# <~ bloom

Disorderly programming.
CALM analysis.

# The future is already here

- Nearly all nontrivial systems are (or are becoming) distributed
- Programming distributed systems is hard
- Reasoning about them is harder

# Outline

1. Disorderly Programming
2. The Bloom programming language
3. CALM Analysis and visualization
4. Challenge app: replicated shopping carts

# Programming distributed systems

# The state of the art

Order is pervasive in the stored program model

- Program state is an ordered array
- Program logic is a list of instructions with a PC

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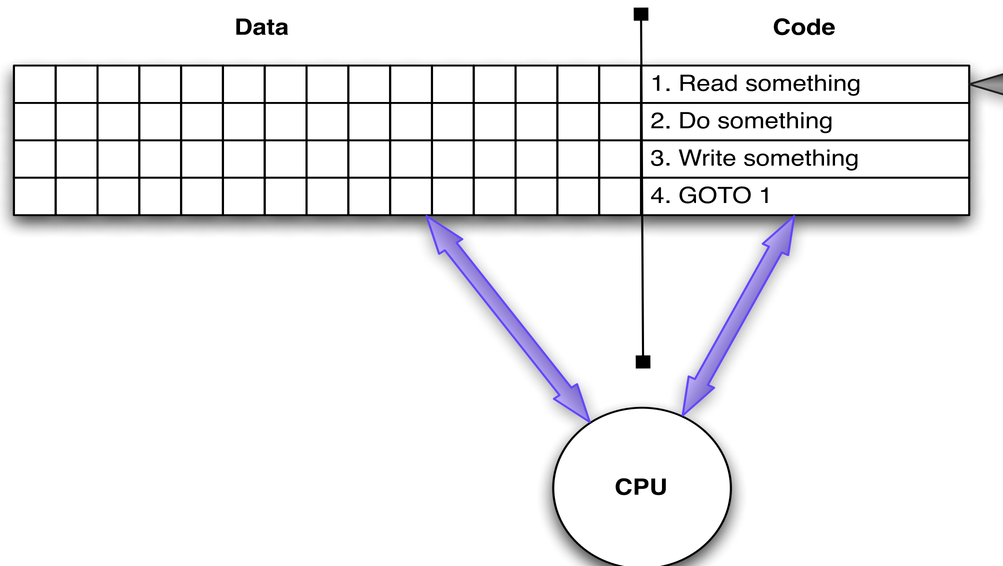

# The state of the art

Order is pervasive in the stored program model

Parallelism and concurrency via retrofits:

- Threads
  - execute many copies of sequential instructions
- Event-driven programming
  - a single sequential program dispatches async processes

# The state of the art

In distributed systems, order is

- expensive to enforce
- frequently unnecessary / overspecified
- easy to get wrong

# The art of the state

**Disorderly programming**

Design maxim:

*Think about the hard stuff.  Forget about the easy stuff.*

# The art of the state

**Disorderly programming**

- Program state is unordered collections
- Program logic is an unordered set of rules

# The art of the state

**Disorderly programming**

- Program state is unordered collections
- Program logic is an unordered set of rules
- Independence and concurrency are assumed
- Ordering of data or instructions are explicit, special-case behaviors
  - This is the hard stuff

<~ bloom

# BUD: Bloom Under Develoment

- Ruby internal DSL
- Set comprehension style of programming
- Fully declarative semantics
  - Based on Dedalus (Datalog + time)

# Bloom Rules

```
multicast <~ (message * members) do |mes, mem|
  [mem.address, mes.id, mes.payload]
end
```

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end
```

<collection>

| | |
|---|---|
| *persistent* | table |
| *transient* | scratch |
| *networked transient* | channel |
| *scheduled transient* | periodic |
| *transient* | interface |

<accumulator>

| | |
|---|---|
| <= | *now* |
| <+ | *next* |
| <- | *del_next* |
| <~ | *async* |

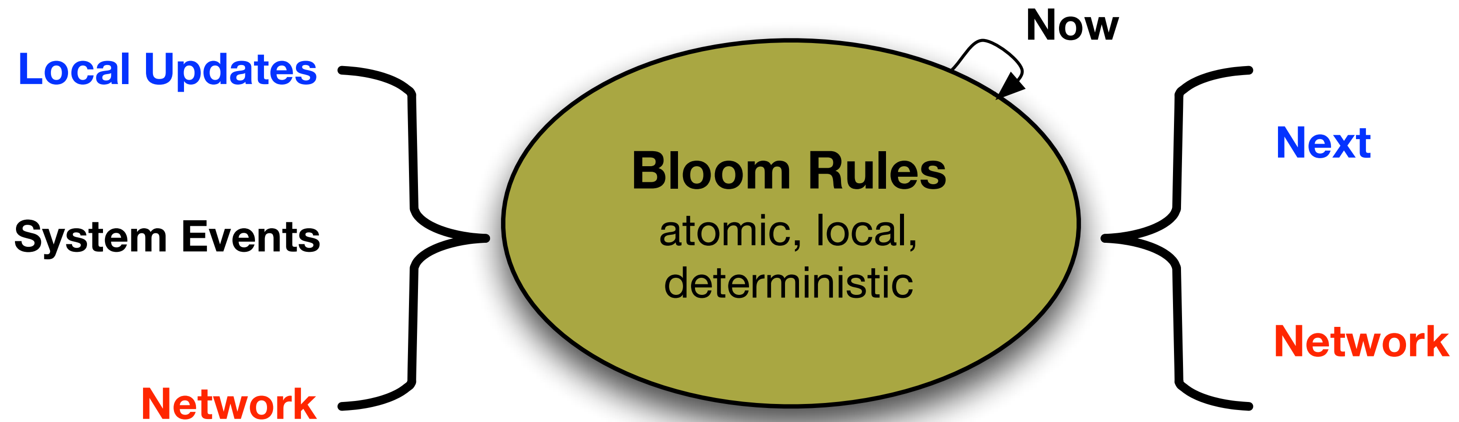
<collection expression>

| |
|---|
| *<collection>* |
| map, flat_map |
| reduce, group |
| join, natjoin, outerjoin |
| empty? include? |

# Bud language features

- Module system
  - Encapsulation and composition via mixins
  - Separation of abstract interfaces and concrete implementations
- Metaprogramming and reflection
  - Program state is program data
- Pay-as-you-code schemas
  - Default is key => value

# Operational model



# Writing distributed programs in Bloom

# Abstract Interfaces and Declarations

```
module DeliveryProtocol
  state do
    interface input, :pipe_in,
      [:dst, :src, :ident] => [:payload]
    interface output, :pipe_sent,
      pipe_in.schema
  end
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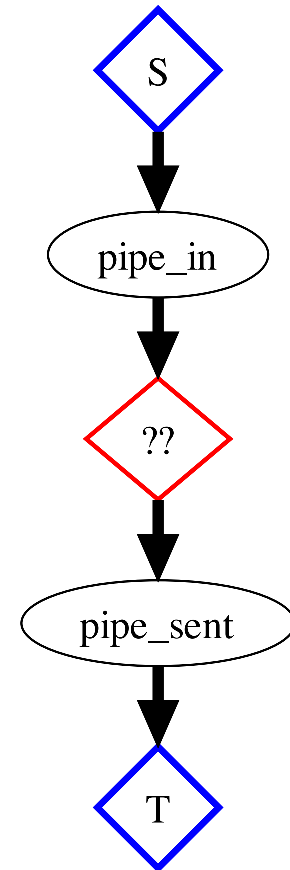

