Weaving Atomicity Through Dynamic Dependence Tracking

Suresh Jagannathan

joint work with Lukasz Ziarek, Philip Schatz, Jeremy Orlow
Jan Vitek

PURDUE UNIVERSITY

Software Transactions

- Classical concurrency control abstractions using locks requires a great deal of programmer care to ensure correctness and efficiency.
  - deadlocks, priority inversion,etc.
- Transactions can significantly relieve this burden:
  - Provide *serializability* properties
    - *Atomicity*: effects of updates seen all-at-once or not-at-all
    - *Isolation*: transactions appear to execute one-at-a-time
  - API
    - *Start* a transaction
    - *Validate* serializability
      - Commit
      - Abort
    - *Contention management* to schedule transactions in case of conflicts

Composability

- Transactions encourage modular reasoning
  - ★ Unlike lock-based mutual-exclusion, we can reason about transactional behavior without exposing details about:
    - ✦ The order in which transactions execute
    - ✦ The data transactions protect
- Transactions support composability
  - ★ The manner in which transactions are combined does not affect correctness
- What happens when transactions need to communicate in ways that (presumably) break isolation and hinder composability?
  - ★ Producer/consumer pipelines
  - ★ Message-passing primitives (ICFP'06)
  - ★ Exceptions or faults
  - ★ Interaction with lock-based code (ECOOP'06)

Composability

- Not easy to prohibit these violations
  - Violations may be buried under many software layers.
- May be necessary for correctness and performance
  - Naive implementations would block communication until the transaction commits.
- Specific instance of more general question of legacy support
- Open-nested transactions are one alternative
  - Impose an abstract notion of serializability based on higher-level invariants of a concurrent data structure
  - Defining abstract serializability for complex communicating actions is non-trivial
  - It's difficult to reason about composability
    - removing the effect of a message send on a channel may require compensating actions on all behavior that witnessed the send

Pragmatics

- Real programs frequently violate isolation:
  - Apache: 68% (mostly acyclic communication patterns)
  - JavaGrande: 50% (mostly cyclic)
  - Splash: 13% (mixture of both)
- These programs exploit some form of producer/consumer communication pattern within their critical sections.
- Using existing techniques requires either:
  - transforming the code to break cycles, and explicitly order communication actions, or
  - allowing communication in an open-nested transaction:
    - permits producers to notify consumers before the outer transaction completes
    - use compensations to undo actions of sends in aborted outer transactions

Robustness

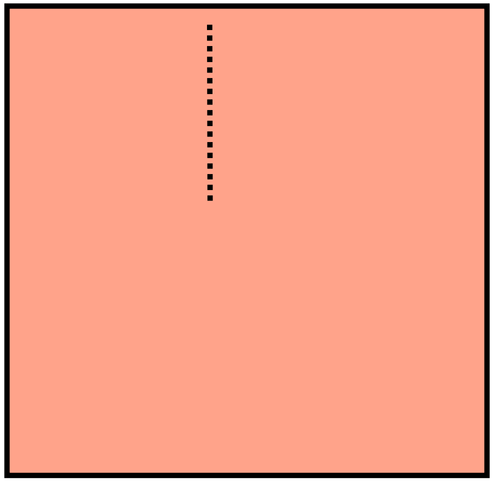
- Once isolation is relaxed, arbitrary actions internal to the transaction may impact global behavior.
  - ★ Consider exceptions or errors within a transaction
  - ★ Or, retry primitives that explicitly abort the transaction
- How do we rationalize visible effects within the transaction that are no longer valid?
  - ★ Reminiscent of a cascading abort model
  - ★ But, how do we keep track of induced dependencies?
  - ★ Can we constrain the scope of influence?
- Hard for applications to encode these dependencies
  - ★ Non-determinism
  - ★ Understanding these dependencies involve reasoning about complex data and control-flow across different threads

Programming Model

- Consider a language with:
  - Closed-nested transactions
    - Retry operations for explicit abort
    - Allow threads to be spawned within transactions
  - Message-passing communication primitives:
    - First-class typed channels
    - Synchronous send and receives
      - Any object (including procedures, references, or channels) can be transmitted along a channel
    - Events and choice (CML)
  - First-class references
- Goal: Devise a precise semantics and implementation for transactional behavior in the presence of channel communication.

