Monitoring Multithreaded Distributed Computations

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Motivation: Software Faults

- Software faults are dominant reasons for system outages
- Approx 2 to 3 bugs per 1000 lines of code! [Gray and Reuter 93]

Testing and Debugging:

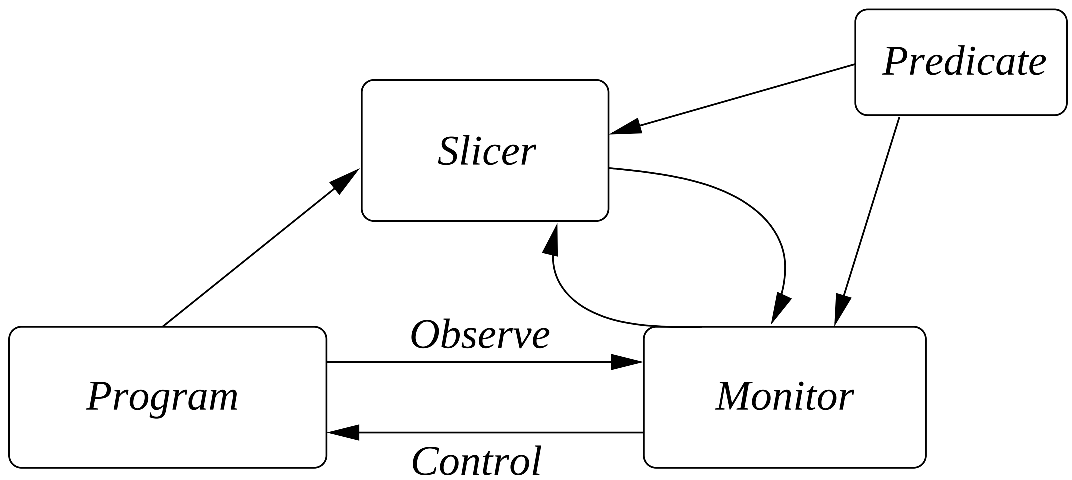
- Distributed programs are prone to errors.
- Traces need to be analyzed to locate bugs.

Software Fault-Tolerance:

- Software fault detection
- Rollback Recovery

Our Approach

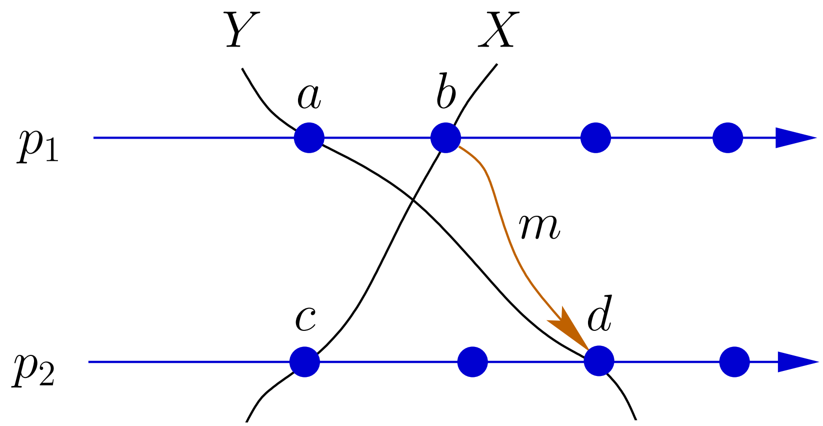
- Three abstractions defined: predicate detection, predicate control and slicing.



Talk Outline

- Motivation
- Predicate Detection
- Computation Slicing
- Predicate Control
- Ongoing and Future Work

System Model



computation: a set of events ordered by "happened before" relation

consistent cut: subset of events that have been executed so far

e.g., X is a consistent cut but Y is not

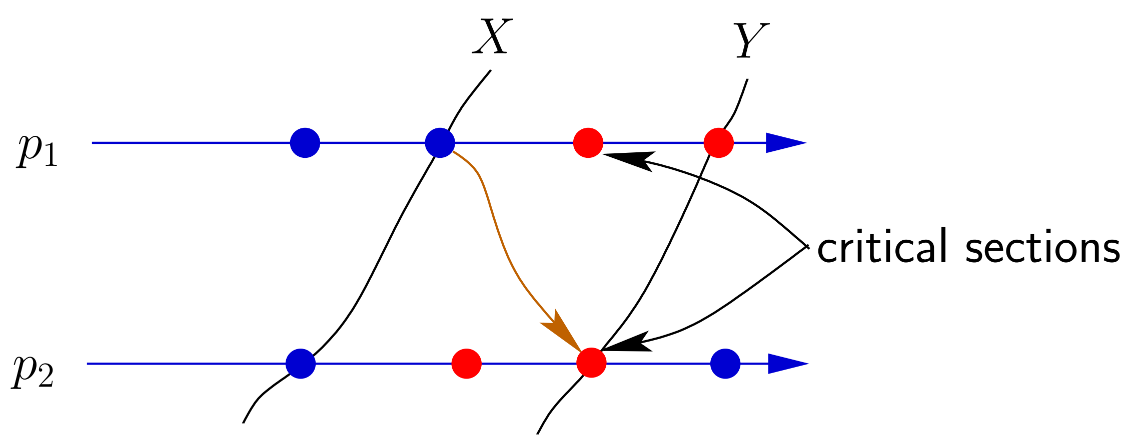
Predicate Detection Problem

Predicate: A global condition expressed using variables on processes

e.g., more than one process is in critical section,
there is no token in the system

Problem: find a consistent cut that satisfies the given predicate

Exponential algorithm for general predicate [Cooper and Marzullo 91]
Polynomial algorithm for conjunctive predicate [Garg and Waldecker 91]

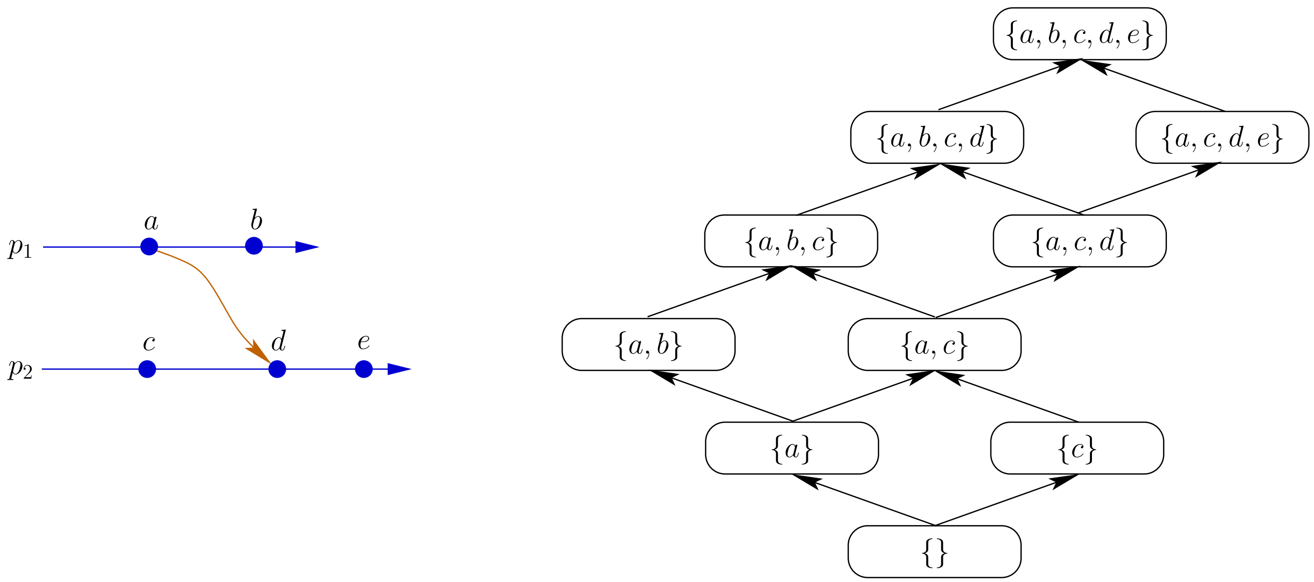


Motivation for Predicate Detection

Dear Watson, you see but you do not observe...

- Distributed Debugging, Testing
  - stop when the predicate q is true
    predicate q = (P1 is in critical section) and (P2 is in critical section).
  - Detect if the program violates any invariant
- Fault-tolerance
  - Monitoring while the program is operational
- Distributed Active Rules
  - On global condition p, trigger rule a
- General paradigm for observing Distributed Algorithms
  - Termination detection, deadlock detection, loss of token

The Main Difficulty



- NP-complete for a conjunction of clauses such that each clause is a disjunction of at most two variables [Mittal and Garg 01]

  e.g., $(x_1 \vee x_2) \wedge (x_3 \vee x_4) \wedge \cdots \wedge (x_{n-1} \vee x_n)$

Problem: Too many consistent cuts (global states)

A computation may contain as many as $O(k^n)$ consistent cuts
k: maximum number of events on a process, n: number of processes

Predicate Detection for Special Cases

Exploit the structure of the predicate:

- **stable predicate:** [Chandy and Lamport 85]

  once the predicate becomes true, it stays true

  e.g., deadlock

- **unstable predicate:**
  - *observer independent predicate* [Charron-Bost *et al* 95]

    occurs in one interleaving $\Rightarrow$ occurs in all interleavings

    e.g., any local predicate
  - *relational predicate:* $x_1 + x_2 + \cdots + x_n \geqslant k$ [Chase and Garg 95]

    e.g., violation of mutual exclusion
  - *linear predicate* [Chase and Garg 95]

    closed under intersection, e.g., conjunctive predicates such as there is no leader in the system

Conjunctive Predicates

A predicate that can be expressed as $l_1 \wedge l_2 \wedge \ldots \wedge l_n$, where l_i is local to P_i.

Examples:

- mutual exclusion problem: (P1 in CS) and (P2 in CS)
- missing primary: (P1 is secondary) and (P2 is secondary) and (P3 is secondary)

Detect errors that may be hidden in some run due to race conditions.