# Concrete Implementations

```
module BestEffortDelivery
  include DeliveryProtocol

  state do
    channel :pipe_chan, pipe_in.schema
  end

  bloom :snd do
    pipe_chan <~ pipe_in
  end

  bloom :done do
    pipe_sent <= pipe_in
  end
end
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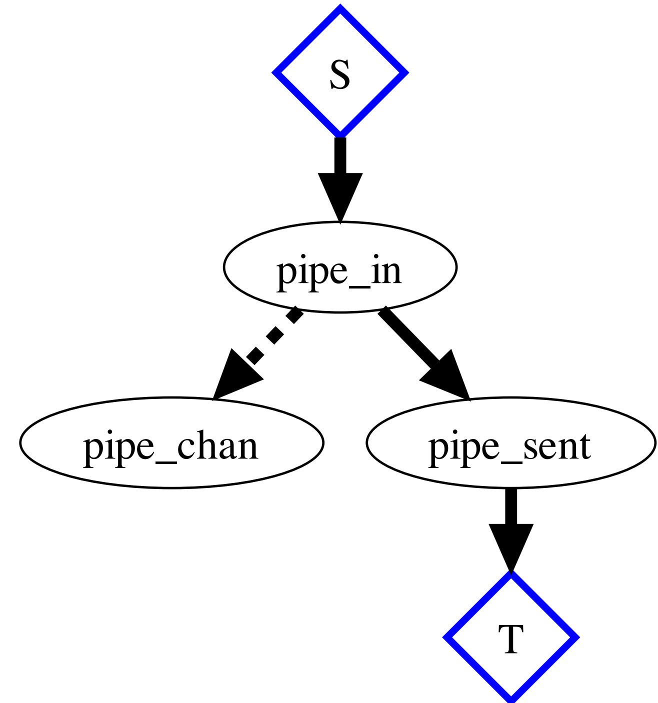

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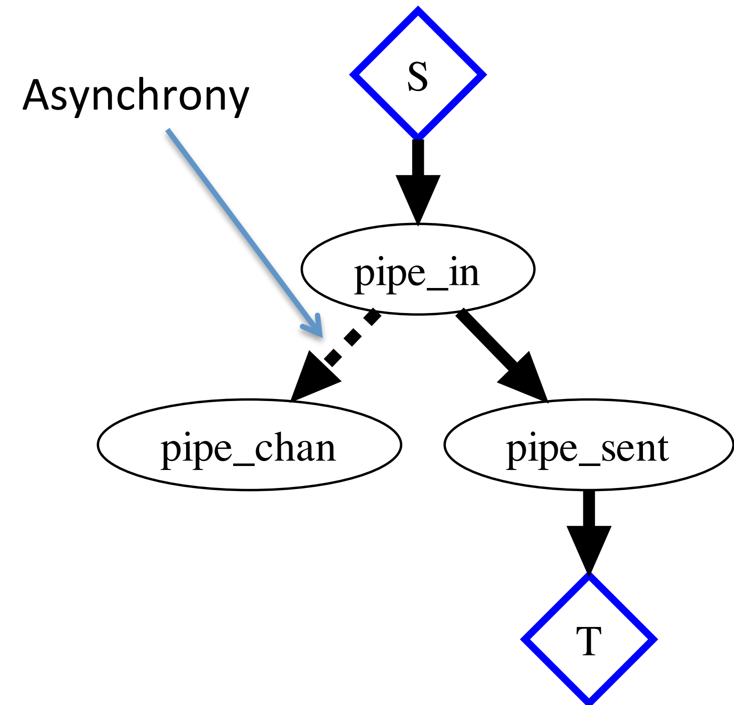

# Concrete Implementations

```
module ReliableDelivery
  include DeliveryProtocol
  import BestEffortDelivery => :bed

  state do
    table :buf, pipe_in.schema
    channel :ack, [:@src, :dst, :ident]
    periodic :clock, 2
  end

  bloom :remember do
    buf <= pipe_in
    bed.pipe_in <= pipe_in
    bed.pipe_in <= (buf * clock).lefts
  end

  bloom :send_ack do
    ack <~ bed.pipe_chan do|p|
      [p.src, p.dst, p.ident]
    end
  end

  bloom :done do
    temp :msg_acked <= (buf * ack).lefts
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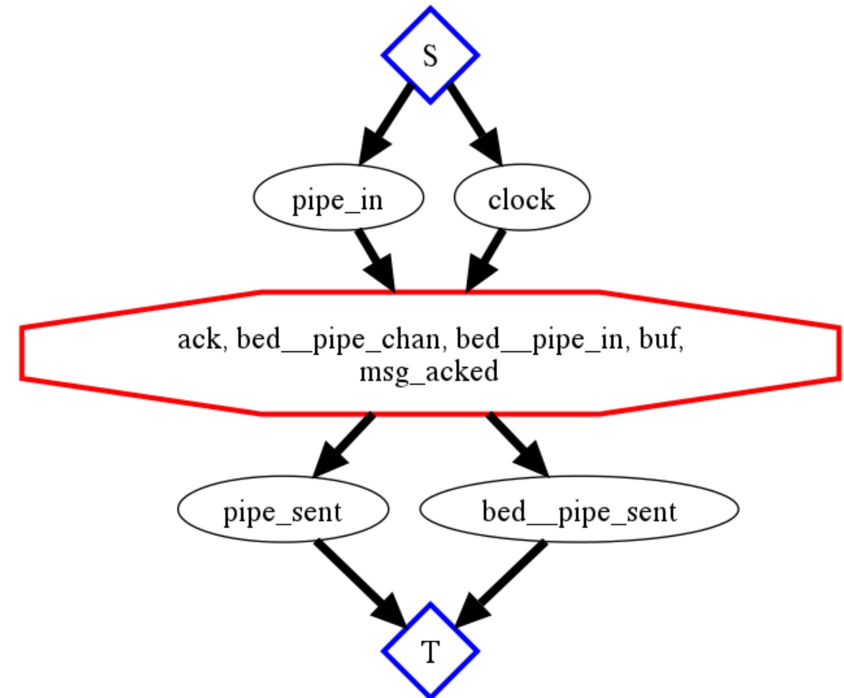

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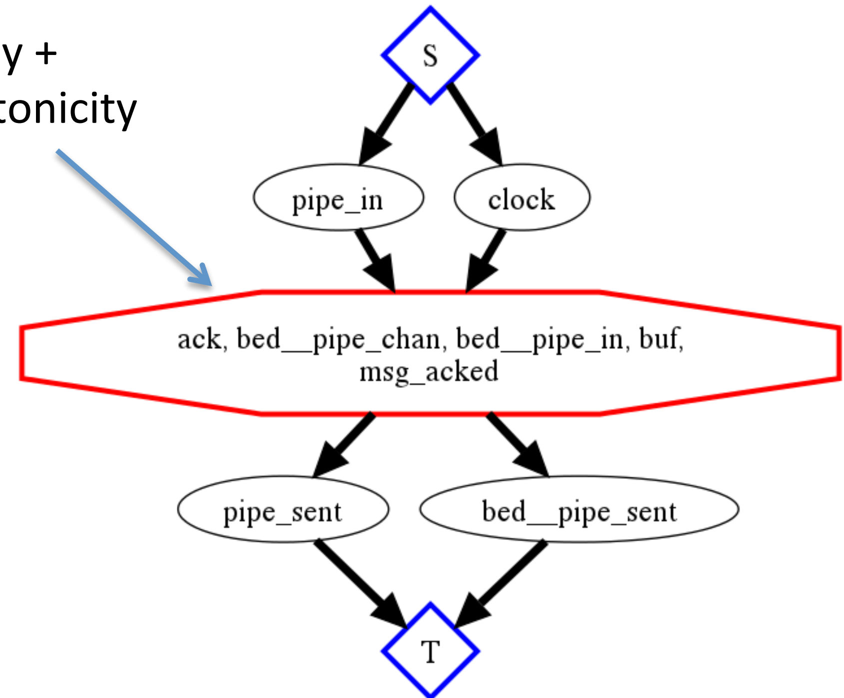
Asynchrony + Nonmonotonicity



# CALM Analysis

# Monotonic Logic

The more you know, the more you know.

