Observation and Control for Debugging Distributed Computations

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Outline of the talk

- Introduction: our model
- Observation: Main ideas
  - Lack of shared clock
  - Lack of shared memory
  - Combinatorial Explosion
- Observation: Algorithms
  - WCP algorithm, Channel predicates
  - Detecting regular expressions
- Control
  - Delaying events: offline
  - Delaying events: online
  - Controlling order: offline
  - Controlling order: online
Characteristics of Distributed Systems

- Lack of shared clock
  - order of events partial

- Lack of shared memory
  - meaning of global state
  - need messages for observing "global state"

- Multiple processes
  - Combinatorial explosion
  - non-determinism

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Model of a Distributed Program

- messages: asynchronous, reliable, no FIFO assumption
- no shared clock or memory
- local states
- Lamport’s causally precede relation, concurrency relation

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Motivation for Observation

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

- **Distributed Debugging, Testing**
  - stop when the predicate $q$ is true
    - predicate $q = (P1 \text{ is in critical section}) \text{ and } (P2 \text{ is in critical section})$.
  - 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
Lack of shared clock

- Problem: define truthness of the predicate $CS_1 \wedge CS_2$
  - based on real time
  - based on causality

- Real-time considered harmful in distributed system.
  - My clock synchronization algorithm achieves 10 ms
  - programs should work independent of processor speeds

- Reject linear time, accept vector time
  - Lamport 78, Fidge 89, Mattern 89
  - Simultaneity vs Concurrency
Clock in a Distributed System

- Property: $s \rightarrow t$ iff $s.v < t.v$.  

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Lack of shared state

• consistent global state
  • if the receive of an event is recorded, then send must be recorded
Camera: Chandy and Lamport’s Algorithm

- Algorithm to compute a snapshot of a computation: $S^*$
  - $S^*$ is a possible global state in the computation
- Stable predicate: once true stays true
  - e.g. termination detection, deadlock detection
- To monitor stable predicates: repeatedly take the snapshots
- Disadvantages of CL Algorithm for predicate detection
  - Not useful for unstable predicates
  - Does not return the first cut
  - How often should the snapshot be taken?
  - Assumes FIFO

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Unstable Predicates

- Multiple timed executions consistent with one run
Two interpretations of predicates

- Two modalities: [Cooper and Marzullo 91], [Garg and Waldecker 91]
  - Possibly: \( q \) (also called weak predicates)
    - exists a path from the initial state to the final state along which \( q \) is true on some state
  - Definitely: \( q \) (also called strong predicates)
    - for all paths from the initial state to the final state \( q \) is true on some state
Communication Complexity

- Consider evaluation of the predicate $q(x_1, x_2)$
  - only $P_1$ knows all the values taken by $x_1$
  - only $P_2$ knows values taken by $x_2$
  - Is $q(x_1, x_2)$ true for some value of $x_1$ and $x_2$?

- Key question: number of values that need to be communicated
  - one value per internal event, or
  - one value per external event
Monotonicity

• Definition
  - Assume $x_1$ takes values from a totally ordered set
  - $q$ is monotone w.r.t. first argument if
    \[ \forall a, b, x_2 : (a < b) \Rightarrow (q(a, x_2) \Rightarrow q(b, x_2)) \]

• Examples
  - $q = (x_1 > x_2)$: monotonic w.r.t $x_1$ and $x_2$
  - $q = l_1 \wedge l_2$: monotonic
  - $q = (x_1 = x_2)$: not monotonic.
Multiple Processes

- Intractability of the Global Predicate Detection Problem
  - Given: an execution $S$ of $N$ processes, $N$ variables $x_1, \ldots, x_N$, and a predicate $q$ defined on $x$.
  - Is there a consistent cut $G \in S$ such that $q(G)$ is true.