Importance of Conjunctive Predicates

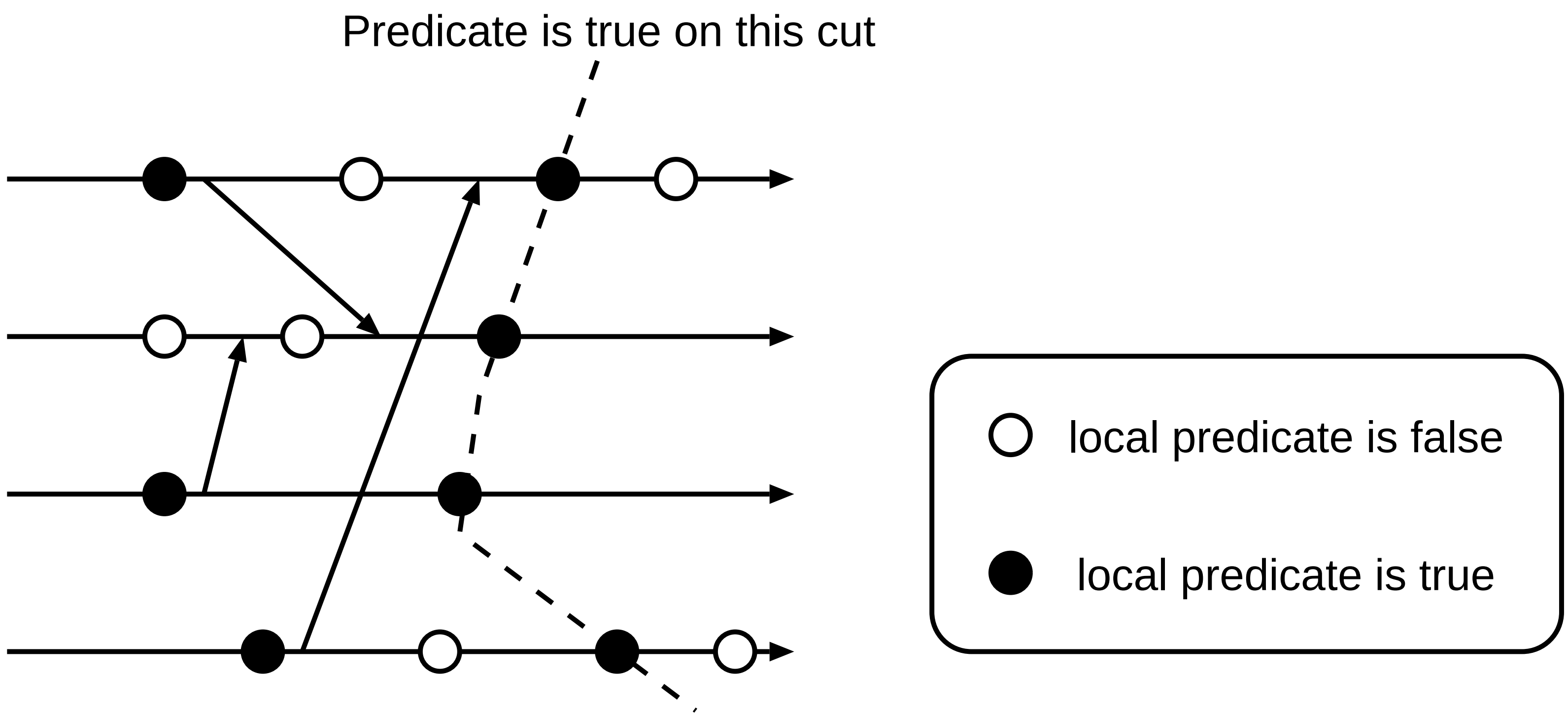
Sufficient for detection of any global

- boolean expression of local predicates which can be expressed as a disjunction of a small number of conjunctions.

  Example: x, y and z are in three different processes. Then,
  $even(x) \wedge ((y < 0) \vee (z > 6))$
  $\equiv$
  $(even(x) \wedge (y < 0)) \vee (even(x) \wedge (z > 6))$

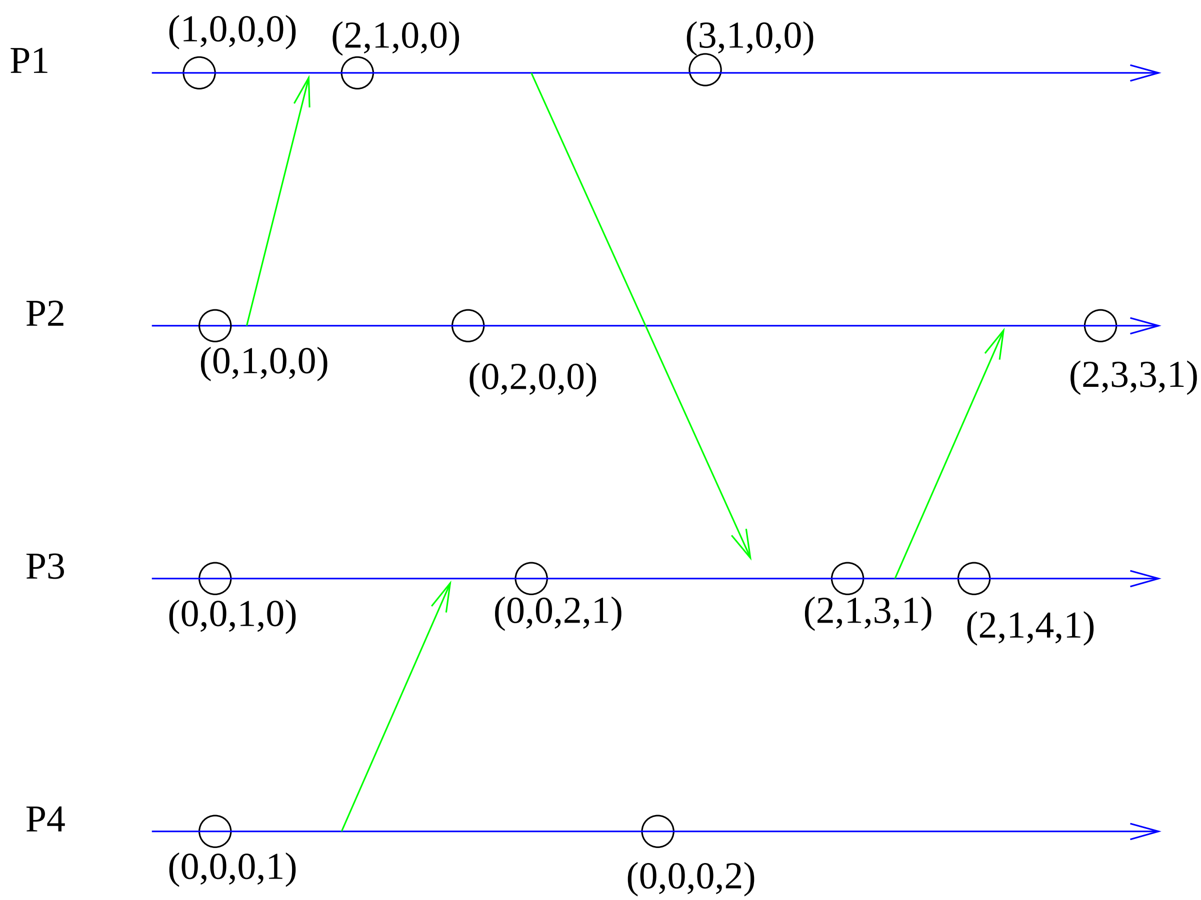
- predicate satisfied by only a small number of values *Example:* x and y are in different processes.
  $(x = y)$ is not a *local* predicate but x and y are binary.

Conditions for Conjunctive Predicates



Possibly $(l_1 \wedge l_2 \wedge \ldots l_n)$ is true **iff** there exist s_i in P_i such that l_i is true in state s_i, and s_i and s_j are incomparable for distinct i, j.

Tracking Causality: Clocks in a Distributed System



Result: s happened before t iff the vector at s is less than the vector at t.
Vector Clocks [Fidge 89, Mattern 89]

Dynamic Chain Clocks

Problem with vector clocks: scalability

Idea: Computing the "chains" in an online fashion [Aggarwal and Garg 04]

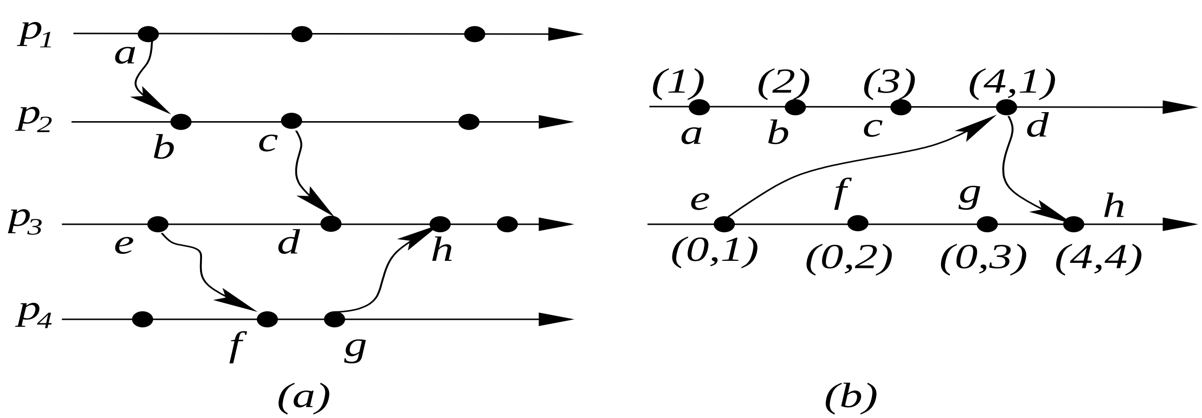
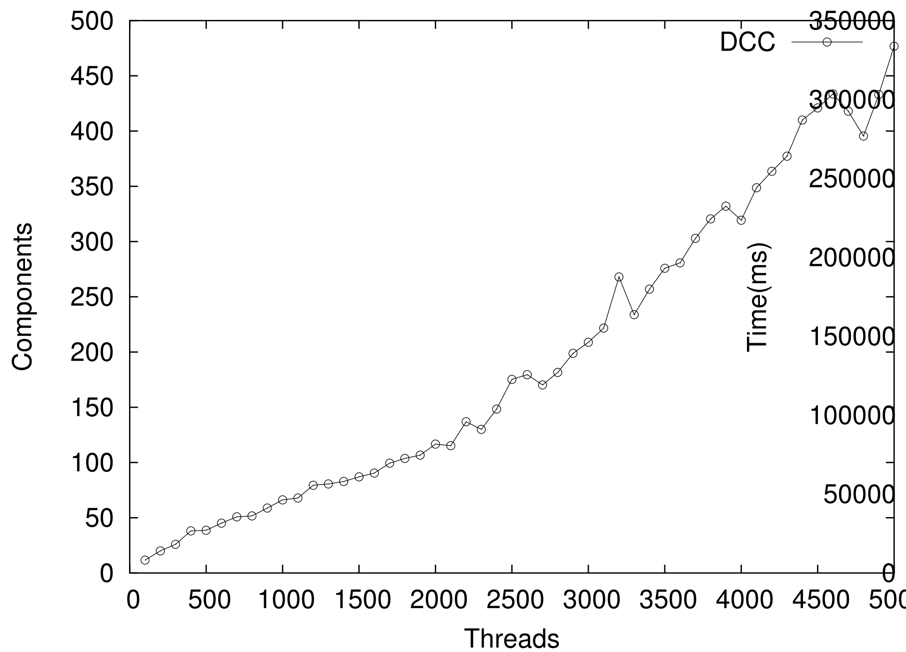