- E.g., select, project, join, union
  - (Filter, map, compose, merge)
- *Pipelinable*
- Insensitive to the ordering of inputs

# Nonmonotonic Logic

Possible belief revision or retraction

*(Un-firing missiles)*

- E.g. aggregation, negation as complement
  - (Counting, taking a max/min, checking that an element isn't in a hash)
- *Blocking*
- Ordering of inputs may affect results

# Consistency

A family of correctness criteria for data-oriented systems

- Do my replicas all converge to the same final state?
- Am I missing any partitions?

State of the art: *choose an extreme*

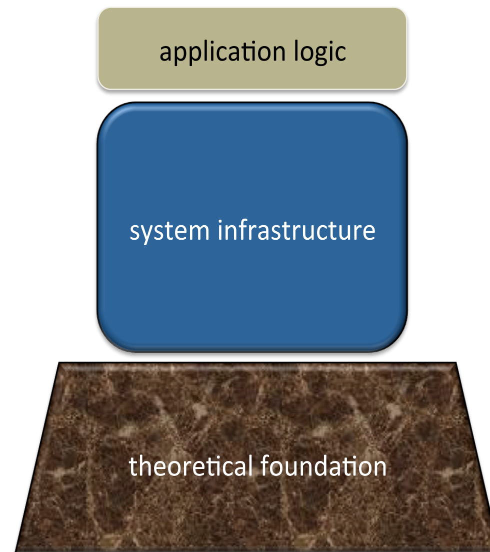
# Strong Consistency

*Coordination*: baked-in consistency via protocol

- Serializable reads and writes, atomic transactions, ACID
- 2PC, paxos, GCS, etc
- **Establish a total order of updates**

**Problem:** latency, availability

# Strong Consistency



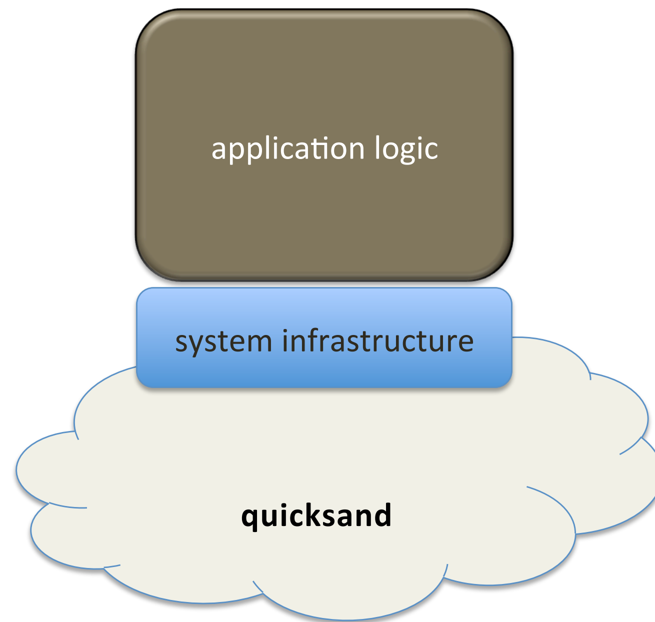
# Loose Consistency

Application-specific correctness via “rules of thumb”

- Asynchronous replication
- Commutative (i.e., reorderable) operations
- Custom compensation / repair logic
- **Tolerate all update orders**

**Problem:** informal, fragile

# Loose Consistency



# CALM Conjecture

Consistency ``is'' logical monotonicity

# CALM Analysis

- Logic programming dependency analysis applied to a distributed system
- Represent program as a directed graph
  - Nodes are collections
  - Arcs are rules
    - may be labeled asynchronous or nonmonotonic
- Tools identify “points of order”
  - Where different input orderings may produce divergent outputs

# Points of order

Nonmonotonicity after asynchrony in dataflow

- Asynchronous messaging => nondeterministic message orders
- Nonmonotonic => order-sensitive
- *Coordination* may be required to ensure convergent results.
- Here (and only here) the programmer should reason about ordering!

# Resolving points of order

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   - Enforce an ordering over inputs
   - Or block till input set is completely determined

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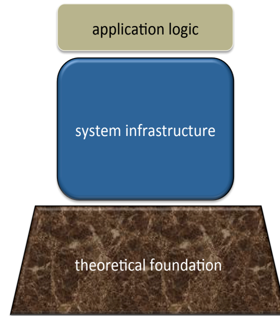


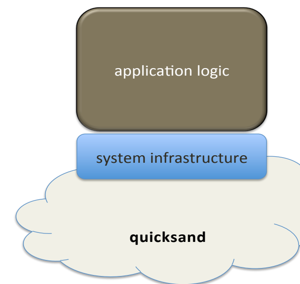

# Shopping Carts

# Example application: a replicated shopping cart

- Replicated to achieve high availability and low latency
- Clients are associated with unique session ids
- Add item, delete item and “checkout” operations

**Challenge**:

Ensure that replicas are ``eventually consistent’’

# Carts done two ways

1. A “destructive” cart
   – Use a replicated KVS as a storage system
   – Client session id is the key
   – Value is an array representing cart contents
   – Checkout causes value array to be sent to client
2. A “disorderly” cart
   – Accumulate (and asynchronously replicate) a set of cart actions
   – At checkout, count additions and deletions, take difference
   – Aggregate the summary into an array “just in time”