- Theorem [Chase and Garg '95]: The predicate detection problem is NP-Complete.
  - Proof: By reduction from SAT $\left( (x_1 \lor \bar{x}_2 \lor x_3) \land (\bar{x}_1 \lor x_2) \land \ldots \right)$

\[ x_1 \quad \begin{array}{c} 0 \quad 1 \end{array} \]
\[ x_2 \quad \begin{array}{c} \circ \quad \circ \end{array} \]
\[ x_3 \quad \begin{array}{c} \circ \quad \circ \end{array} \]
Linearity

Forbidden predicate: forbidden(G,i) iff
\[ \forall H : G \leq H : (G[i] = H[i]) \Rightarrow \neg q(H) \]

Predicate \( q \) is linear w.r.t. a computation \( S \) if
\[ \forall G : \neg q(G) \Rightarrow \exists i : \text{forbidden}(G,i) \]

Examples
- \( l_1 \land l_2 \land ... \land l_n \)
- \( x + y \geq k \), \( x \) is non-increasing
- channel is empty

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### Summary of Observation: Problems and Solutions

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Cooper and Marzullo’s Algorithm

- **Possibly:** \( p \)
  - construct the lattice of global states, check each global state for truthness of \( p \)

- **Definitely:** \( p \)
  - for all paths from the initial state to the final state \( p \) is true on some state
  - construct the lattice of global states
  - remove states satisfying \( p \)
  - Is last state reachable from the initial state

- **Complexity:** \( O(k^n) \) where
  - \( k \): Number of local states per process
  - \( n \): Number of processes
Weak Conjunctive Predicates

- WCP $\equiv$ Possibly: $l_1 \land l_2 \land \ldots \land l_n$
- useful for bad or undesirable predicates
  - Example: the classical mutual exclusion problem.
  - Example: (John is sleeping) and (Mary is sleeping) and (Robert is sleeping)
- detect errors that may be hidden in some run due to race conditions.
Importance of Weak Conjunctive Predicates

- Sufficient for detection of any boolean expression
  - which can be expressed as a disjunction of a small number of conjunctions.
  - Example $x, y$ and $z$ are in three different processes. Then,
    \[
    \text{even}(x) \land ((y < 0) \lor (z > 6))
    \]
    \[
    \equiv
    \]
    \[
    (\text{even}(x) \land (y < 0)) \lor (\text{even}(x) \land (z > 6))
    \]

- the global predicate is satisfied by only a finite number of possible global states.
  - Example, $x$ and $y$ are in different processes.
    - $(x = y)$ is not a local predicate
Conditions for Weak Conjunctive Predicates

- Possibly \((l_1 \land l_2 \land \ldots \land l_n)\) 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 \(i, j\).

- Key problems and solutions
  - number of states satisfying local predicates may be large: Use monotonicity (at most one state per message)
  - combinatorial explosion when combining them together: Use Linearity

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Weak Conjunctive Predicates: Centralized Algorithm

- Each non-checker process maintains its local *vector*
  - send to the checker process the vector clock whenever
    - local predicate is true
    - at most once in each message interval.
  - **Optimization:** Sufficient to send the vector once after each message is sent

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Checker Process

- **Steps**
  - Begin with the initial global state
  - Eliminate any state that happened before any other state along the current cut.
- **Predicate true for the first time**
  - if no states can be eliminated.
- **Predicate false**
  - if we eliminate the final state from any process
Overhead: Non-checker processes

- **Space complexity**
  - the array vector: \( O(n) \).

- **Message complexity**
  - \( O(m_s) \) where \( m_s \) is the number of program messages sent.
  - In addition, program messages have to include time vectors.

- **Time complexity**
  - detection of local predicates
  - maintain vector clock \( (O(n)/message) \).
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]
Disadvantages of above algorithm

- Centralized
  - Checker process may become a bottleneck
- Space requirements
  - Queues at the checker process may grow large
- Message complexity
  - may result in too many additional messages
Other WCP algorithms

- token based algorithm [Garg and Chase 95]
  - eliminate centralized checker process
- Completely distributed algorithm [Garg and Chase 95]
  - Uses Scholten and Dijkstra’s termination detection
- Distributed Offline-algorithm [Venkatesan and Dathan 92]
  - assume FIFO and off-line
- Keeping queues shorter [Chiou and Korfhage 95]
  - eliminate vectors that are useless
- Avoiding control messages[Hurfin, Mizuno et al 96]
  - piggyback info/token with application messages
Channel Predicates: Observing hallways

- Many properties require channels
  - termination detection: all processes are idle and all channels are empty

- A channel predicate: a boolean function on the state of the channel
  - uni-directional
  - memoryless. i.e. channel state = sequence of messages sent - set of messages received

