides, and Gul Agha. Automated inference of atomic sets for safe concurrent execution. Technical Report, University of Illinois at Urbana--Champaign, April 2013.

References II: Probabilistic Programming, Statistical Model Checking, Euclidean Model Checking and Sensor Networks

- Kwon, YoungMin, and Gul Agha. "Linear inequality LTL (iLTL): A model checker for discrete time markov chains." *International conference on formal engineering methods*. Springer Berlin Heidelberg, 2004.
- Sen, Koushik, Mahesh Viswanathan, and Gul Agha. "Statistical model checking of black-box probabilistic systems." *International Conference on Computer Aided Verification*. Springer Berlin Heidelberg, 2004.
- Sen, Koushik, Mahesh Viswanathan, and Gul Agha. "On statistical model checking of stochastic systems." *International Conference on Computer Aided Verification*. Springer Berlin Heidelberg, 2005.
- Agha, Gul, José Meseguer, and Koushik Sen. "PMaude: Rewrite-based specification language for probabilistic object systems." *Electronic Notes in Theoretical Computer Science* 153.2 (2006): 213-239.
- Korthikanti, Vijay Anand, et al. "Reasoning about MDPs as transformers of probability distributions." *Quantitative Evaluation of Systems (QEST), 2010 Seventh International Conference on the*. IEEE, 2010.
- Kwon, YoungMin, and Gul Agha. "Verifying the evolution of probability distributions governed by a DTMC." *IEEE Transactions on Software Engineering* 37.1 (2011): 126-141.
- Rice, Jennifer A., et al. "Flexible smart sensor framework for autonomous structural health monitoring." *Smart structures and Systems* 6.5-6 (2010): 423-438.
- Jang, Shinae, et al. "Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation." *Smart Structures and Systems* 6.5-6 (2010): 439-459.
- Kwon, YoungMin, Kirill Mechitov, and Gul Agha. "Design and implementation of a mobile actor platform for wireless sensor networks." *Concurrent objects and beyond*. Springer Berlin Heidelberg, 2014. 276-316.