# A simple key/value store

```
module KVSProtocol
  state do
    interface input, :kvput, [:key] => [:reqid, :value]
    interface input, :kvdel, [:key] => [:reqid]
    interface input, :kvget, [:reqid] => [:key]
    interface output, :kvget_response,
      [:reqid] => [:key, :value]
  end
end
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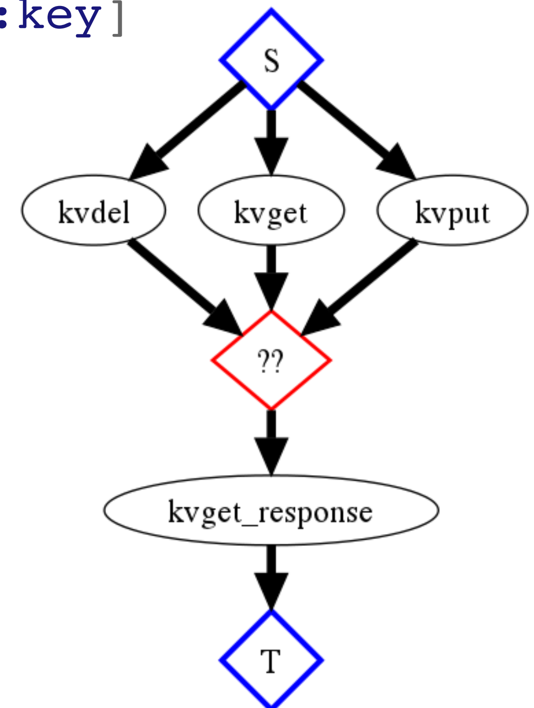

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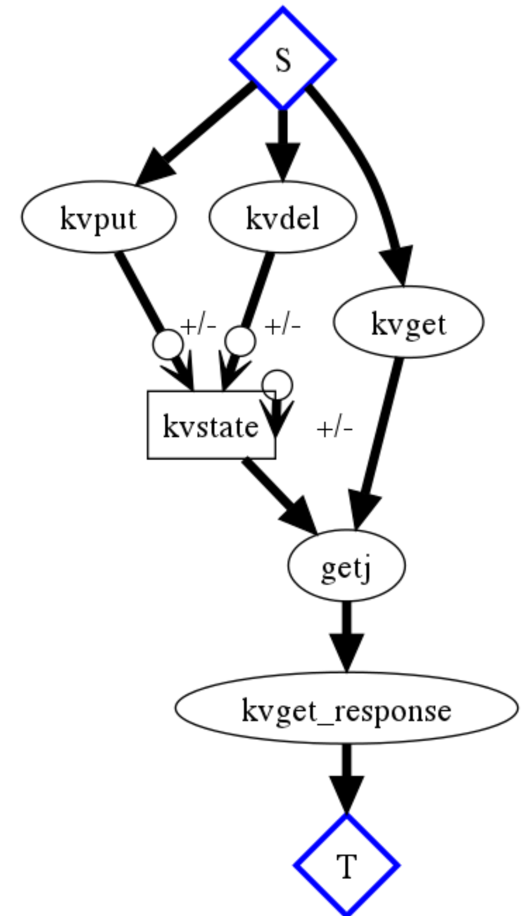

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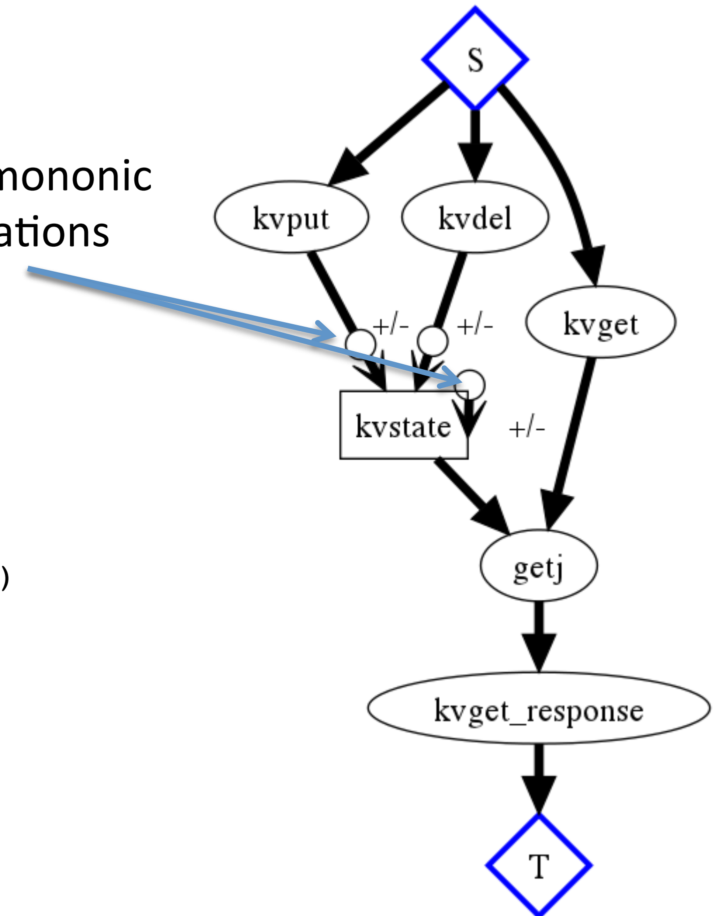
Nonmononic operations



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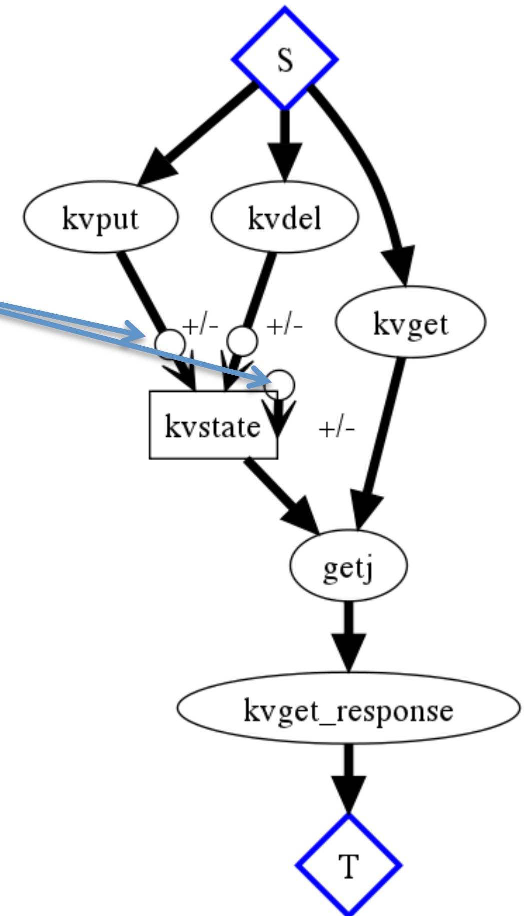

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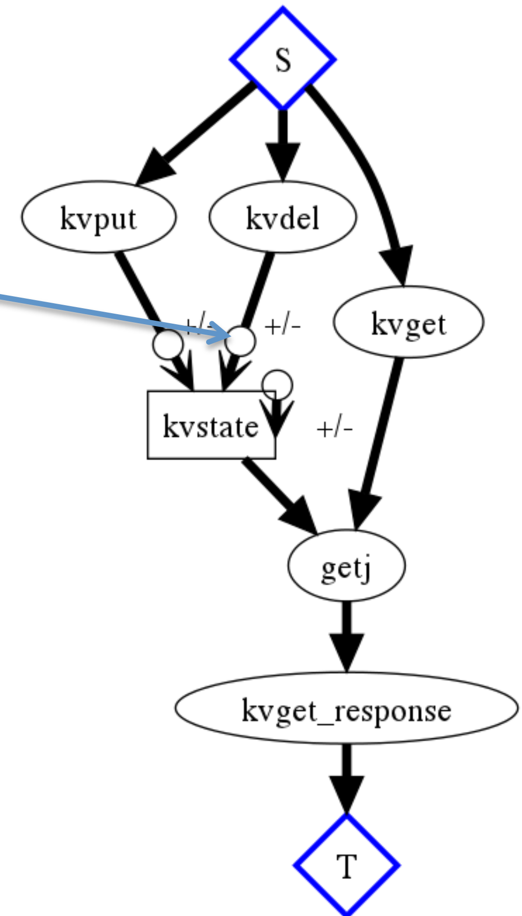

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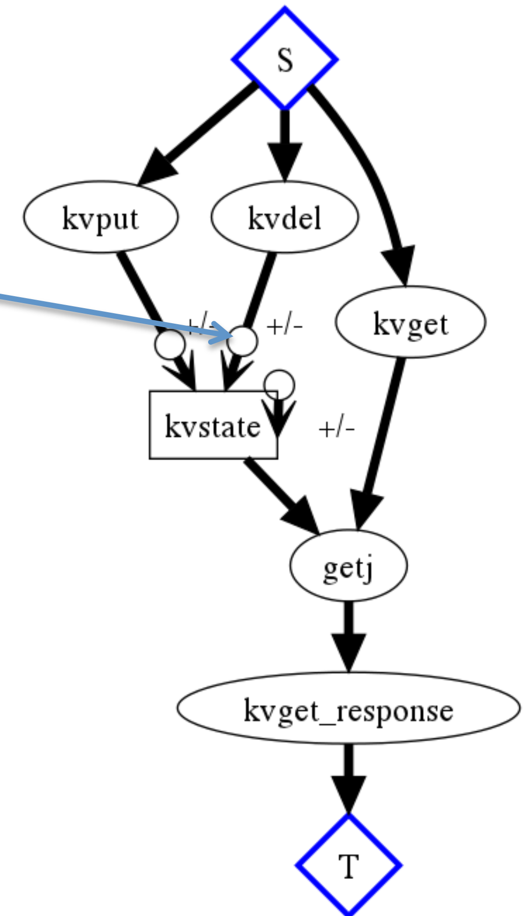

# ``Destructive'' Cart