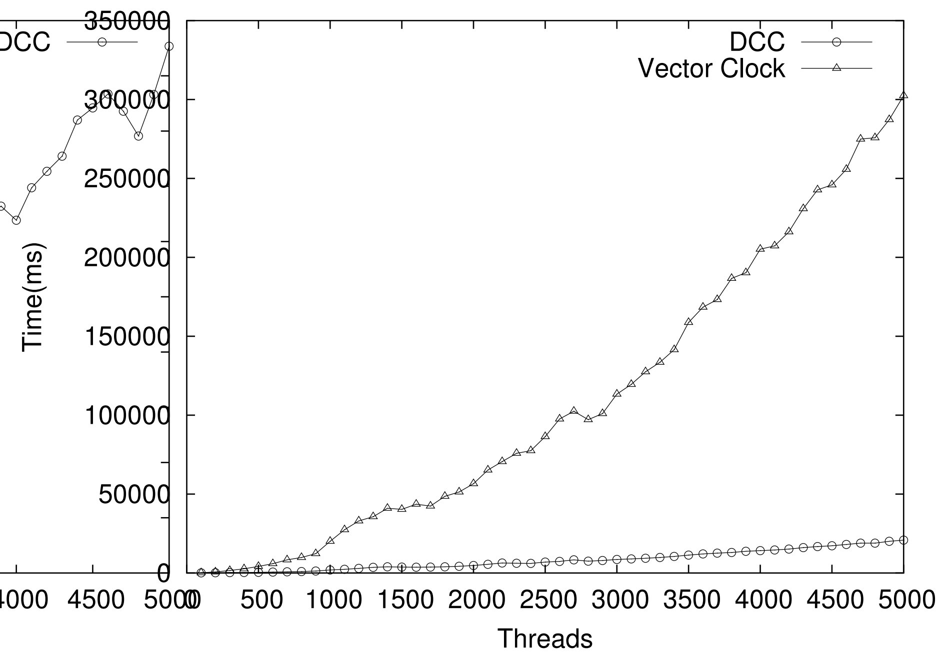
Figure 1: (a) A computation with 4 processes (b) The relevant subcomputation

Experimental Results

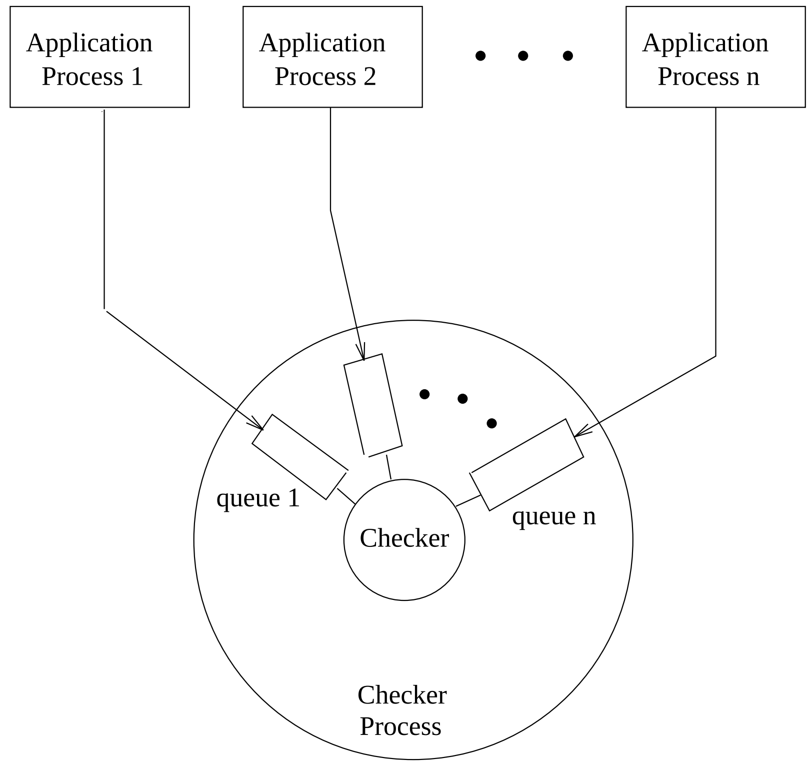
Simulation of a computation with 1% relevant events
Measured

- number of components vs number of threads
- total time overhead vs number of threads





Weak Conjunctive Predicates: Centralized Algorithm



[Garg and Waldecker 92] Each non-checker process maintains its local $vector$ and sends to the checker process the chain clock whenever

- local predicate is true
- at most once in each message interval.

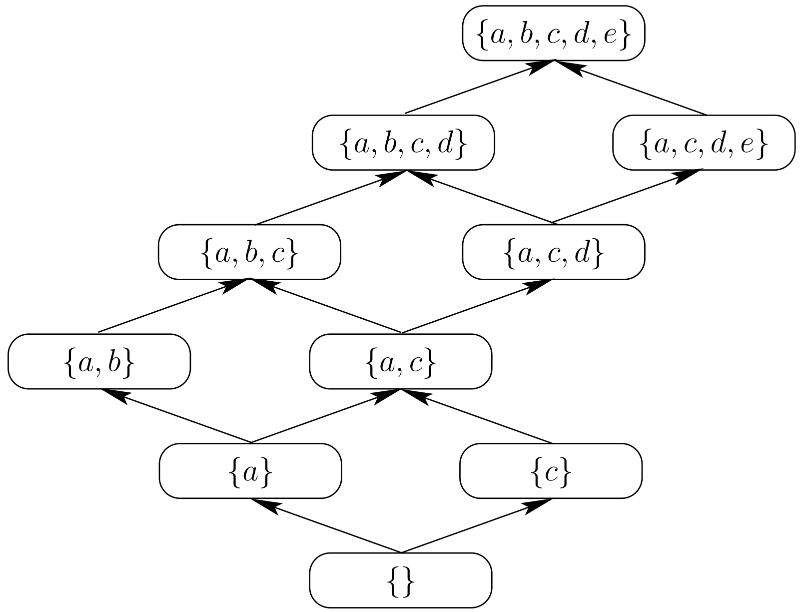
Overhead: Checker processes

Space complexity: n queues, each containing at most m vectors

Time complexity:

- The algorithm for checker requires at most $O(n^2m)$ comparisons.
- Any algorithm which determines whether there exists a set of incomparable vectors of size n in n chains of size at most m, makes at least $mn(n-1)/2$ comparisons. [Garg and Waldecker 94]

Predicate Detection in General



Construct the state-space (need to examine all consistent cuts)

- *breadth first manner* [Cooper and Marzullo 91]
  space-complexity: number of consistent cuts
- *depth first manner* [Alagar and Venkatesan 94]
  space-complexity: number of events
- *lexical order* [Garg 03]
  space-complexity: number of processes

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- Computation Slicing
- Predicate Control
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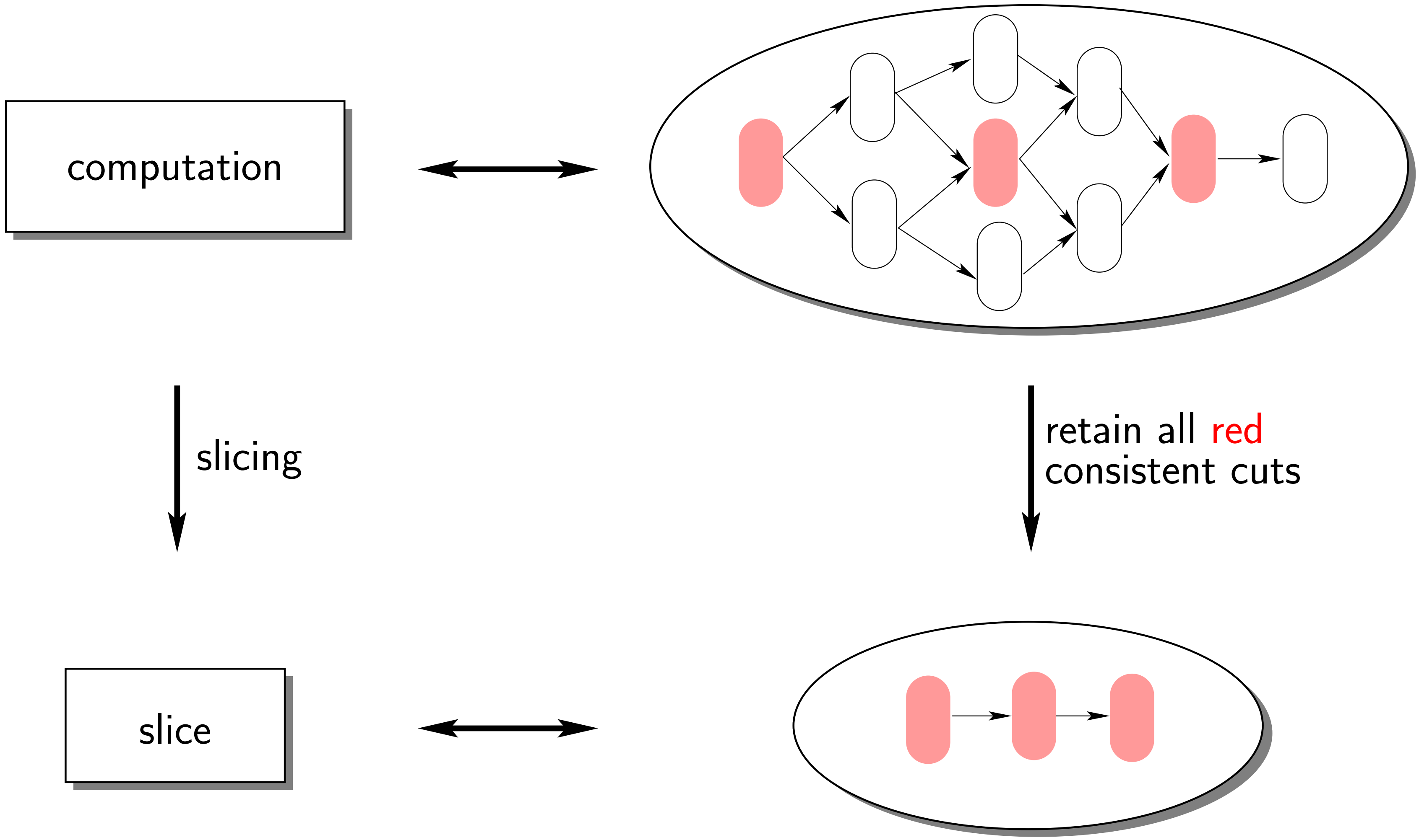
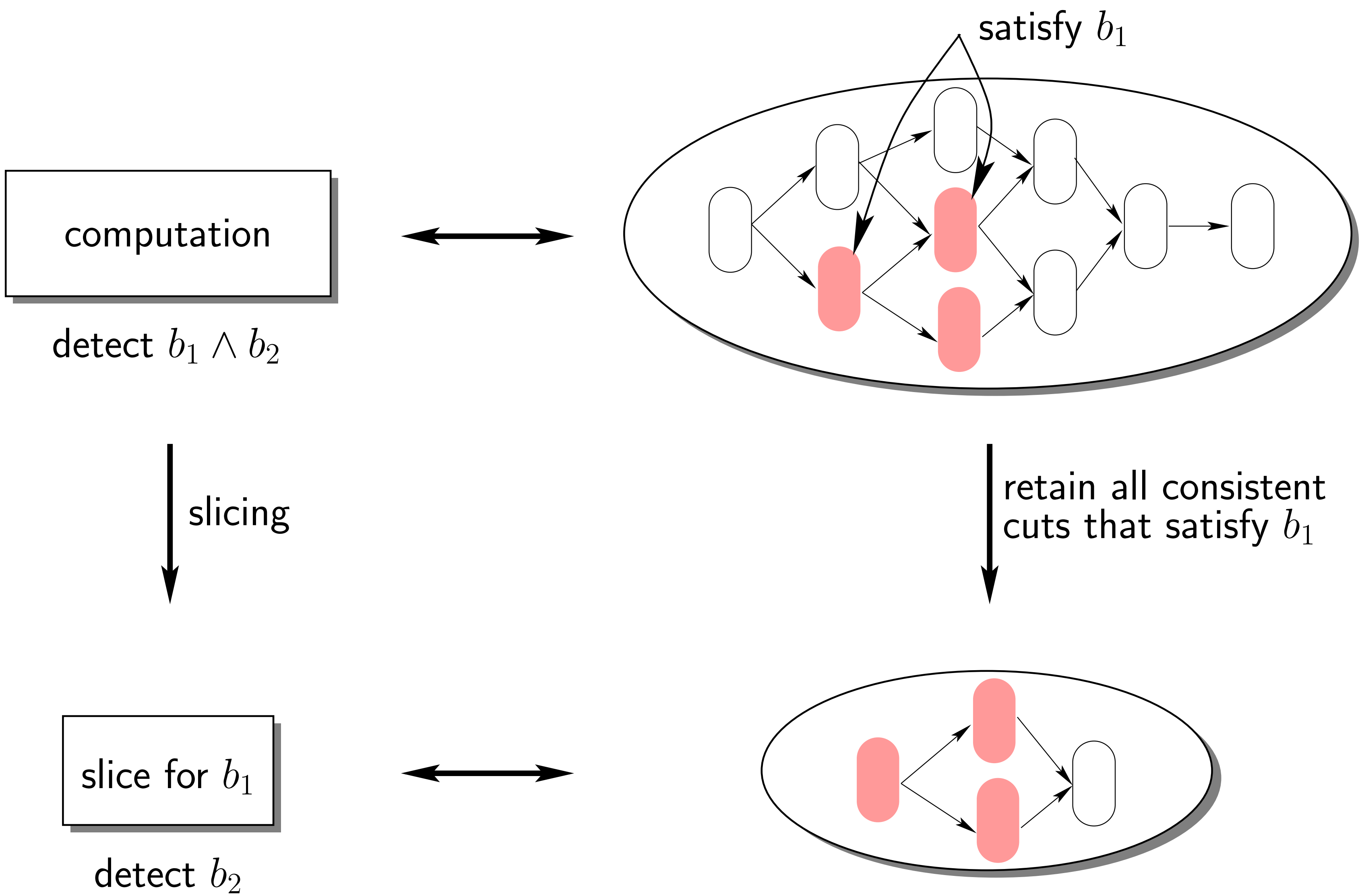
The Main Idea of Computation Slicing