- Linearity: Given any channel state in which the predicate is false, then
  - cannot be made true by sending more messages without receiving any messages, or
  - cannot be made true by receiving more messages without sending any messages.
Linear Channel Predicates

- Empty channels
  - If false, then it cannot be made true by sending more messages,

- Channel has exactly three red messages
  - If less than three, then it cannot be made true by receiving more messages,
  - If more than three, then it cannot be made true by sending more messages,
Non-linear Channel Predicates

- Channel has an odd number of messages

- Key result: \( \text{linearity} = \text{first cut is well defined} \)
Relational Predicates

- $k$: tokens corresponding to $k$ resources in the system
  - $x_i$: number of token at $P_i$
  - $\sum x_i < k$: loss of tokens
  - $\sum x_i > k$: License violation problem

- Predicate, global function
  - $\exists G : \text{consistent}(G) : \sum_{s_i \in G} s_i \cdot x_i < K$
  - $\min G : \text{consistent}(G) : \sum_{s_i \in G} s_i \cdot x_i$

- Ideas:
  - max-flow technique: [Chase and Garg 95]
  - Matrix clocks: detect predicate of the form $x_1 + x_2 < k$ [Tomlinson and Garg 93]
  - Use Dilworth's theorem: [Tomlinson and Garg 96]
Other Algorithms

- Conjunction of global predicates
  - Example: \((x_1 = x_2) \land (x_3 > x_4)\)

  Stoller and Schneider 95, Garg and Mitchell 96

- Notion of fixed set [Stoller and Schneider 95]
  - set of variables such that on fixing them we get a WCP
  - fix \(x_1 = 4\) and \(x_4 = 6\), we get \((4 = x_2) \land (x_3 > 6)\)
  - evaluate all WCP obtained by using all values of fixed-set.

- Definitely True predicates
  - strong conjunctive predicates [Garg and Waldecker 93]
Causal Predicates

- Predicate based on control flow
  - useful for expressing and observing the flow of information.

- Early work
  - sequence of local predicates [Miller and Choi 88]
    - $l_1 \rightarrow l_2 \rightarrow \ldots l_m$.

- regular expression of local predicates [Fromentin, Raynal, Garg, Tomlinson 94]
Detection of Regular Expression

- Example of a regular expression?
  - $a + cb^*c$

- A regular expression is true in a run iff there exists a path in the run (poset) which matches the expression.

- Complexity of problem
  - Many states
  - Many paths per state
  - Many strings per path
Algorithm

- Regular expression: $a + cb^c$
- convert it to non-deterministic finite state machine (fsm)
- simulate it during the execution (piggybacking state of the fsm)
  - keep $z[1..m]$ with each process
  - $z[i] = 1$ iff there exists a causal path that takes the fsm to state $i$.

![Finite State Machine Diagram]

- Define one bit for each state

  $z_1 := \text{init}$
  $z_2 := (c \land \diamond z_1) \lor (b \land \diamond z_2)$
  $z_3 := (a \land \diamond z_1) \lor (c \land \diamond z_2)$
Other Approaches

- DAG patterns of local predicates [Garg, Tomlinson, Fromentin, Raynal 95]
- Atomic Sequences [Hurfin, Plouzeau, Raynal 93]
  - $l_i[r_i]l_{i+1}$
  - $r_i$ does not occur between $l_i$ and $l_{i+1}$
- Dynamic Properties [Babaoglu and Raynal 95]
  - Generalization of atomic sequences
- Event Normal Form [Chiou and Korfhage 94]
  - sequences of conjunctive predicates
- Recursive Poset Logic [Tomlinson and Garg 95]
  - Recursive combination of sequencing, conjunction, and linear predicates
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 $busy_1 \lor busy_2$ is always true
  - ensure that $m_1$ is delivered before $m_2$
- Resource Allocation
  - maintain $\neg CS_1 \lor \neg CS_2$
- Fault tolerance
  - On fault, rollback and execute under control
- Adaptive policies
  - procedure A (B) better under light (heavy) load
Models for Control

• Is the future known?
  • Yes: offline control
    • applications in distributed debugging, recovery, fault tolerance..
  • No: online control
    • applications: global synchronization, resource allocation