```
module DestructiveCart
  include CartProtocol
  include KVSProtocol

  declare
  def queueing
    kvget <= action_msg {|a| [a.reqid, a.session] }
    kvput <= action_msg do |a|
      if a.action == "Add" and not kvget_response.map{|b| b.key}.include? a.session
        [a.client, a.session, a.reqid, Array.new.push(a.item)]
      end
    end

    old_state = join [kvget_response, action_msg], [kvget_response.key, action_msg.session]
    kvput <= old_state do |b, a|
      if a.action == "Add"
        [a.client, a.session, a.reqid, (b.value.clone.push(a.item))]
      elsif a.action == "Del"
        [a.client, a.session, a.reqid, delete_one(b.value, a.item)]
      end
    end
  end

  declare
  def finish
    kvget <= checkout_msg {|c| [c.reqid, c.session] }
    lookup = join([kvget_response, checkout_msg], [kvget_response.key, checkout_msg.session])
    response_msg <~ lookup do |r, c|
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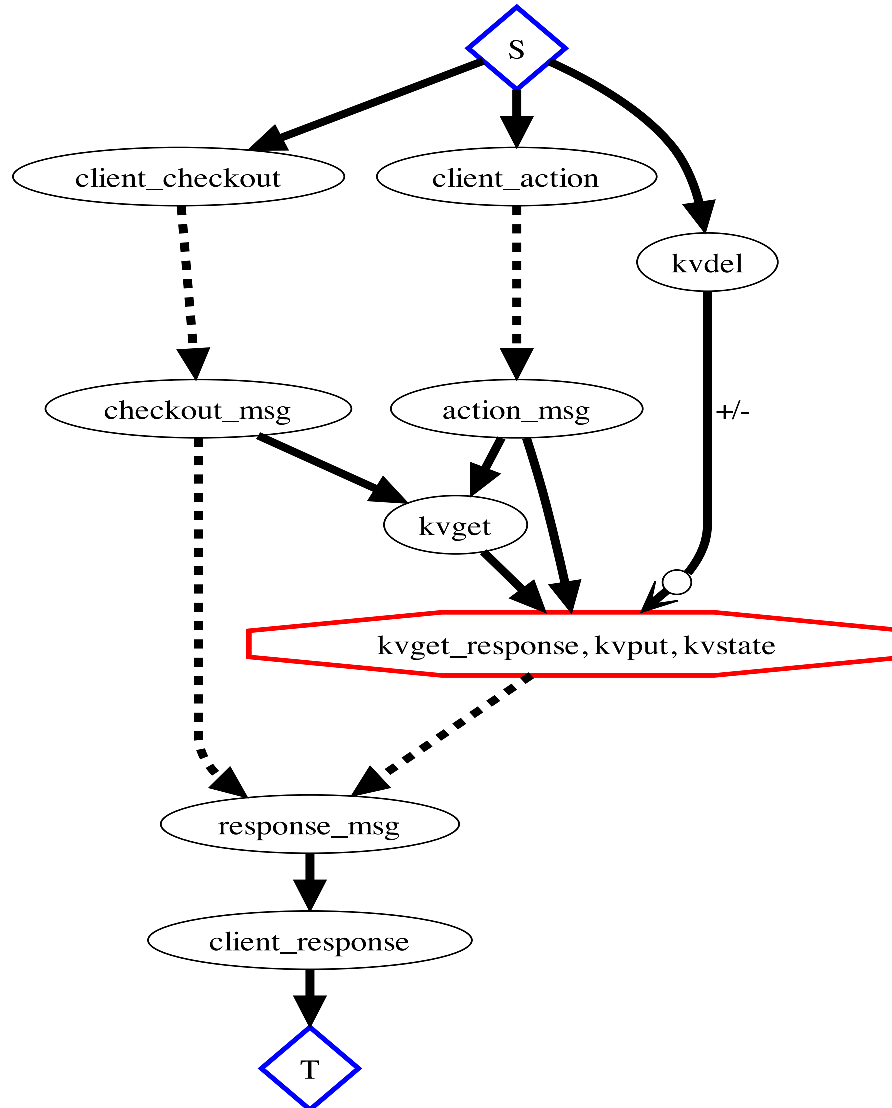
React to client updates

React to client checkout

# ``Destructive'' Cart



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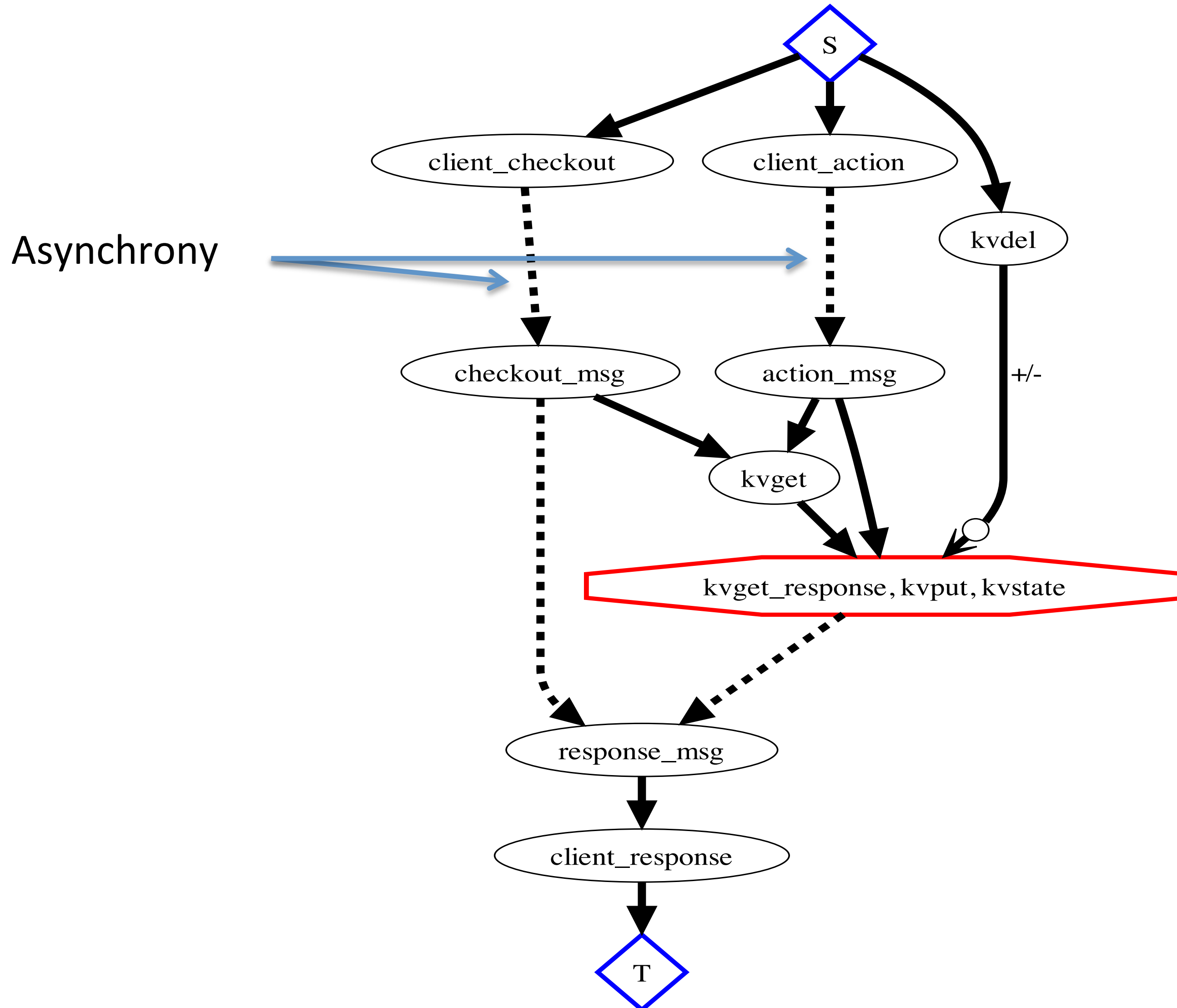