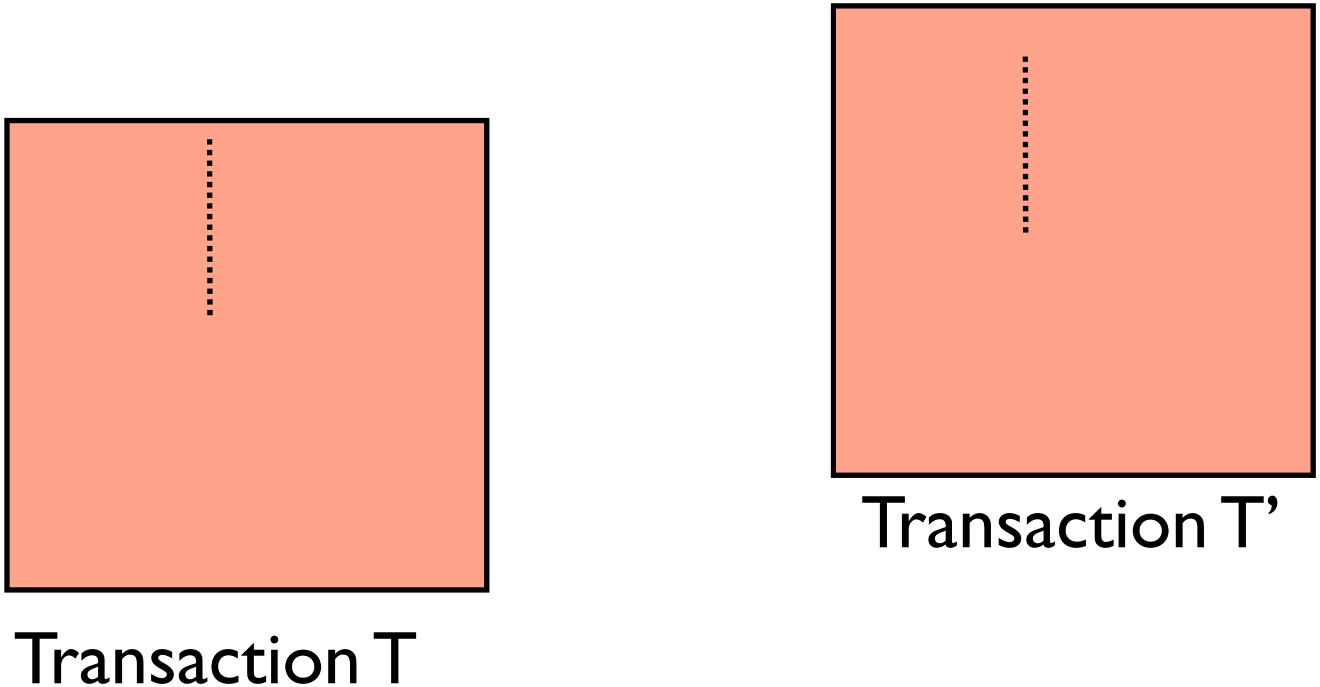
Model

Model

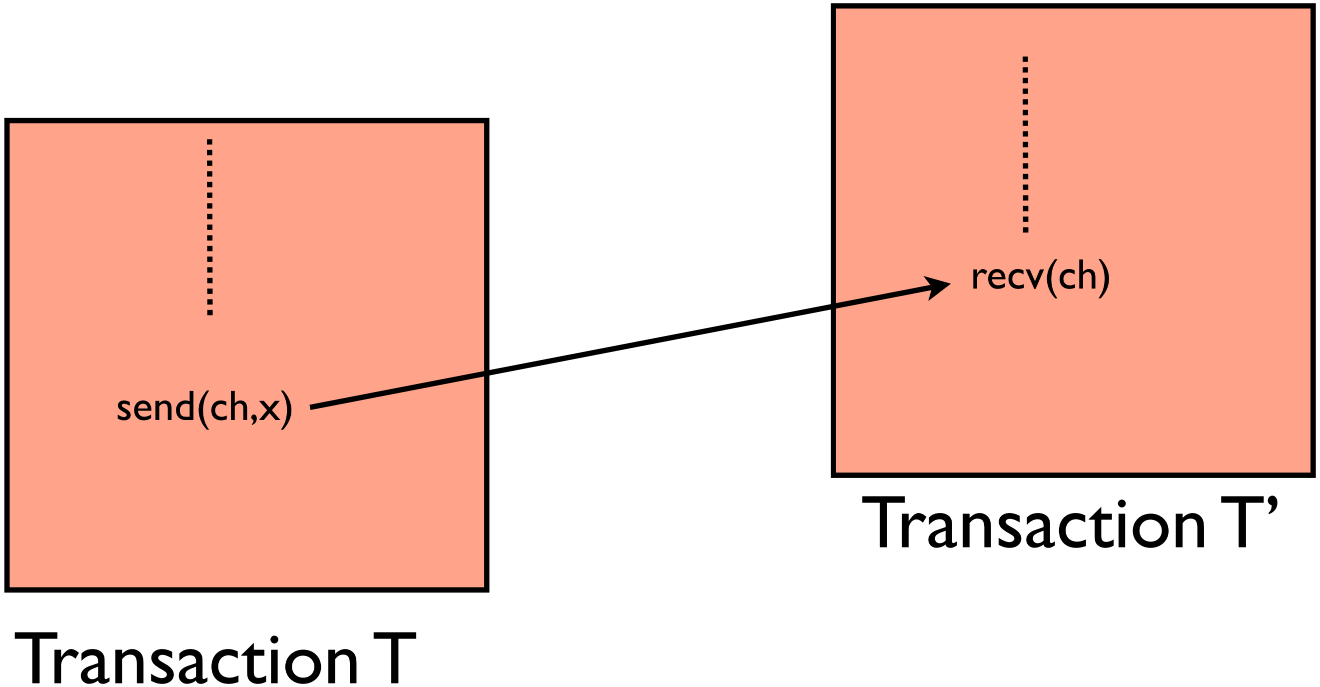


Transaction T

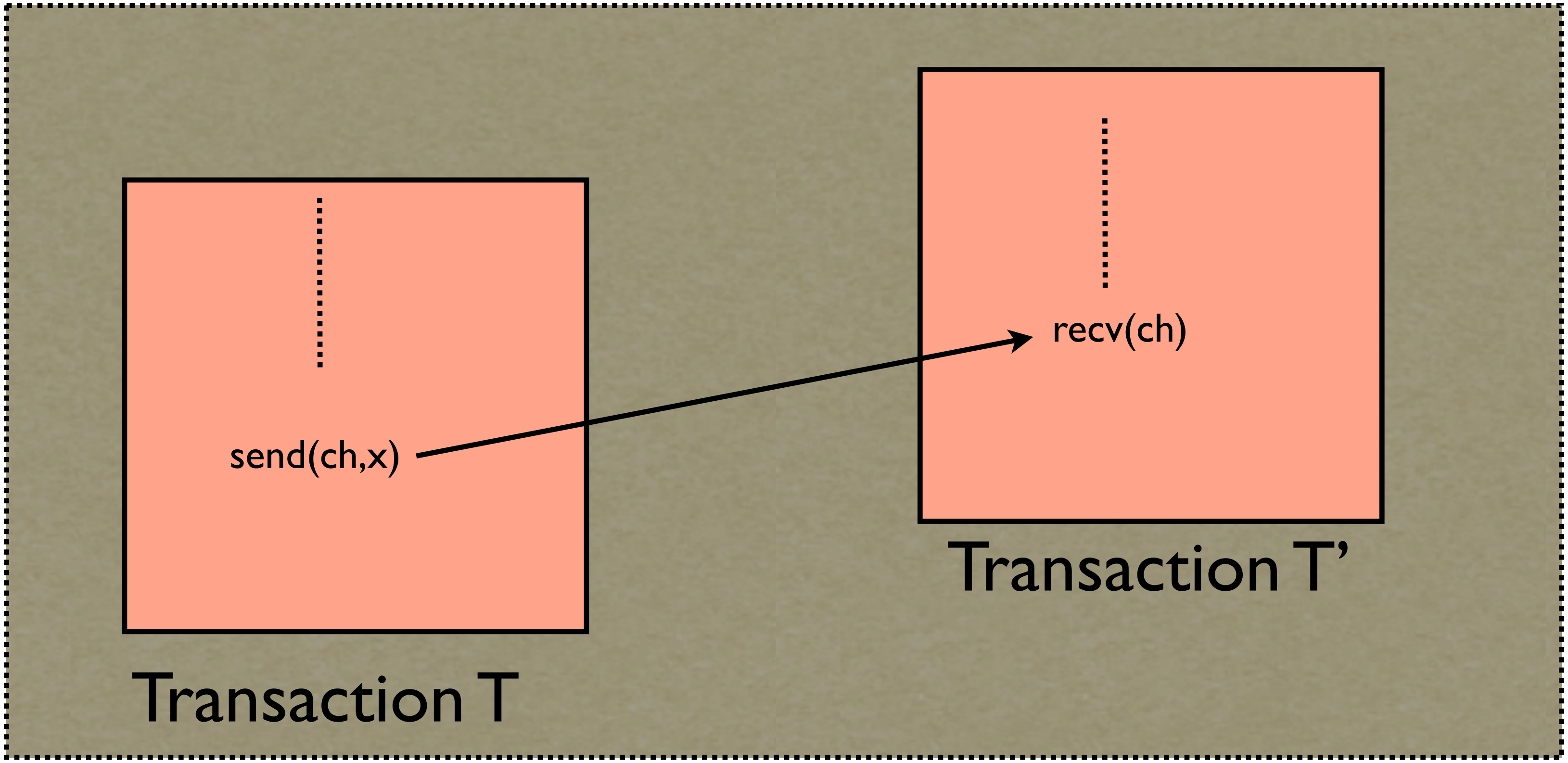
Model



Model

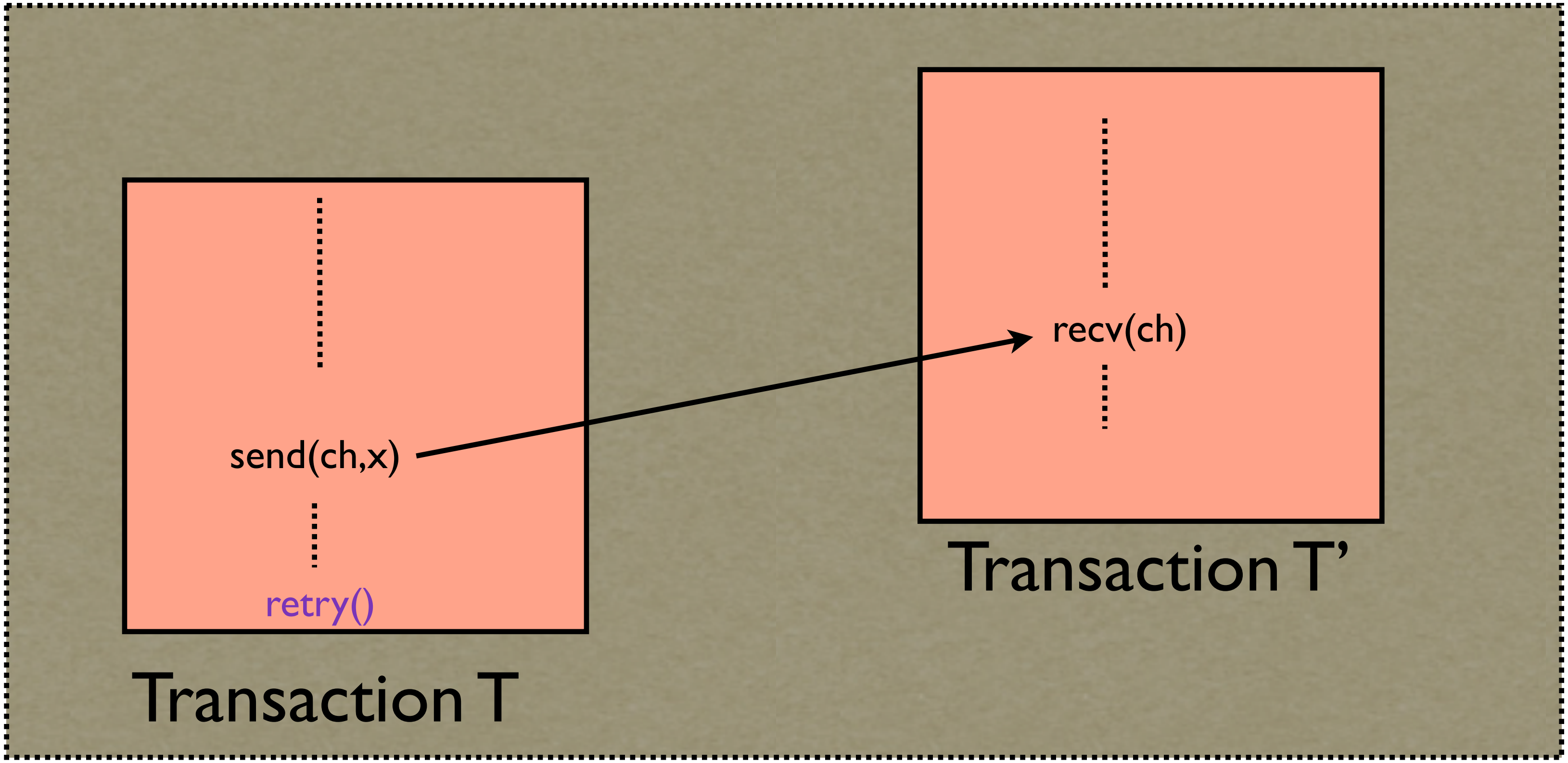


Model



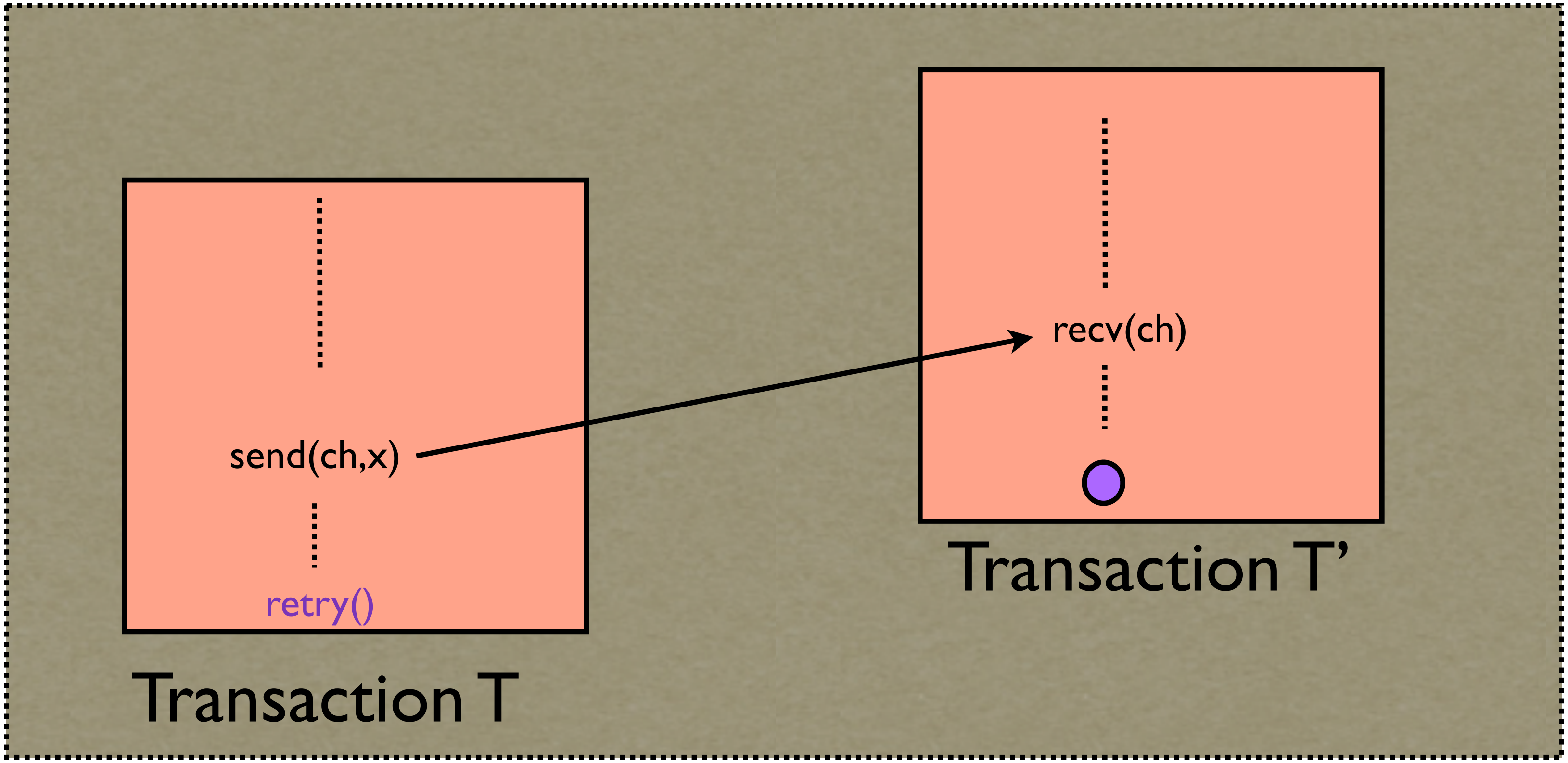
Inter-Transaction Dependency

Model



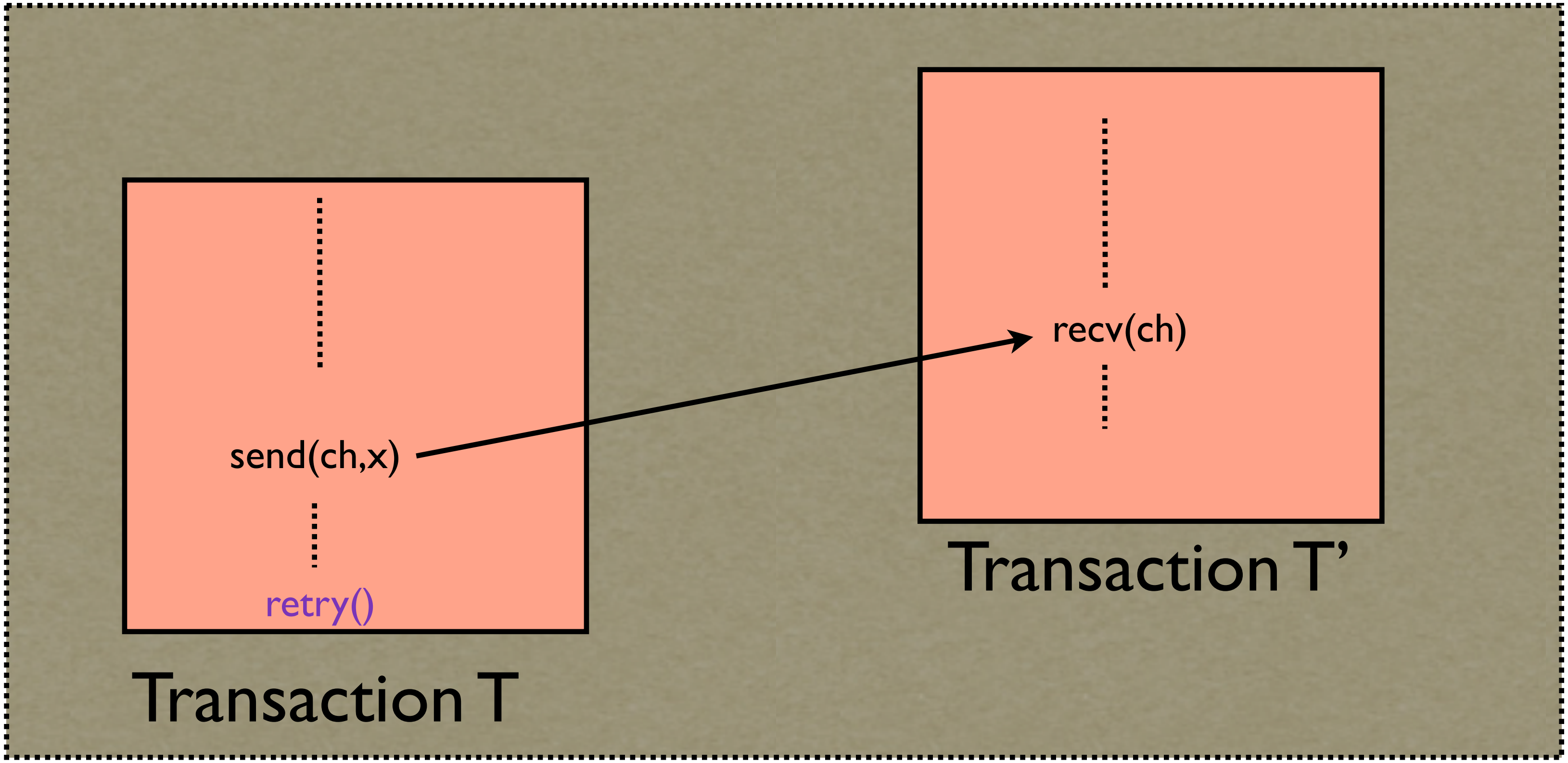
Inter-Transaction Dependency

Model



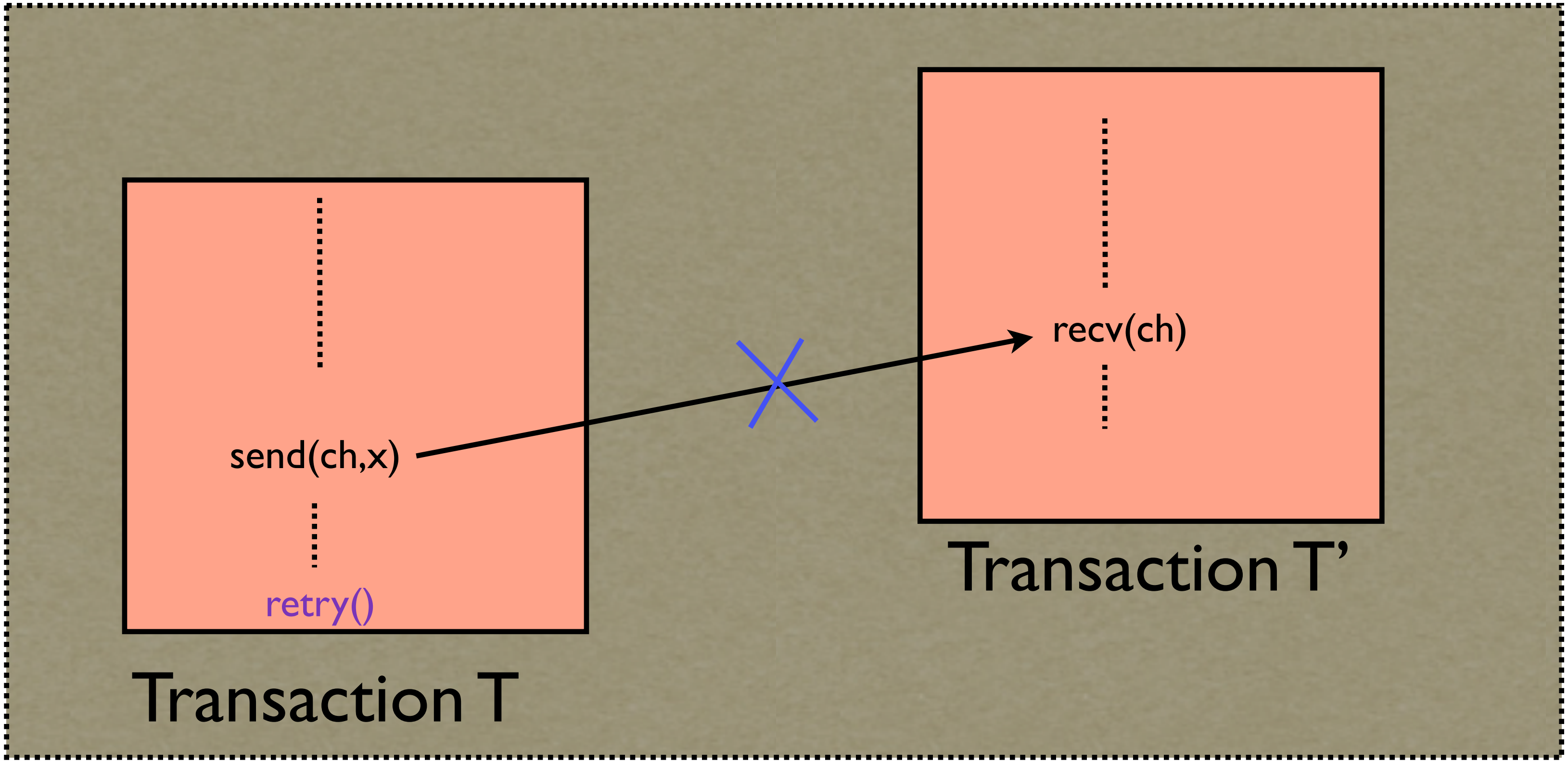
Inter-Transaction Dependency

Model



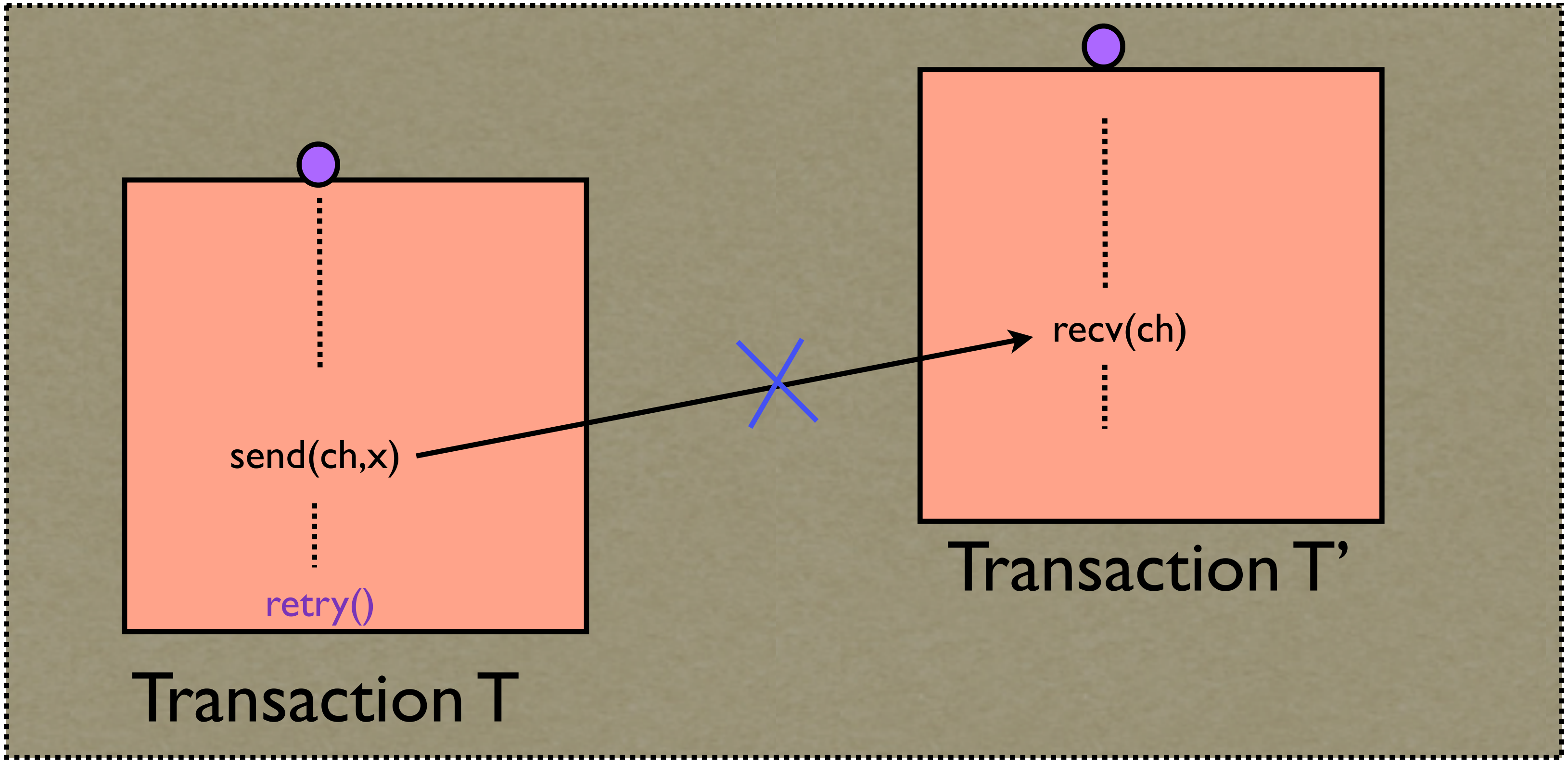
Inter-Transaction Dependency

Model



Inter-Transaction Dependency

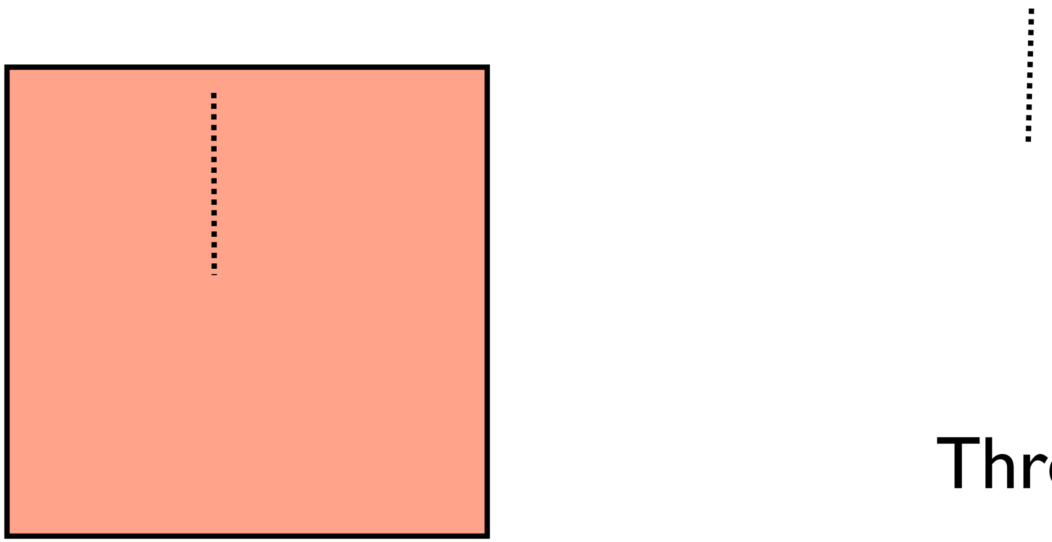
Model