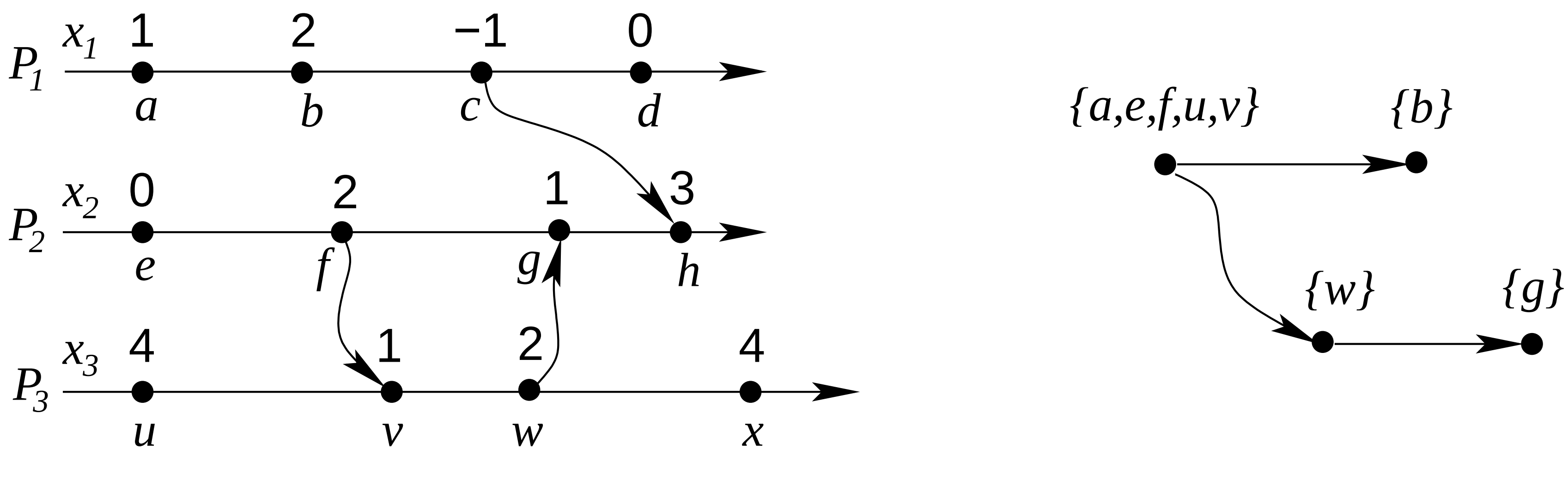


How does Computation Slicing Help?



Example

Detect predicate $(x_1 * x_2 + x_3 < 5) \wedge (x_1 \geq 1) \wedge (x_3 \leq 3)$



(a) (b)

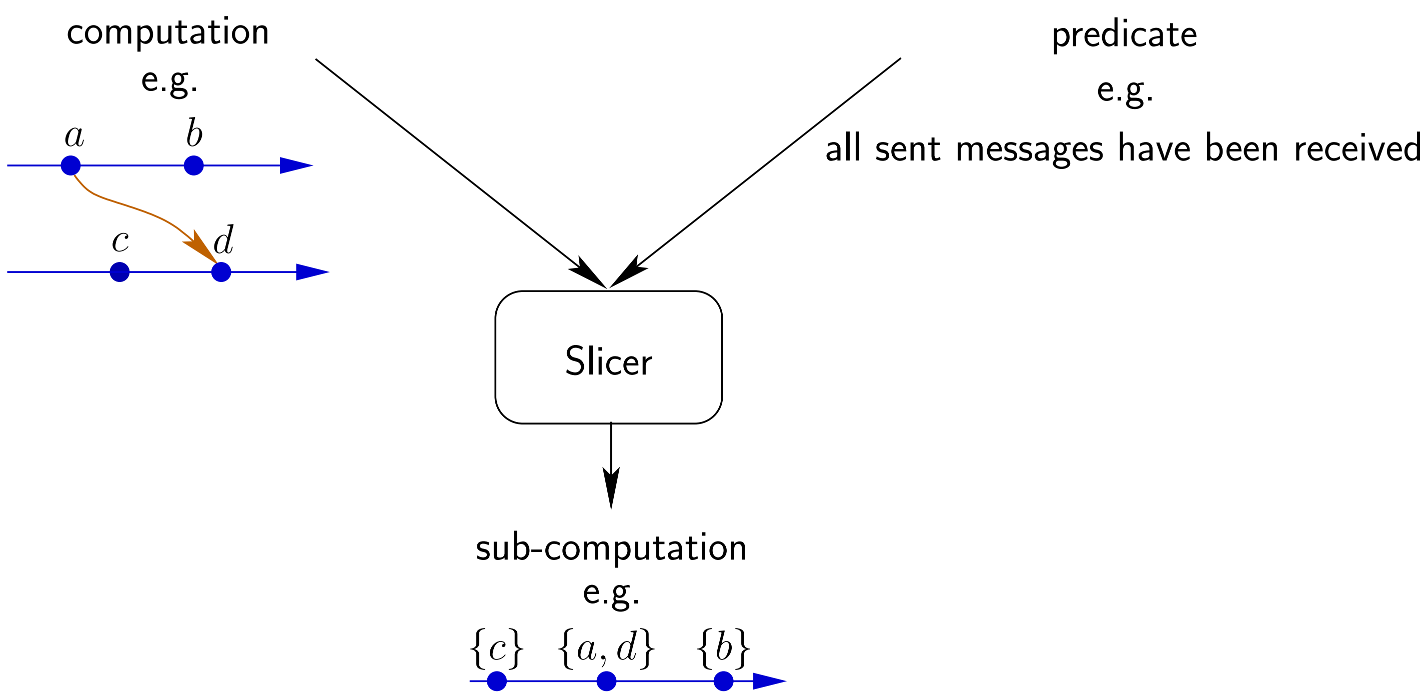
Slice with respect to $(x_1 \geq 1) \wedge (x_3 \leq 3)$

Computation Slice

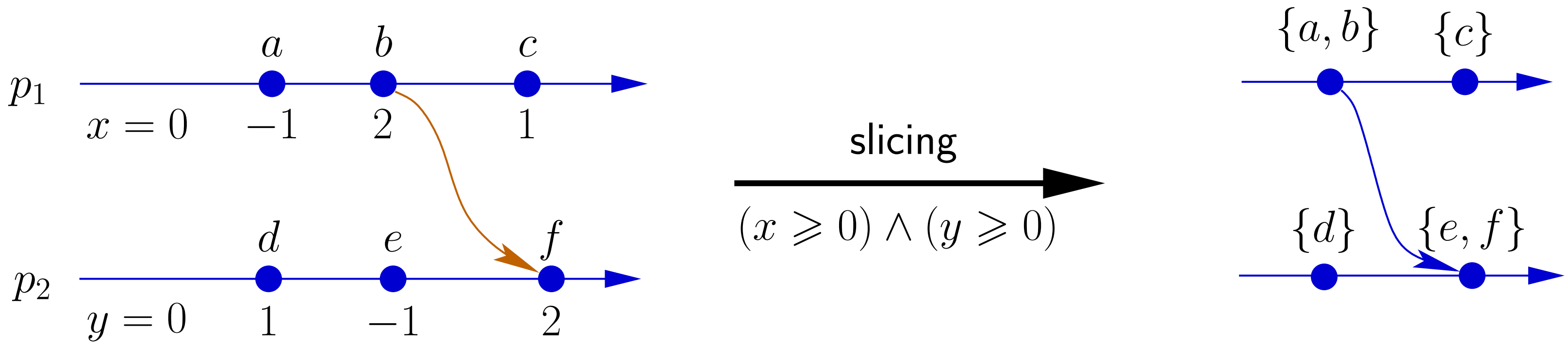
computation slice: a sub-computation such that: [Mittal and Garg 01]