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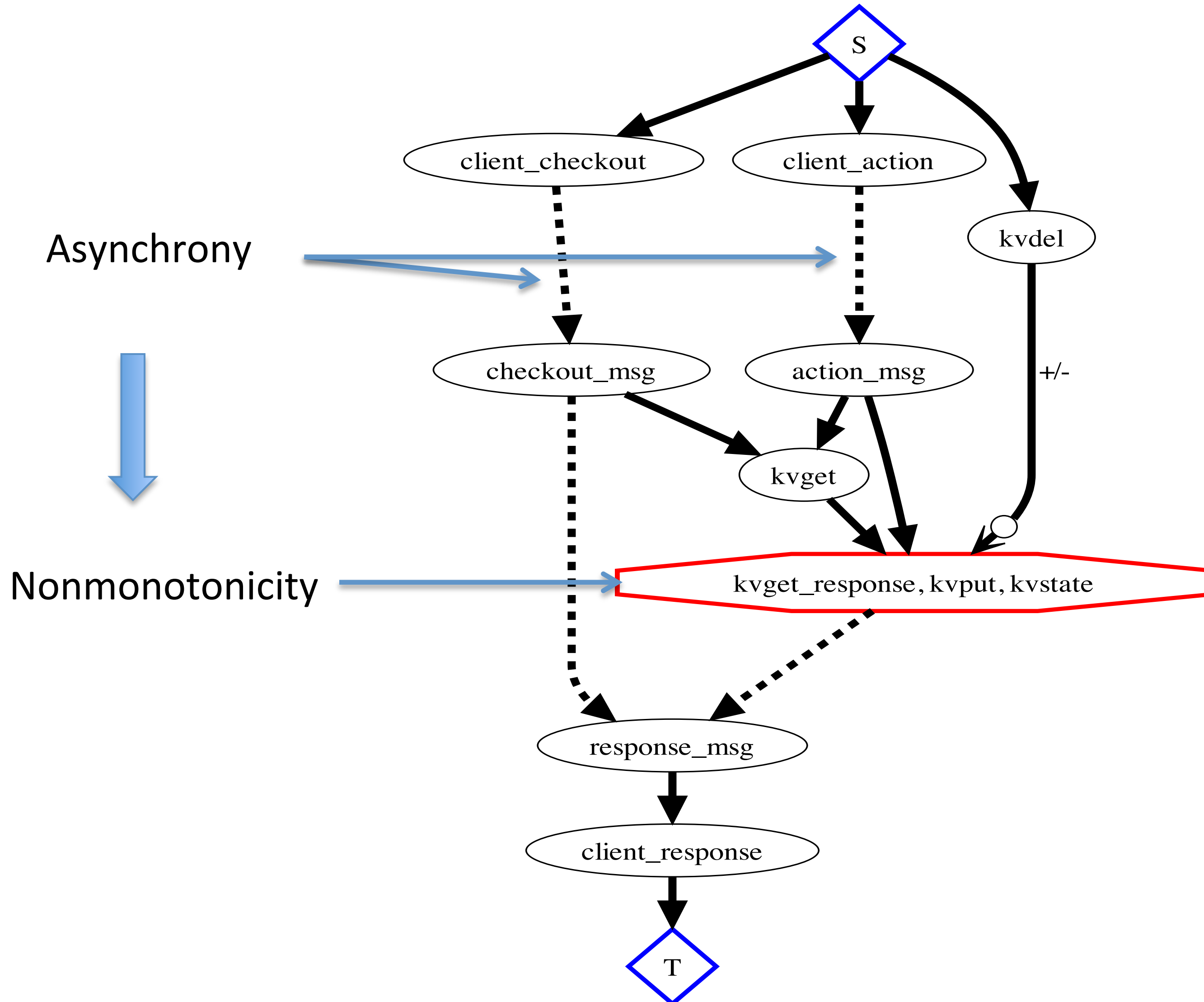

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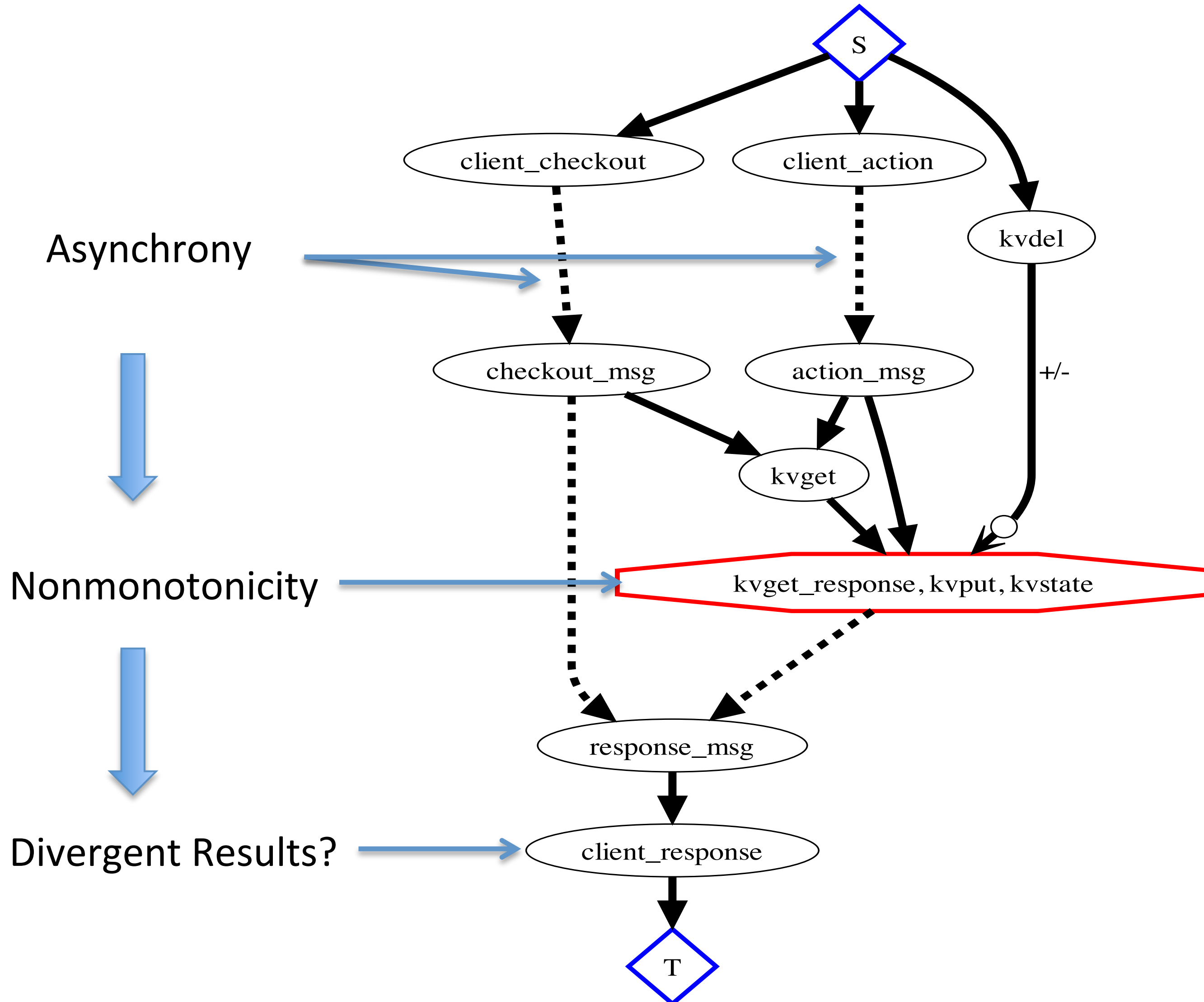
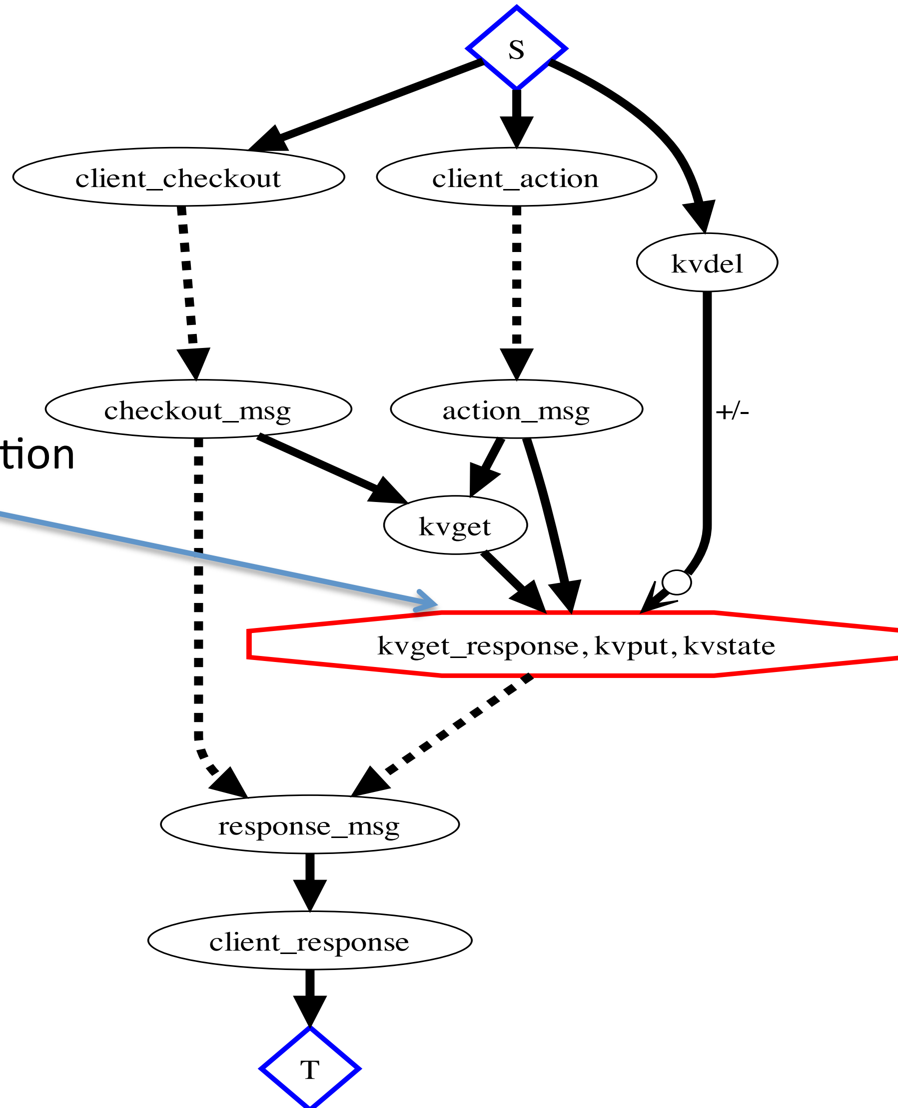