Inter-Transaction Dependency

Interaction with Non-Transactional Code

Interaction with Non-Transactional Code

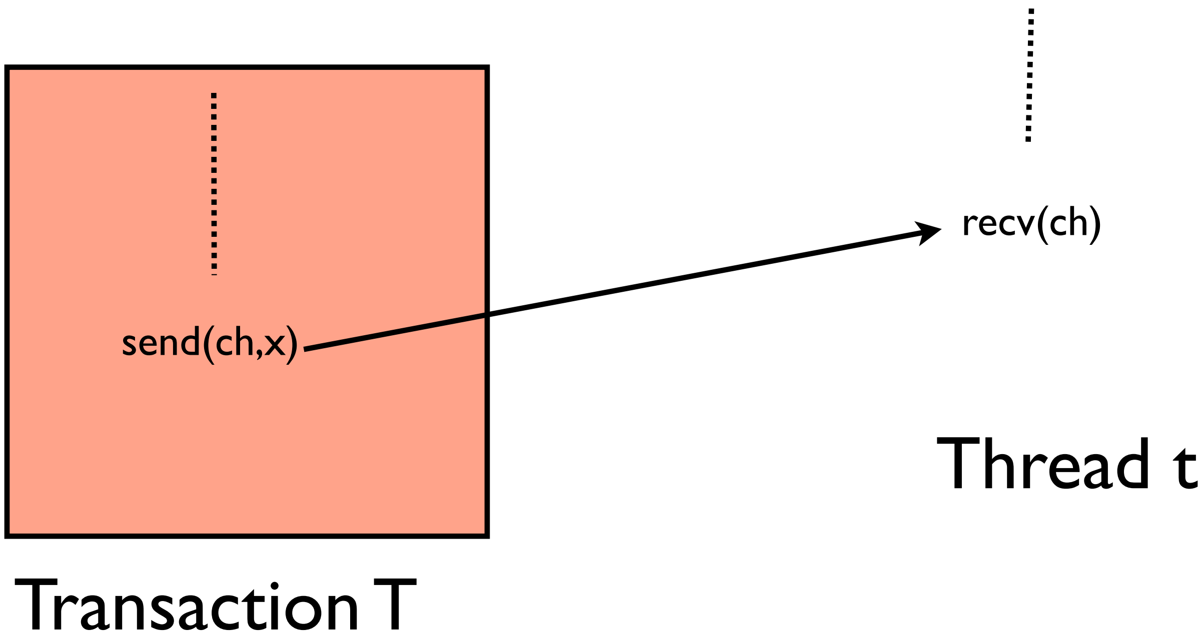


Transaction T

Thread t

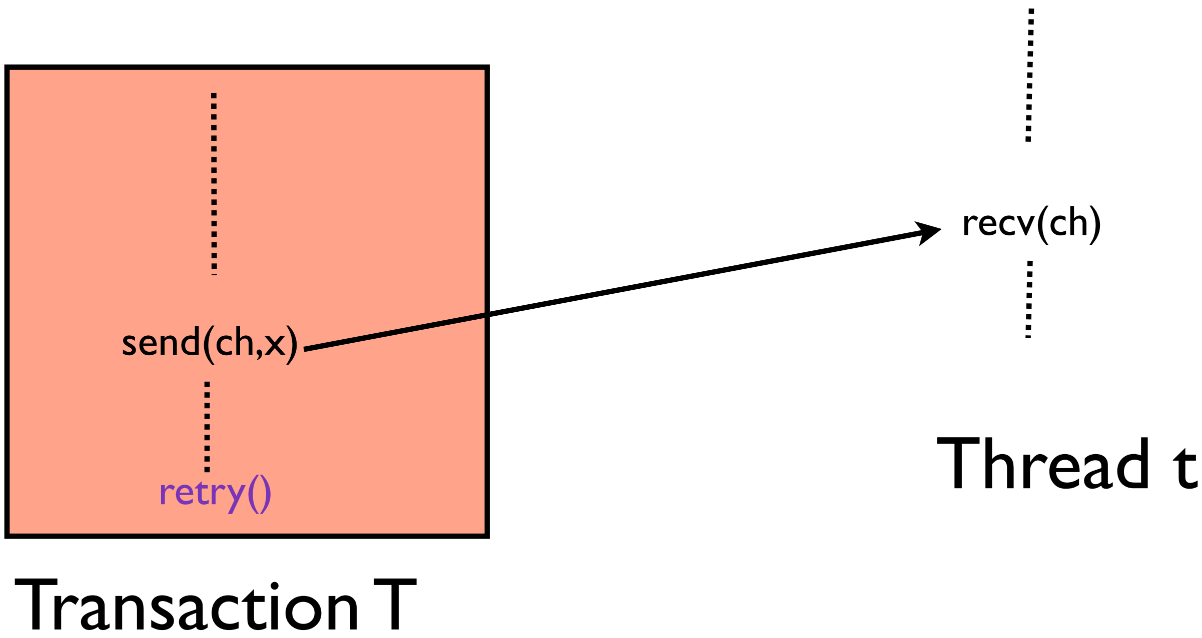
9

Interaction with Non-Transactional Code

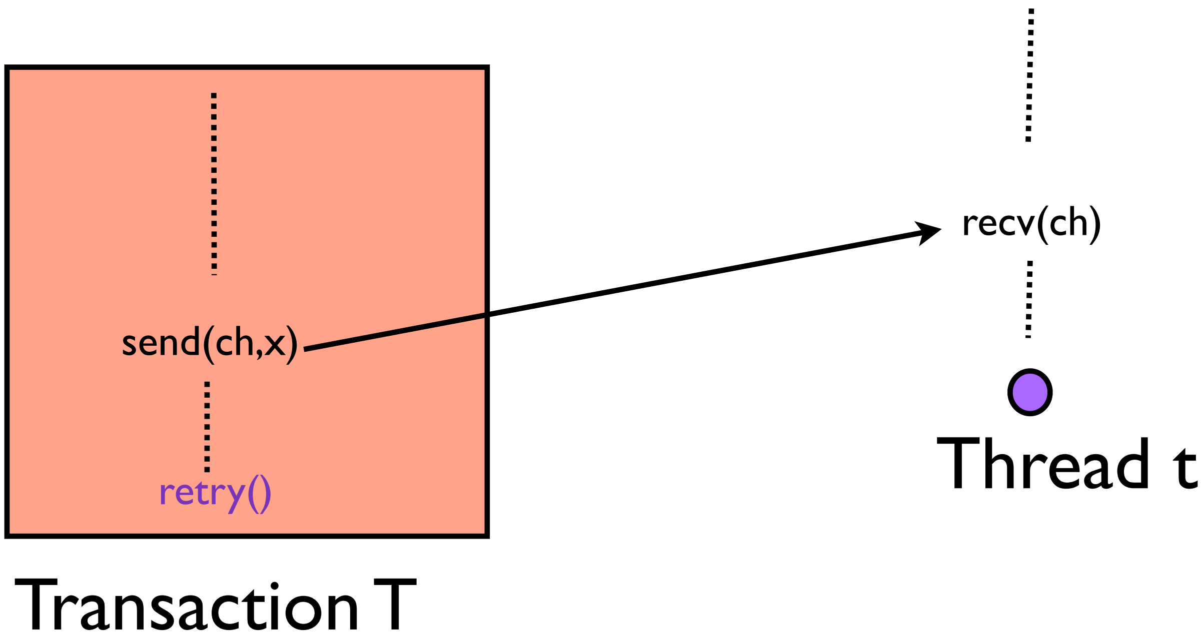


9

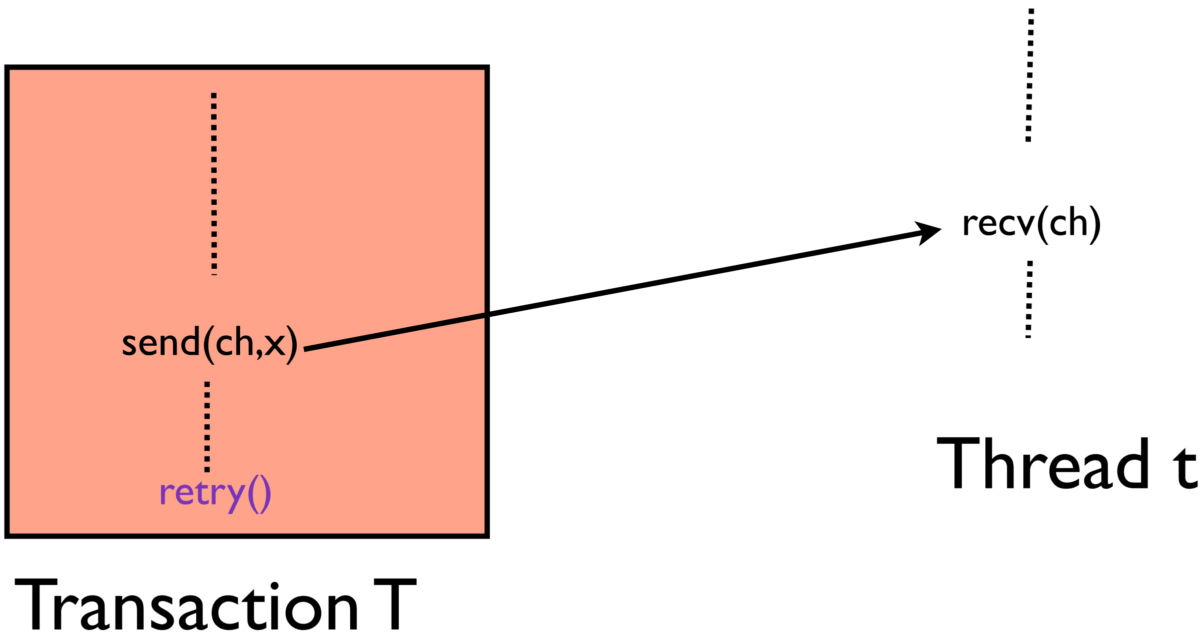
Interaction with Non-Transactional Code



Interaction with Non-Transactional Code

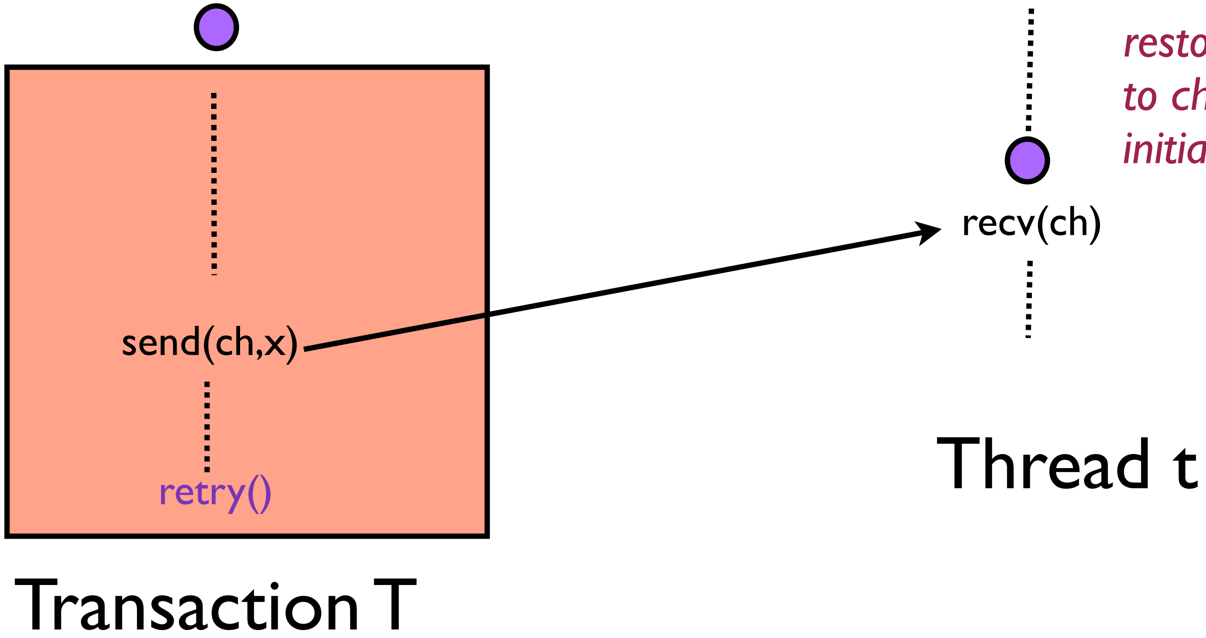


Interaction with Non-Transactional Code



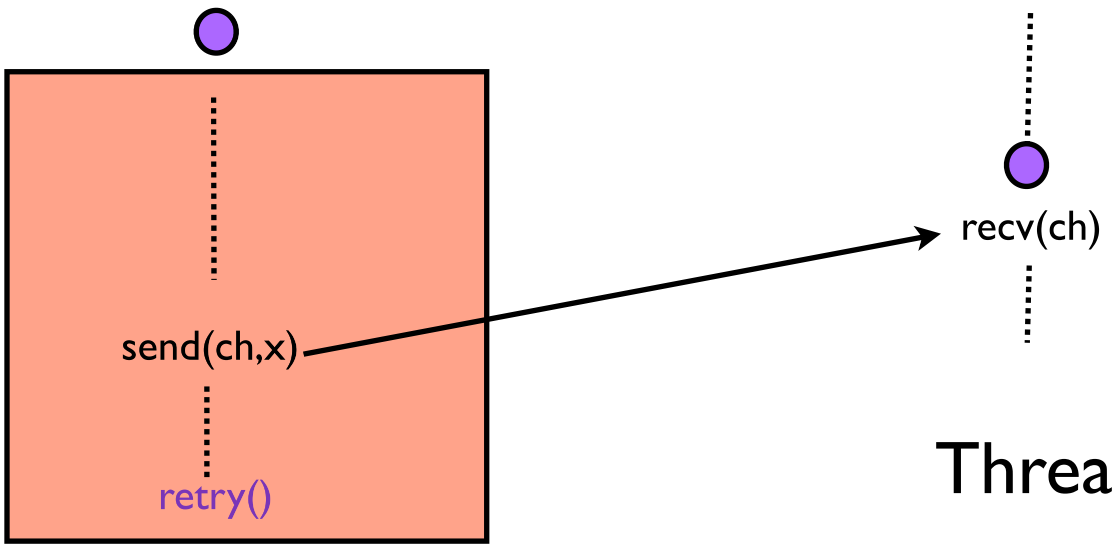
9

Interaction with Non-Transactional Code



restore thread to state prior to channel communication initiated by the transaction

Interaction with Non-Transactional Code



Transaction T

restore thread to state prior to channel communication initiated by the transaction

Thread t

strong atomicity

Semantics

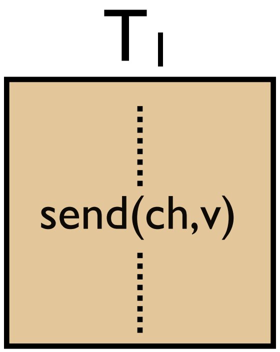
- Transactions that communicate via non-isolated communication actions must commit together
- If any transaction in a group of transactions aborts, the entire group aborts
- Reads and writes to memory still implemented using basic transactional machinery:
  - ★Pessimistic writes
  - ★Optimistic reads
- A transactional group can commit only if each transaction in the group is conflict-free
  - ★Operations performed within a transaction group are serializable with respect to other transactions outside the group.
  - ★Allows progress in the presence of synchronous communication

Observations

- Transactions must still adhere to serializability constraints on memory accesses with respect to other transactions
- Non-isolated actions augment constraints:
  - ★The success of a transaction commit within a transaction group depends on the successful commit of all other transactions within that group
  - ★Non-local reasoning limited to communication actions
- Congruence:

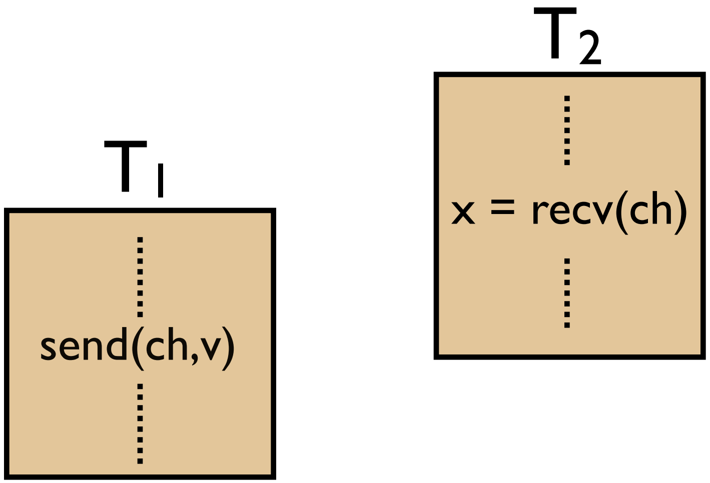
Observations

- Transactions must still adhere to serializability constraints on memory accesses with respect to other transactions
- Non-isolated actions augment constraints:
  - ★The success of a transaction commit within a transaction group depends on the successful commit of all other transactions within that group
  - ★Non-local reasoning limited to communication actions
- Congruence:



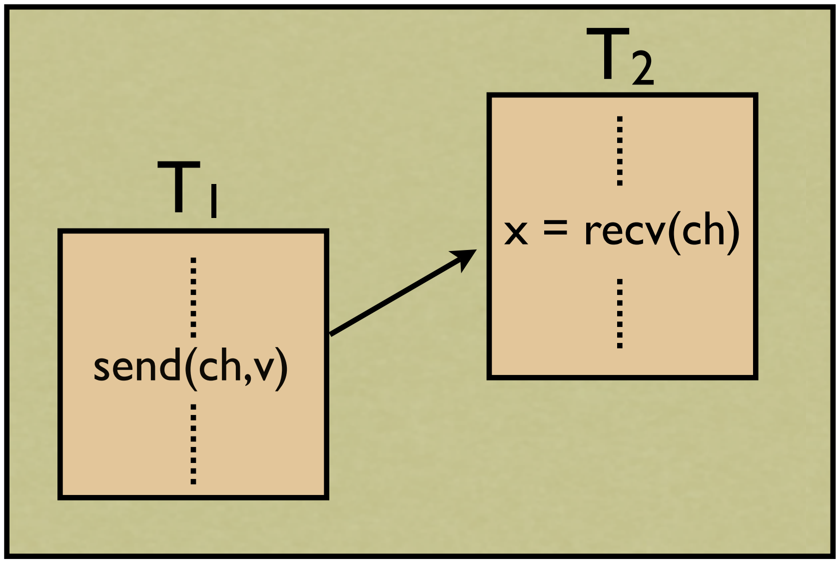
Observations

- Transactions must still adhere to serializability constraints on memory accesses with respect to other transactions
- Non-isolated actions augment constraints:
  - ★The success of a transaction commit within a transaction group depends on the successful commit of all other transactions within that group
  - ★Non-local reasoning limited to communication actions
- Congruence:



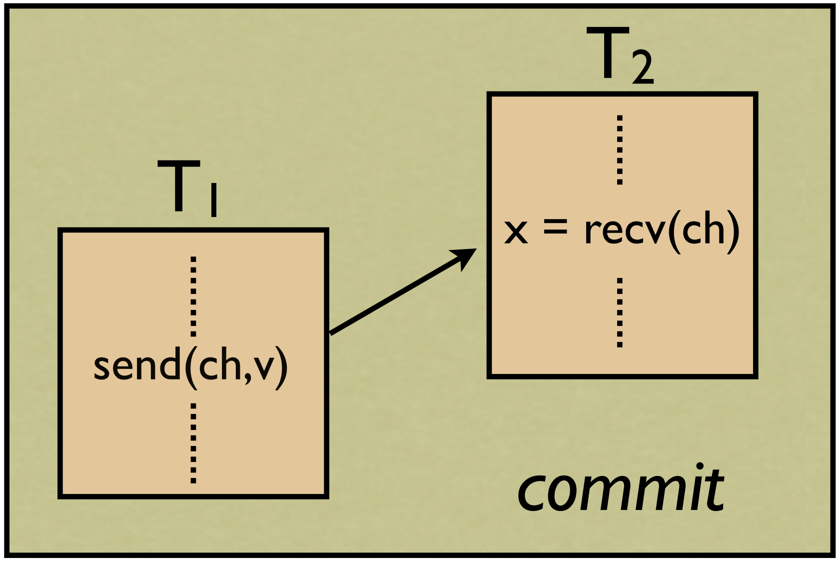
Observations

- Transactions must still adhere to serializability constraints on memory accesses with respect to other transactions
- Non-isolated actions augment constraints:
  - ★The success of a transaction commit within a transaction group depends on the successful commit of all other transactions within that group
  - ★Non-local reasoning limited to communication actions
- Congruence:



Observations

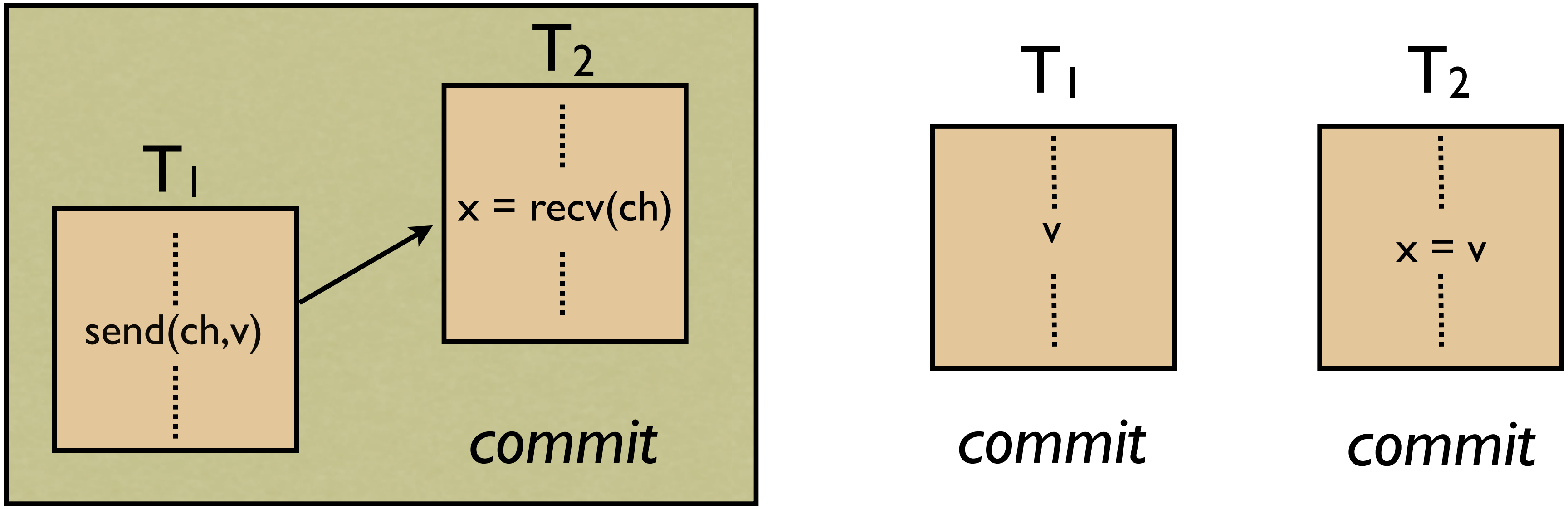
- Transactions must still adhere to serializability constraints on memory accesses with respect to other transactions
- Non-isolated actions augment constraints:
  - ★The success of a transaction commit within a transaction group depends on the successful commit of all other transactions within that group
  - ★Non-local reasoning limited to communication actions
- Congruence:



11

Observations

- Transactions must still adhere to serializability constraints on memory accesses with respect to other transactions
- Non-isolated actions augment constraints:
  - ★The success of a transaction commit within a transaction group depends on the successful commit of all other transactions within that group
  - ★Non-local reasoning limited to communication actions
- Congruence:



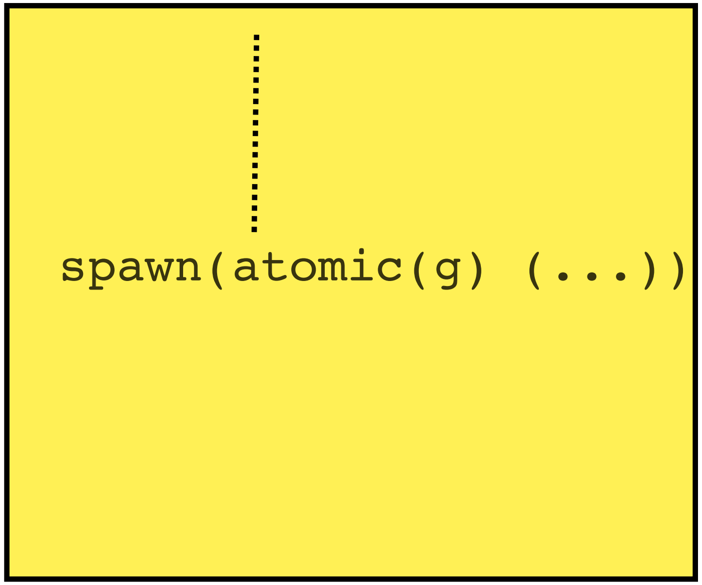
Issues

- Key issues:
  - ★How do we effectively track communication actions across transactions?
  - ★How do we deal with nesting?
  - ★How do we build transaction groups?
  - ★What happens when a communication event within a transaction is paired with an action that occurs outside?
  - ★Progress properties. Loss of obstruction-freedom?
- Build a runtime communication graph that records dependencies among communication actions
  - ★Structure of the graph determines how transactions coalesce into groups