(1) it contains **all** consistent cuts of the computation satisfying the given predicate, and

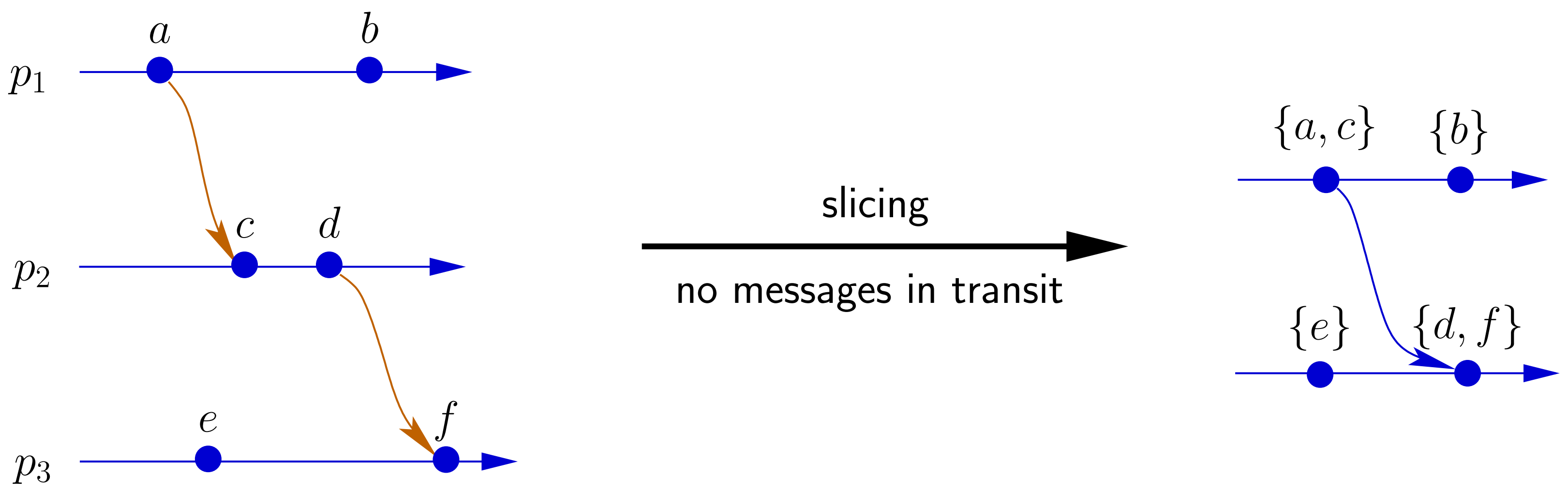
(2) it contains the **least** number of consistent cuts



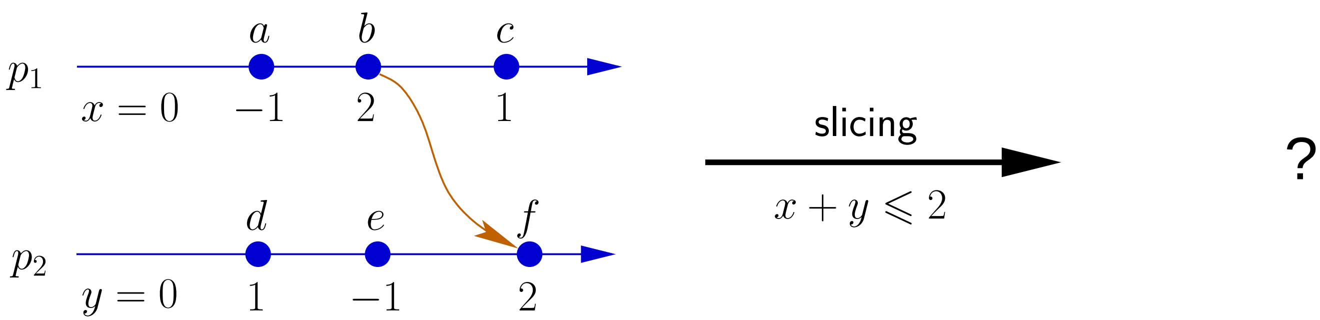
Example: Conjunctive Predicate



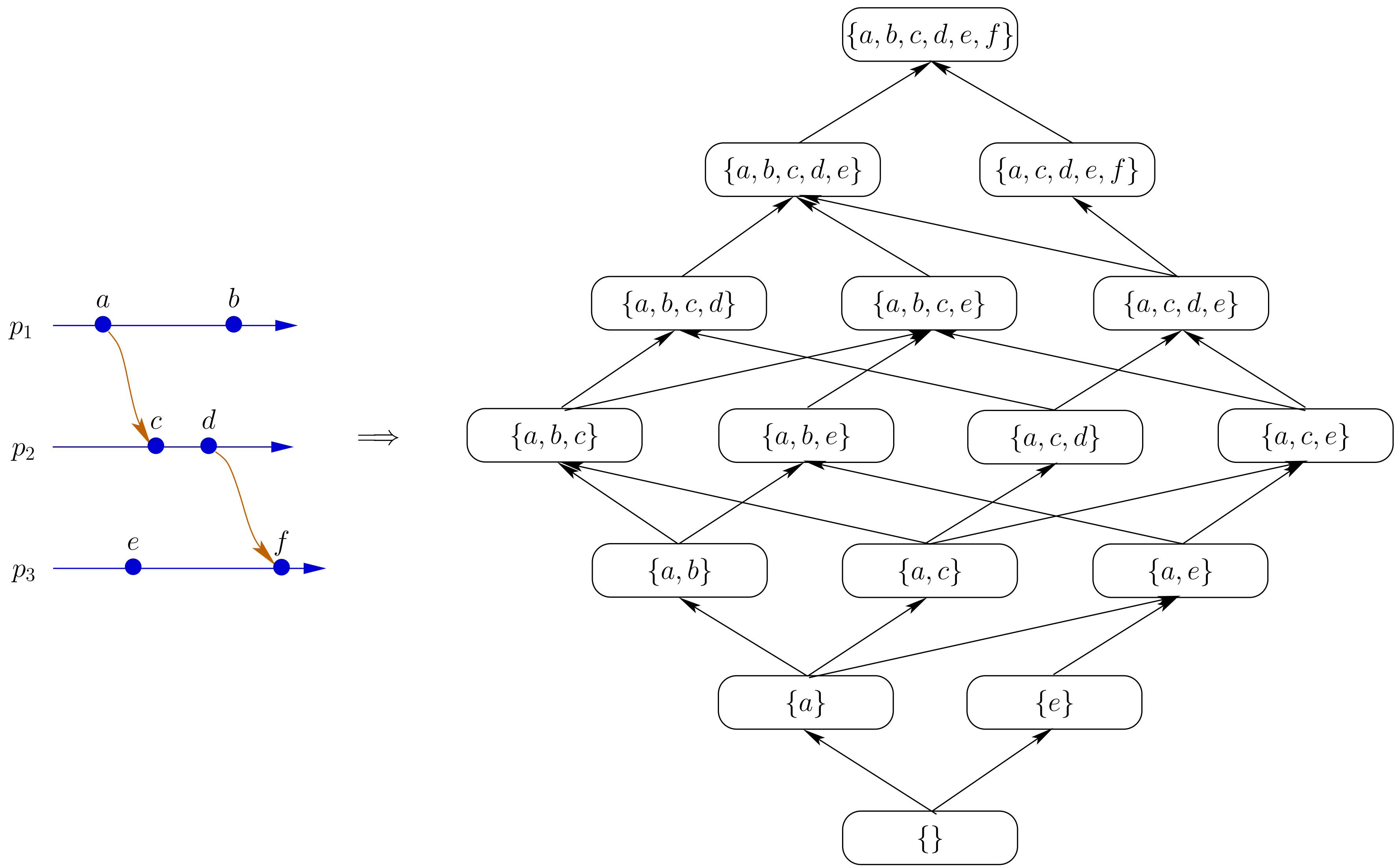
Example: Channel Predicate



Third Example



Slicing Example



Characterization of Consistent Cuts

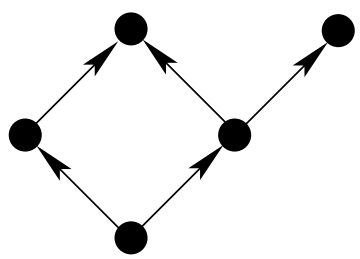
The set of consistent cuts of a computation forms a **distributive lattice**

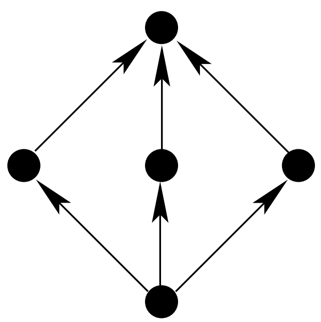
(1) The set forms a **lattice**

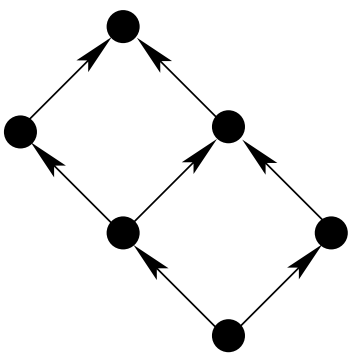
- if X and Y are consistent cuts then so are $X \cap Y$ and $X \cup Y$
- meet (infimum, greatest lower bound) $\rightarrow$ intersection
- join (supremum, least upper bound) $\rightarrow$ union