# ``Destructive'' Cart

Add coordination? E.g.,
- Synchronous replication
- Paxos



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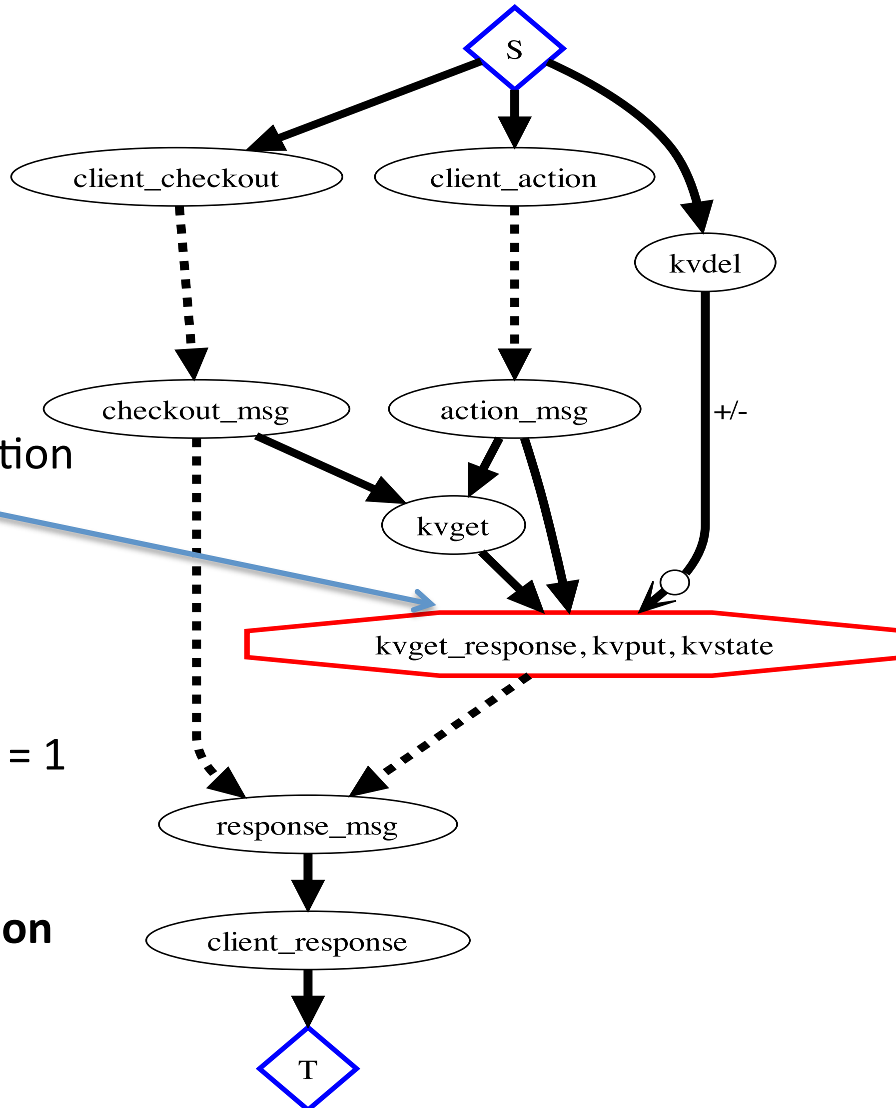



*n* = |client_action|

*m* = |client_checkout| = 1

***n* rounds of coordination**

# ``Disorderly Cart’’

```
module DisorderlyCart
  include CartProtocol
  state do
    table :cart_action, [:session, :reqid] => [:item, :action]
    scratch :action_cnt, [:session, :item, :action] => [:cnt]
    scratch :status, [:server, :client, :session, :item] => [:cnt]
  end

  declare
  def saved
    cart_action <= action_msg { |c| [c.session, c.reqid, c.item, c.action] }
    action_cnt <= cart_action.group([cart_action.session, cart_action.item, cart_action.action], count
(cart_action.reqid))
  end

  declare
  def consider
    status <= (action_cnt * action_cnt * checkout_msg) do |a1, a2, c|
      if a1.session == a2.session and a1.item == a2.item and a1.session == c.session and a1.action == "Add" and
       a2.action == "Del"
          [c.client, c.server, a1.session, a1.item, a1.cnt - a2.cnt] if (a1.cnt - a2.cnt) > 0
    end
    status <= (action_cnt * checkout_msg) do |a, c|
      if a.action == "Add" and not action_cnt.map{|d| d.item if d.action == "Del"}.include? a.item
        [c.client, c.server, a.session, a.item, a.cnt]
      end
    end
    out = status.reduce({}) do |memo, i|
      memo[[i[0],i[1],i[2]]] ||= []; i[4].times {memo[[i[0],i[1],i[2]]] << i[3]}; memo
    end.to_a
    response_msg <~ out {|k, v| k << v}
  end
end
```