12

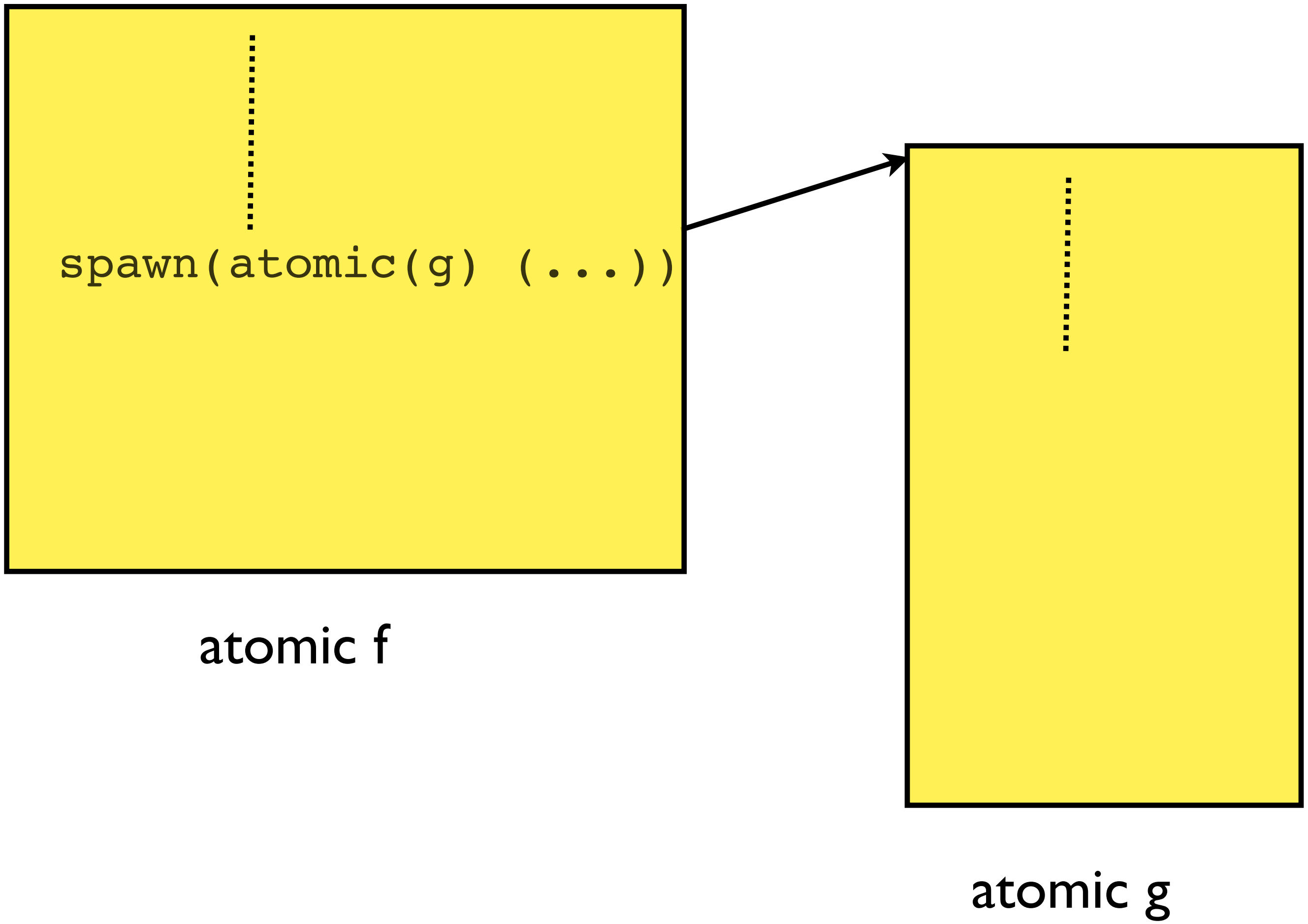
Approach

Approach



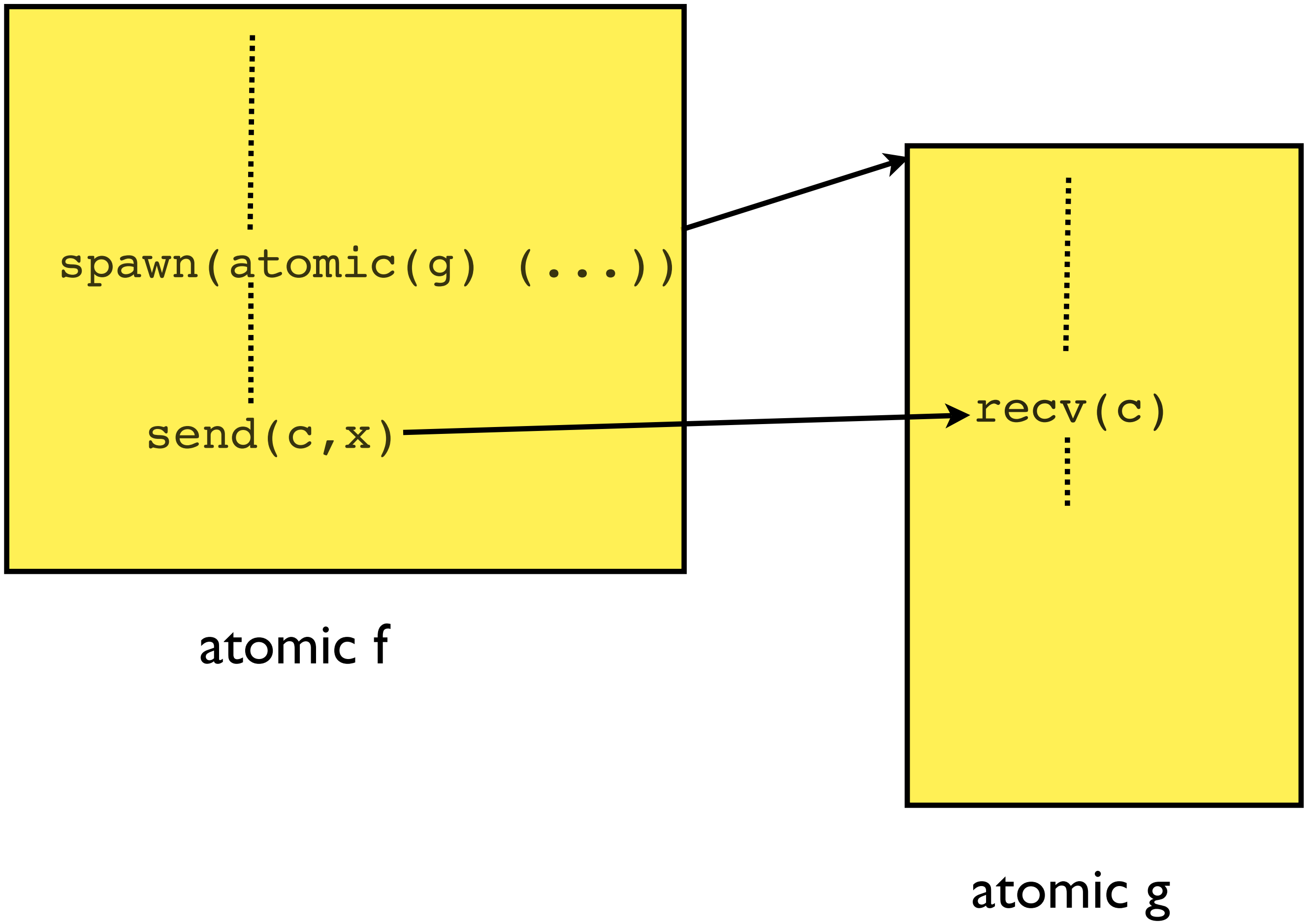
atomic f

Approach

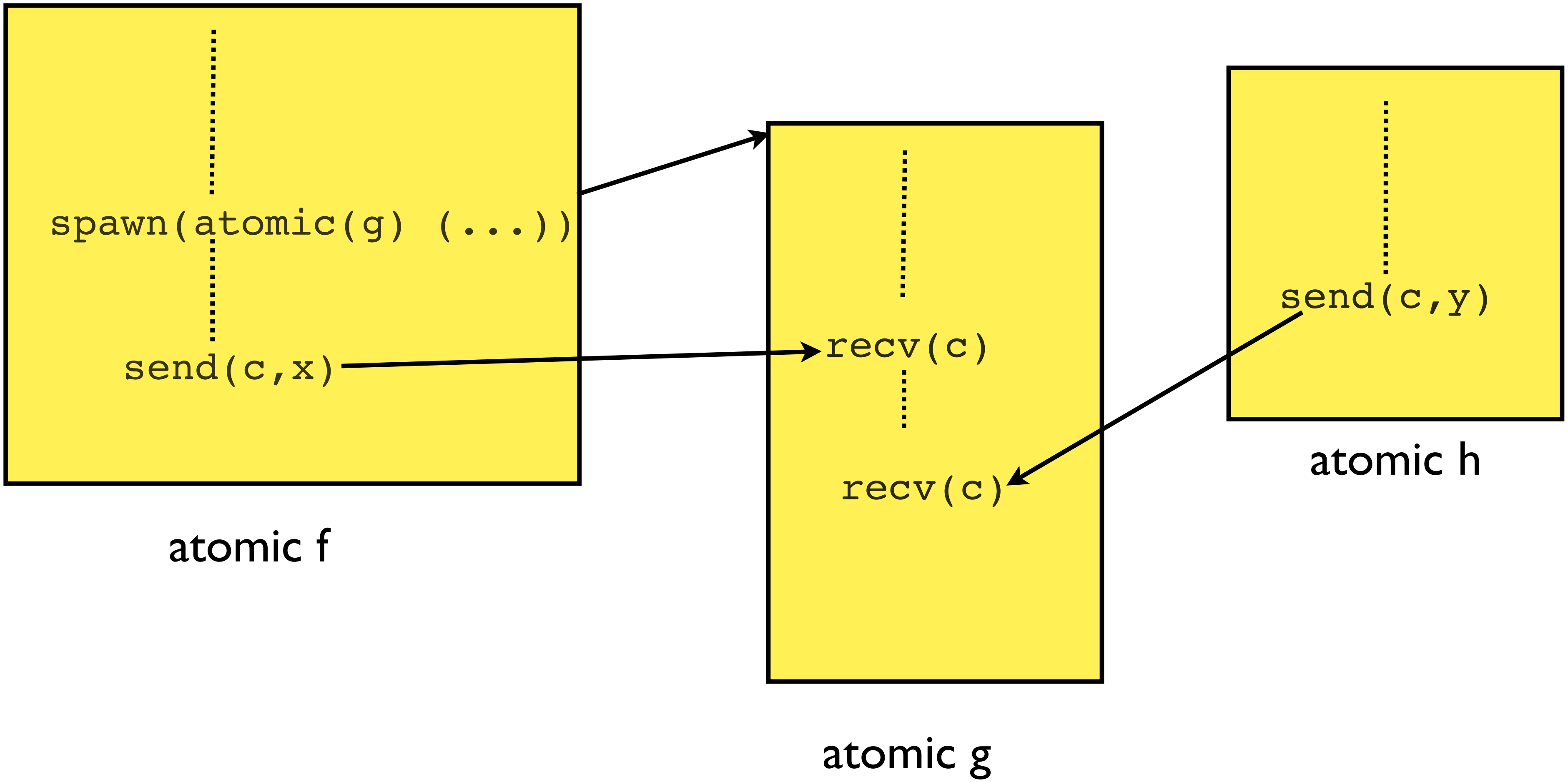


13

Approach

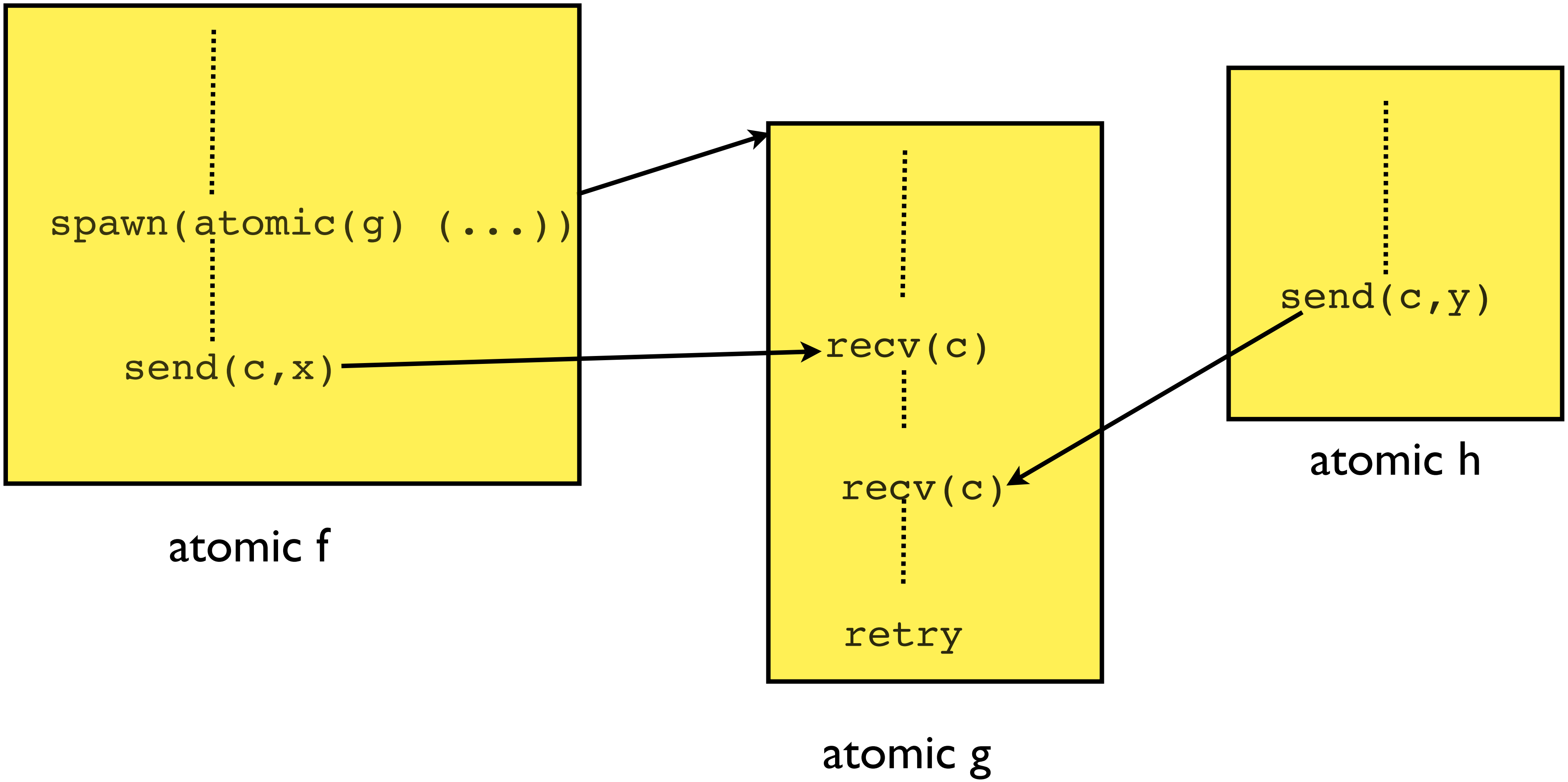


Approach



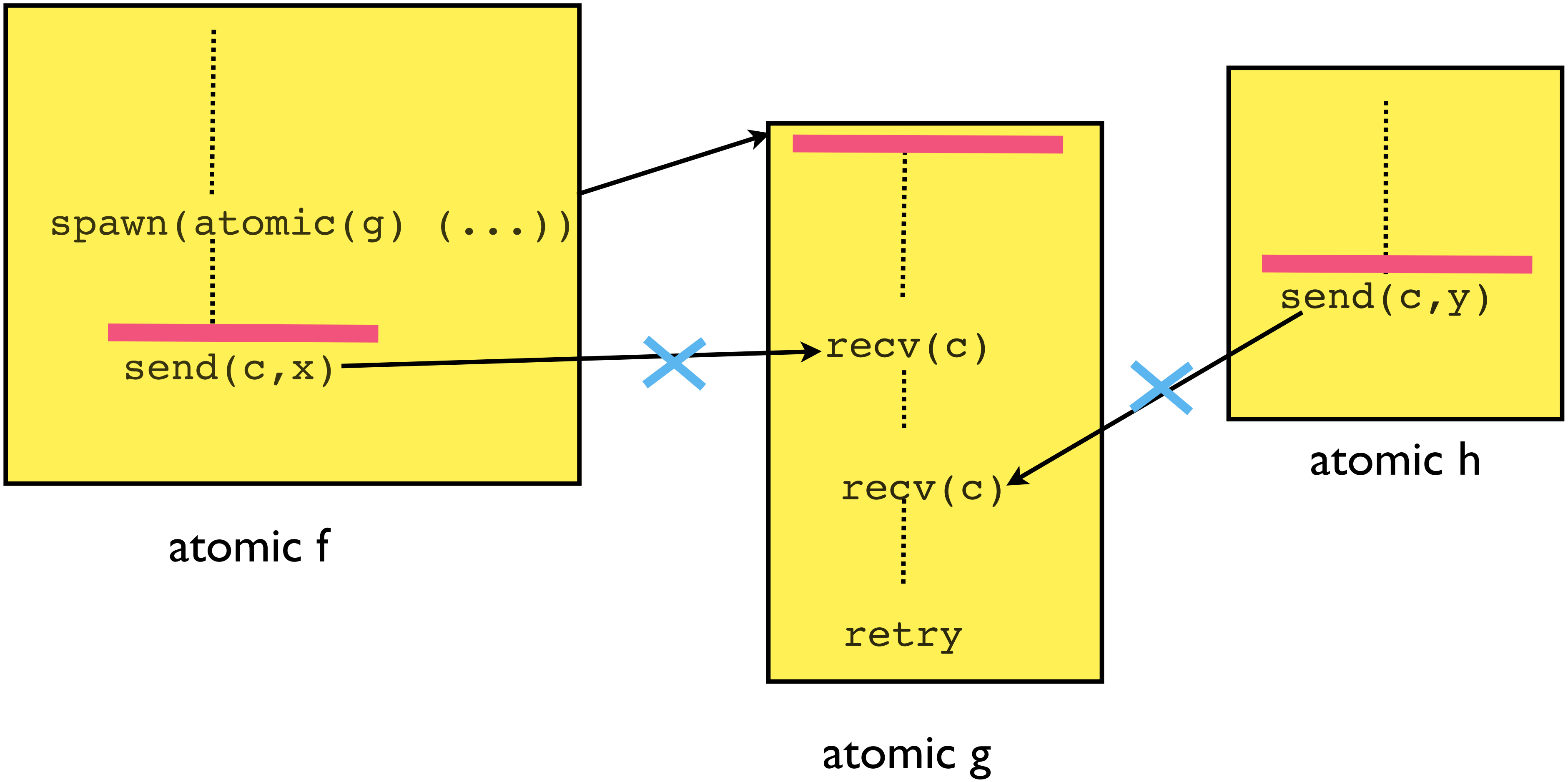
spawn(atomic(g) (...))
send(c,x)
atomic f
recv(c)
recv(c)
atomic g
send(c,y)
atomic h

Approach


spawn(atomic(g) (...))
send(c,x)
atomic f
recv(c)
recv(c)
retry
atomic g
send(c,y)
atomic h

13

Approach



spawn(atomic(g) (...))
send(c,x)
recv(c)
recv(c)
retry
send(c,y)
atomic f
atomic g
atomic h

13

Behavior

- Atomic sections delimited by programmer
- Safety violations may be due to serializability violations or explicit retry
- Save continuations to allow thread execution to resume within a partially executed atomic section
- Abort semantics
  - ★ Revert control to globally consistent state based on communication events observed within an atomic section.

Compiler Support

- What are the best continuation-save points within an atomic section?
- Memoization opportunities in the presence of synchronous communication
  - ★ Can lead to substantial savings: 40% execution improvement on STMBench7
- Only need to record a specific communication event once
  - ★ Only a single edge between two atomic sections needs to be recorded