(2) The lattice is **distributive**

- meet distributes over join

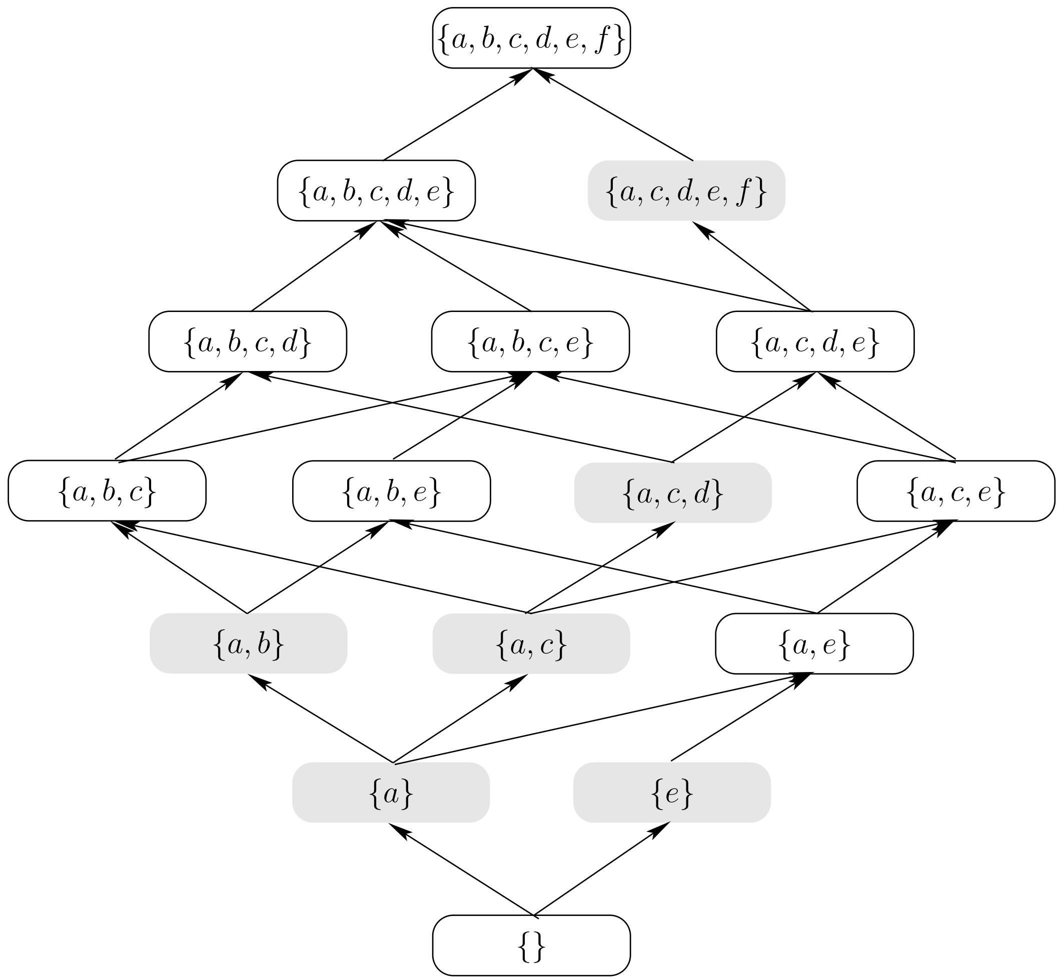






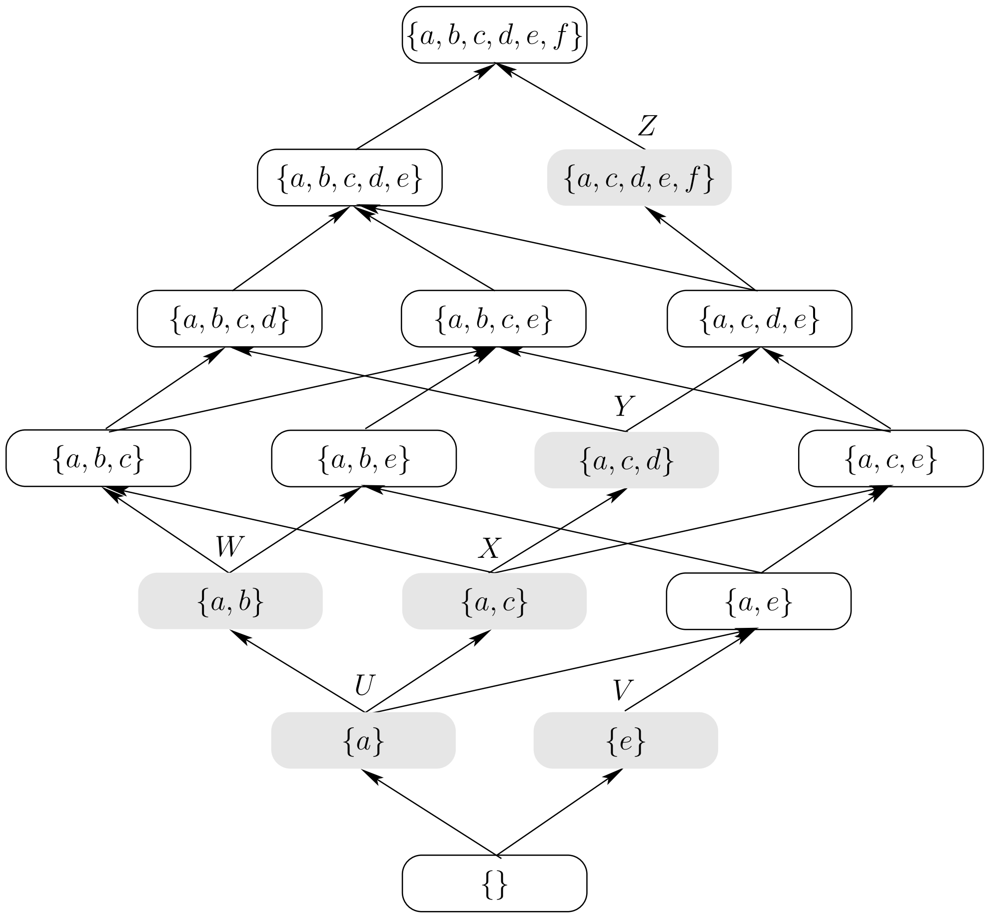
Join-irreducible Elements

A **join-irreducible element** has exactly one incoming edge

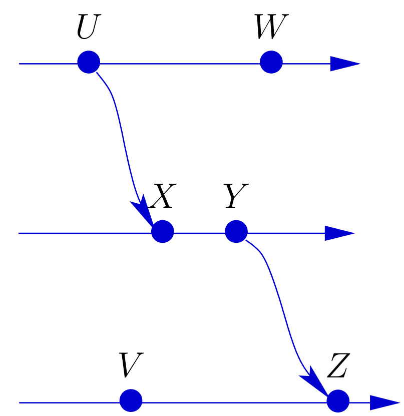


Birkhoff's Representation Theorem

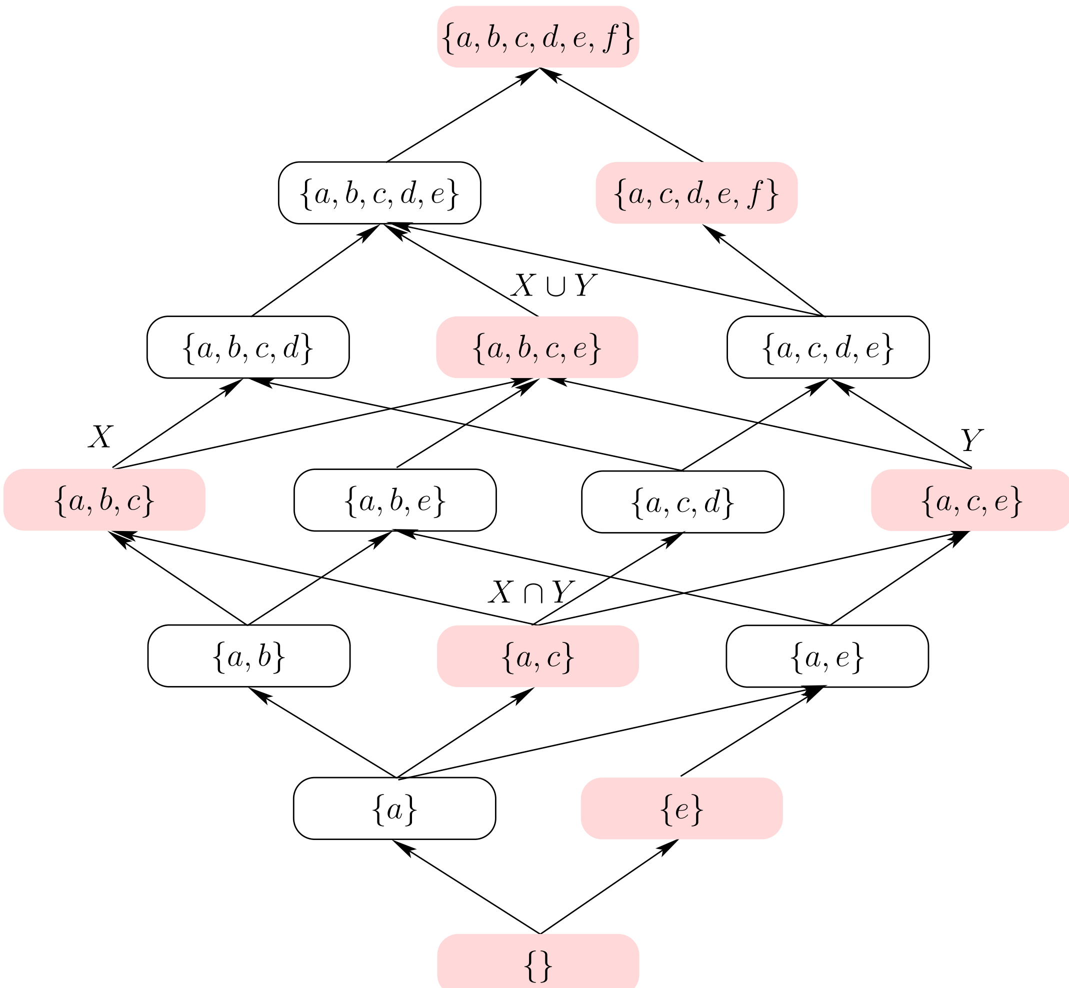
A distributive lattice can be **recovered exactly** from the set of its join-irreducible elements



$\Longleftrightarrow$



What about a Subset of Consistent Cuts?