• Delaying events vs Changing order of events
  • supervisor simply adds delay between events
  • supervisor changes order of events
Delaying events: Offline control

- Maintain at least one of the process is not red
- Can add additional arrows in the diagram
- the control relation should not interfere with existing causality relation
  - otherwise, the system deadlocks
Delaying events: Offline control

- **Problem:**
  - **Instance:** Given a computation and a boolean expression $q$ of local predicates
  - **Question:** Is there a non-interfering control relation that maintains $q$

- **This problem is NP-complete** [Tarafdar and Garg 97]
Delaying events: disjunctive predicates

- Efficient algorithm for disjunctive predicates
  - Example: at least one of the philosopher does not have a fork
  - Result: a control strategy exists iff there is no set of overlapping false intervals
    - \( \text{overlap}(I_1, I_2) = (I_1.\text{lo} \rightarrow I_2.\text{hi}) \land (I_2.\text{lo} \rightarrow I_1.\text{hi}) \)
  - Result: There exists an \( O(n^2m) \) algorithm to determine the strategy
    - \( n = \text{number of processes} \)
    - \( m = \text{number of states per process} \)
Delaying events: Online control

- Only the past is known
  - deadlock is impossible to avoid

Assume: a process cannot block when its local predicate is false
  - maintaining $l_1 \lor l_2 \lor \ldots \lor l_n$ is equivalent to $n - 1$ mutual exclusion problem
    - in CS = local predicate false
  - i.e., all $n$ processes cannot be in the CS
  - can be solved using token which is a liability rather than privilege
Controlling order: Offline control

- **Problem:** Given a computation enforce an order of messages in a repeated run
  - **Same order**
    - Replay of distributed execution (distributed debugging)
    - need to store messages or message order
  - **Different order**
    - Testing of a distributed program [Kilgore, Chase 97]
    - Recovery of a distributed program
    - can change the order of two independent messages
    - the computation may change after first reorder
Controlling order: Online control

- Simple example: FIFO ordering of messages
- External events:
  - invocation of a message
  - send of a message
  - receive of a message
  - delivery of a message
- constraints on supervisor
  - invocation and receive events are uncontrollable
  - liveness requirement
    - if only events possible are send and delivery then at least one must be enabled.
Limitations of Online Supervision

- **Specification:** set of computation possible with a fixed set of messages
  - **Question:** Is there a control strategy to meet the specification?
- **Assumption:** Supervisor can send control messages and tag user messages
  - Control possible iff specs include all synchronously order computations [Murty and Garg 97]
- **Assumption:** Supervisor can only tag user messages
  - control possible iff specs include all causally ordered computations [Murty and Garg 97]
Online supervision: Algorithms

- Forbidden predicate [Murty and Garg 97]
  - sub-structure that is not allowed in the computation
  - Example 1: Causal ordering
    - $\exists x, y : (x.s \rightarrow y.s) \land (y.r \rightarrow x.r)$
  - Example 2: Local forward flush channels
    - $(\text{process}(x.s) = \text{process}(y.s)) \land (\text{process}(x.r) = \text{process}(y.r) \land (\text{color}(x) = \text{red}) \land (x.s \rightarrow y.s) \land (y.r \rightarrow x.r)$

- There exists an algorithm with
  - input: a forbidden predicate
  - output: either ”not possible”, or a protocol to meet specs
Applications to Distributed Debugging

- **Additional command**
  - `do action when condition`
  - Also assume `run` and `rerun`

- **Conditions**
  - boolean predicate on the global state
    - requirement of (semi)-linearity
  - regular expression

- **Actions**
  - `stop pids`
  - `print expressions`
  - maintain boolean predicate
  - maintain order-expression

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Summary

• Observation
  • Use causality instead of time to define ”and”
  • Use monotonicity to reduce communication complexity
  • Global observation is quite efficient for many practical cases
    • linearity for boolean predicates
    • regular expressions of local predicates

• Control
  • desirable for many applications
  • offline vs online has implications on limitations
  • delay vs change of order model
Future Work

- Predicate detection under faulty environment
  - processes, channels or messages may fail
  - messages from different incarnations

- More complex model of control
  - plant variables vs control variables
  - unobservable events, uncontrollable events