- Use weak references to collect unreachable portions of the graph
- Need to track read and write operations to shared data accessed outside atomic blocks
  - ★ State of live variables at a communication point must be saved
  - ★ Avoid saving variables that have been previously recorded and which have not changed
  - ★ Use write barriers

Overheads

- Implemented in MLton
  - ★ Insertion of write barriers
  - ★ hooks in the CML library to update the dependency graph
- Overheads to maintain dependency graph small, roughly 6%
  - ★ eXene: a windowing toolkit
  - ★ Swerve: a web server

	Threads	Channels	Events	Shared Writes	Shared Reads	Graph Size (MB)	Runtime Overheads (%)
Triangle	205	79	187	88	88	.19	.59
N-Body	240	99	224	224	273	.29	.81
Pretty	801	340	950	602	840	.74	6.23
Swerve	10532	231	902	9339	80293	5.43	6.60

Conclusions

- Can rationalize a semantics and implementation for atomic transactions that engage in non-isolated communication actions.
- Makes transactions more useful in distributed message-passing environments.
- Improve robustness and expressivity of concurrency and synchronization abstractions
  - ★ Valuable for long-lived applications
  - ★ Useful to help coordinate activities of dynamically-related threads
- Provides useful safety guarantees
- Can be implemented with relatively small overhead