X in subset and
Y in subset

$\Rightarrow$

$X \cap Y$ in subset and
$X \cup Y$ in subset

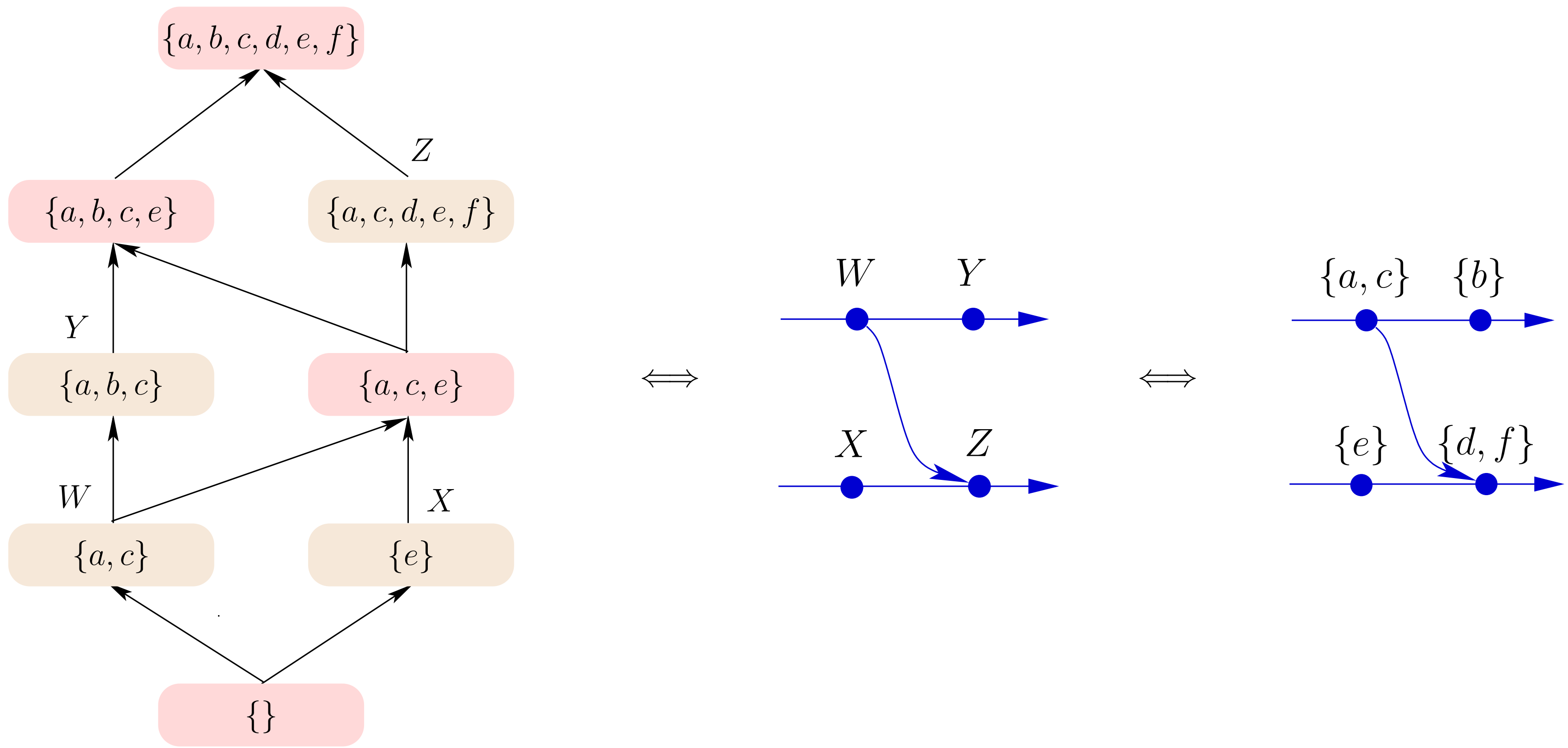
sublattice: subset of consistent cuts closed under intersection and union

Representing a Sublattice

A sublattice of a distributive lattice is also a **distributive lattice**

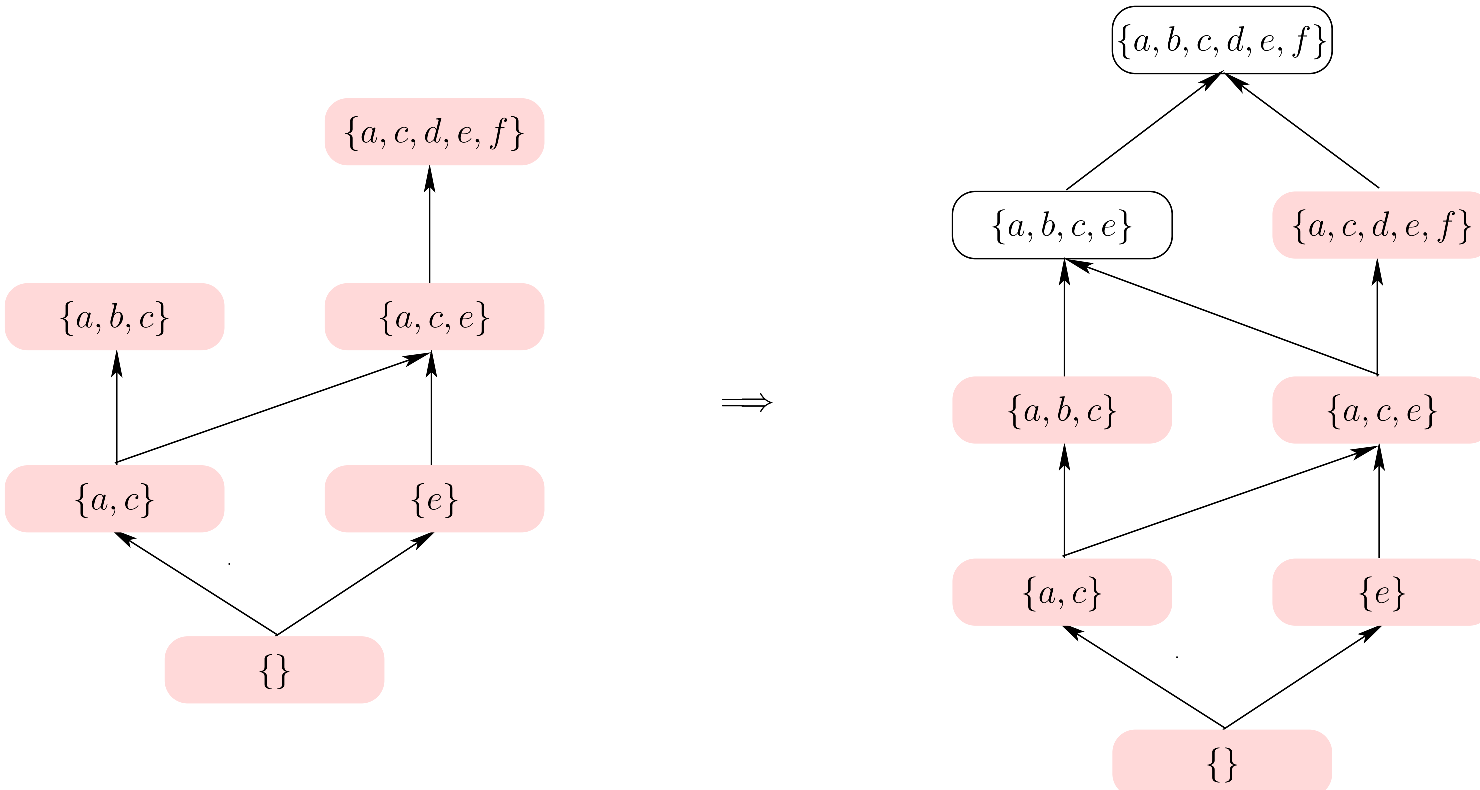
$\Rightarrow$

A sublattice has a **succinct representation**



What if the Subset is not a Sublattice?

Add consistent cuts to complete the sublattice



Computing the Slice

Algorithm:

(1) Find all consistent cuts that satisfy the predicate

(2) Add consistent cuts to complete the sublattice

(3) Find the basis elements of the sublattice

Can we find the basis elements without computing the sublattice?

Regular Predicate

regular predicate: the set of consistent cuts satisfying the predicate is closed under intersection and union [Garg and Mittal 01]

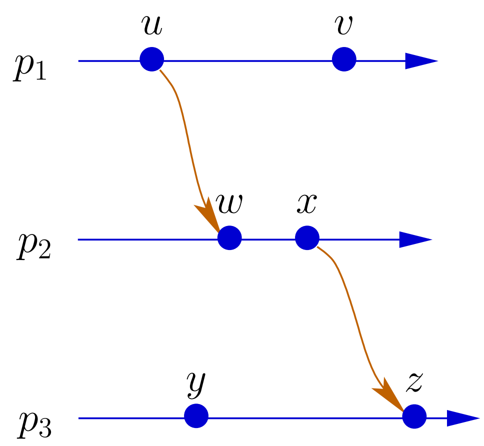
Examples:

- conjunctive predicate—conjunction of local predicates
- there are at most (or at least) k messages in transit from process i to process j
- every "request" message has been "acknowledged" in the system

The class of regular predicates is *closed* under conjunction:

If b_1 and b_2 are regular predicates then so is $b_1 \wedge b_2$

Computing the Slice for Regular Predicate



$b =$ "no messages in transit"

Algorithm:

Step 1: Compute the least consistent cut L that satisfies b

$L = \{\}$

Step 2: Compute the greatest consistent cut G that satisfies b

$G = \{u, v, w, x, y, z\}$

Computing the Slice for Regular Predicate

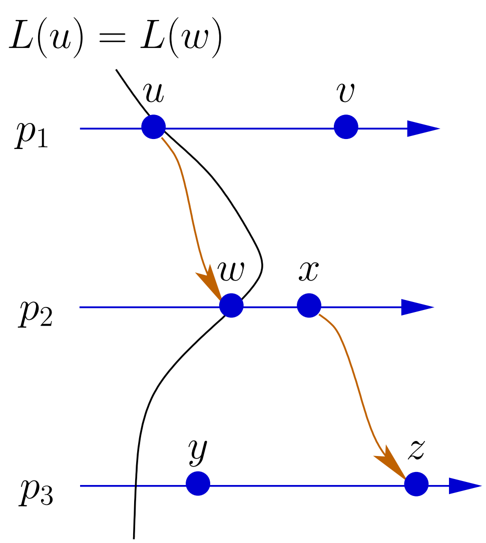
Algorithm:

Step 3: For every event $e \in G - L$, compute $L(e)$ defined as:

(1) $L(e)$ contains e

(2) $L(e)$ satisfies b

(3) $L(e)$ is the least consistent cut satisfying (1) and (2)



$L(u) = \{u, w\}$
$L(v) = \{u, v, w\}$
$L(w) = \{u, w\}$ (duplicate)
$L(x) = \{u, w, x, y, z\}$
$L(y) = \{y\}$
$L(z) = \{u, w, x, y, z\}$ (duplicate)

Results

Efficient polynomial-time algorithms for computing the slice for:

- **regular predicate:** [Garg and Mittal 01]

  time-complexity:

  – general: $O(n^2m)$

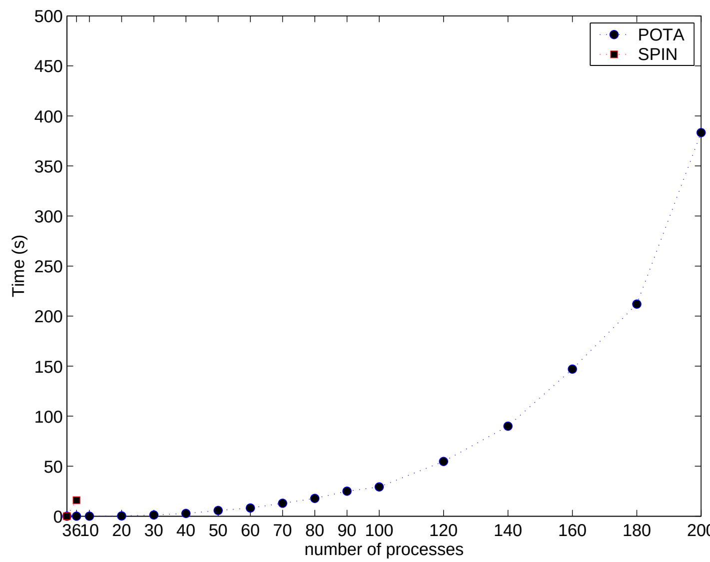
  – special cases (e.g., conjunctive predicate): $O(m)$

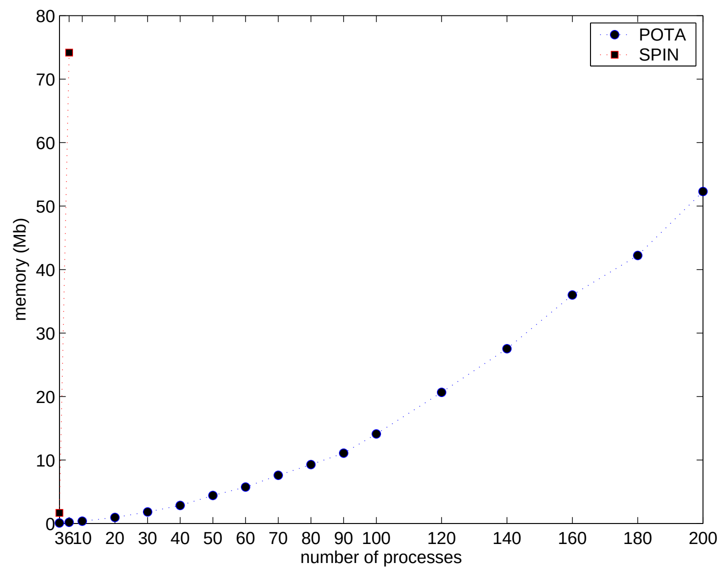
- **general predicate:**
  Theorem: Given a computation, if a predicate b can be detected efficiently then the slice for b can also be computed efficiently. [Mittal, Sen and Garg 02]

n: number of processes
m: number of events

Experimental Evaluation: Dining Philosophers Verification

POTA: Partial Order Trace Analyzer (based on slicing) [Sen and Garg 03]
SPIN: A widely used model checking tool [Holzmann 97]





SPIN: 250 seconds for n = 6, runs out of memory for $n > 6$.
POTA: can handle n= 200. Used 400 seconds.
Predicate: Two neighboring dining philosophers do not eat concurrently

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Motivation for Control

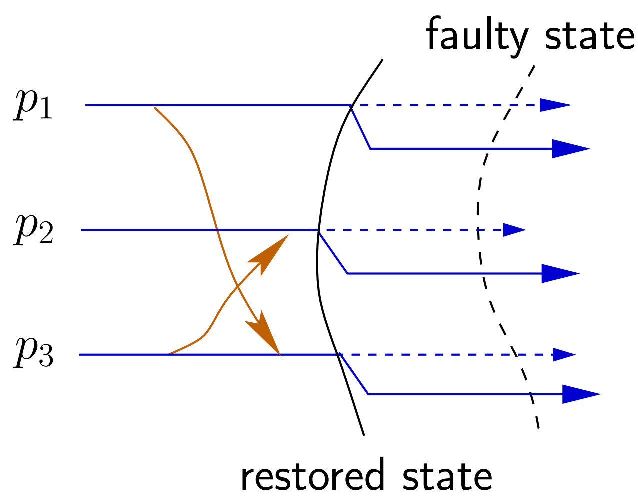
Who controls the past controls the future, who controls the present controls the past...

George Orwell,

Nineteen Eighty-Four.

- maintain global invariants or proper order of events
  Examples: Distributed Debugging
  - ensure that $busy_1 \vee busy_2$ is always true
  - ensure that m_1 is delivered before m_2
- Resource Allocation
  - maintain $\neg CS_1 \vee \neg CS_2$
- Fault tolerance
  - On fault, rollback and execute under control
- Adaptive policies

Rollback Recovery for Software Faults

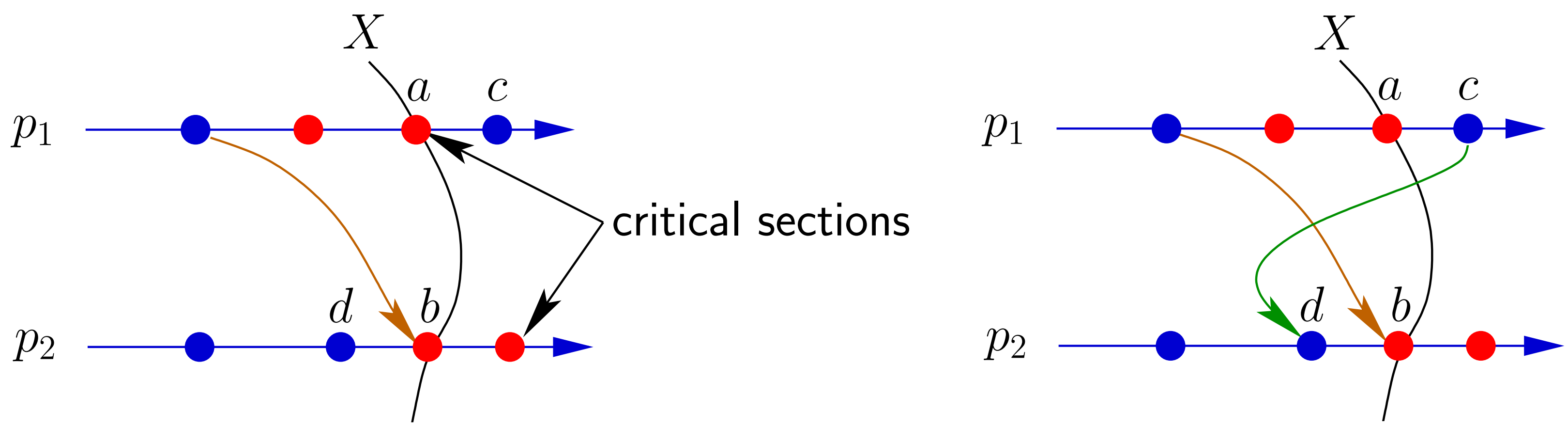


Re-execution Problem:

To re-execute in order to avoid a recurrence of a previously detected failure

- Progressive Retry [Wang *et al* 97]
- Controlled Re-execution [Tarafdar and Garg 98]

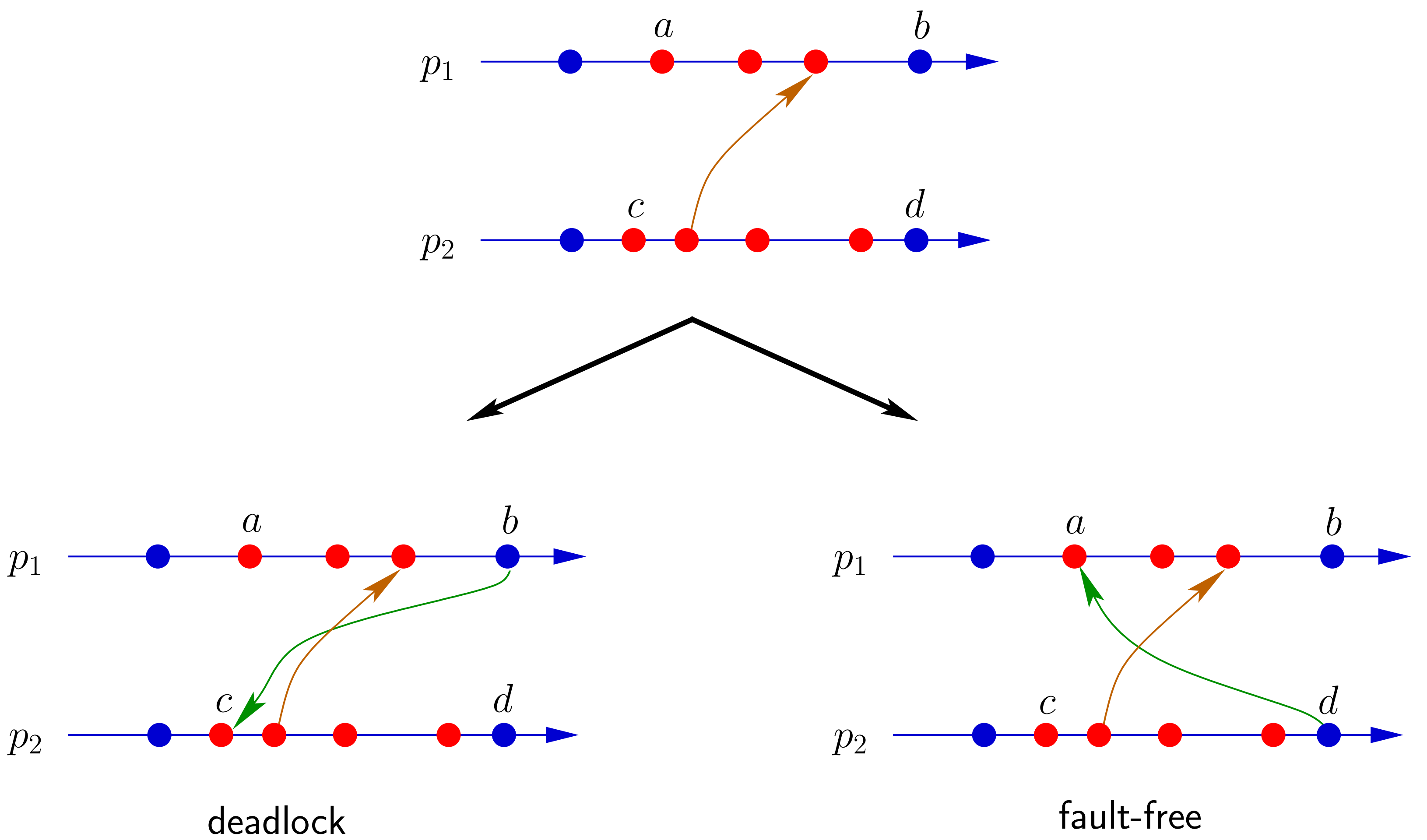
Controlled Re-execution



Add the synchronization necessary to maintain safety property

e.g., mutual exclusion

The Main Difficulty



Results

Efficient algorithms for computing the synchronization for:

- **Locks** [Tarafdar and Garg 98]
  - *time-complexity:* $O(nm)$
- **disjunctive predicate** [Mittal and Garg 00]

  e.g., $(n-1)$-mutual exclusion
  - *time-complexity:* $O(m^2)$
  - minimizes the number of synchronization arrows
- **region predicate** [Mittal and Garg 00]

  e.g., virtual clocks of processes are "approximately" synchronized
  - *time-complexity:* $O(nm^2)$
  - maximizes the concurrency in the controlled computation

n: number of processes, m: number of events

Ongoing and Future Work

- Predicate Detection: Temporal logic predicates (Anurag Agarwal), Online relational predicates (Selma Ikiz)
- Slicing: Distributed and online algorithms (Vinit Ogale)
- Predicate Control: Controlling message order (Arindam Chakraborty)
- Model Checking: Based on predicate detection and slicing (Sujatha Kashyap)

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