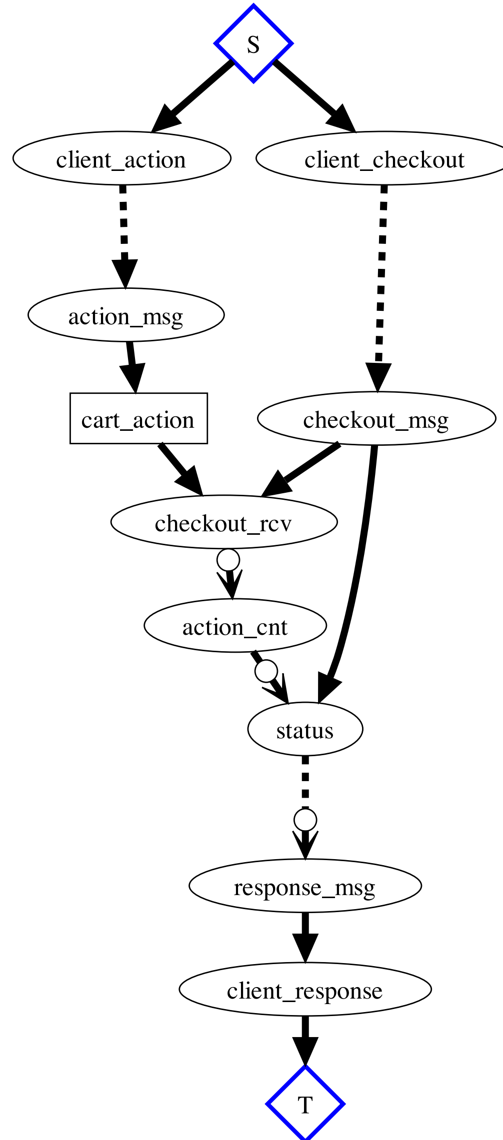
# ``Disorderly Cart''

```
module DisorderlyCart
  include CartProtocol
  state do
    table :cart_action, [:session, :reqid] => [:item, :action]
    scratch :action_cnt, [:session, :item, :action] => [:cnt]
    scratch :status, [:server, :client, :session, :item] => [:cnt]
  end

  declare
  def saved
    cart_action <= action_msg { |c| [c.session, c.reqid, c.item, c.action] }
    action_cnt <= cart_action.group([cart_action.session, cart_action.item, cart_action.action], count
(cart_action.reqid))
  end

  declare
  def consider
    status <= (action_cnt * action_cnt * checkout_msg) do |a1, a2, c|
      if a1.session == a2.session and a1.item == a2.item and a1.session == c.session and a1.action == "Add" and
       a2.action == "Del"
          [c.client, c.server, a1.session, a1.item, a1.cnt - a2.cnt] if (a1.cnt - a2.cnt) > 0
    end
    status <= (action_cnt * checkout_msg) do |a, c|
      if a.action == "Add" and not action_cnt.map{|d| d.item if d.action == "Del"}.include? a.item
        [c.client, c.server, a.session, a.item, a.cnt]
      end
    end
    out = status.reduce({}) do |memo, i|
      memo[[i[0],i[1],i[2]]] ||= []; i[4].times {memo[[i[0],i[1],i[2]]] << i[3]}; memo
    end.to_a
    response_msg <~ out {|k, v| k << v}
  end
end
```

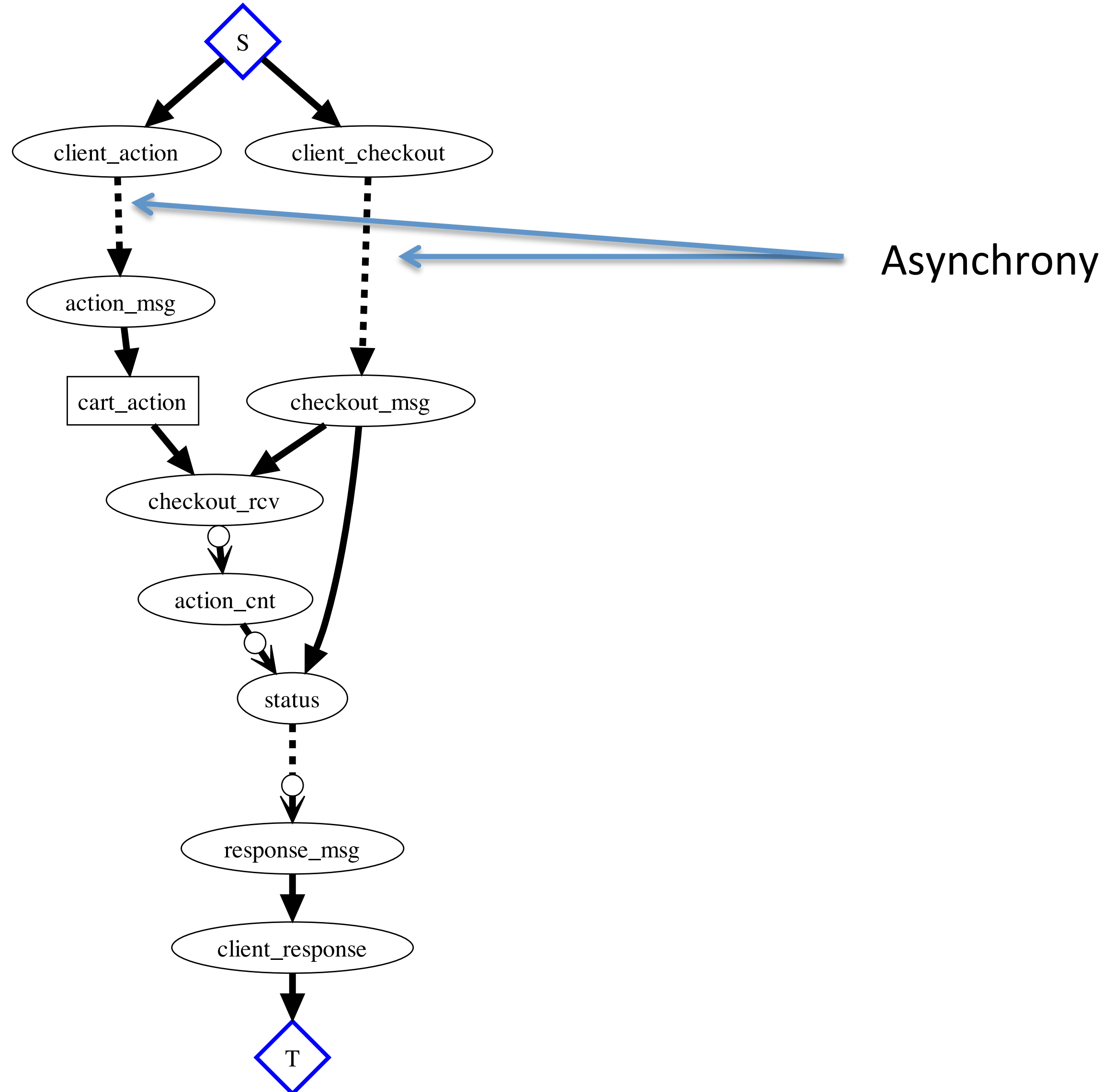
Actions

Checkout

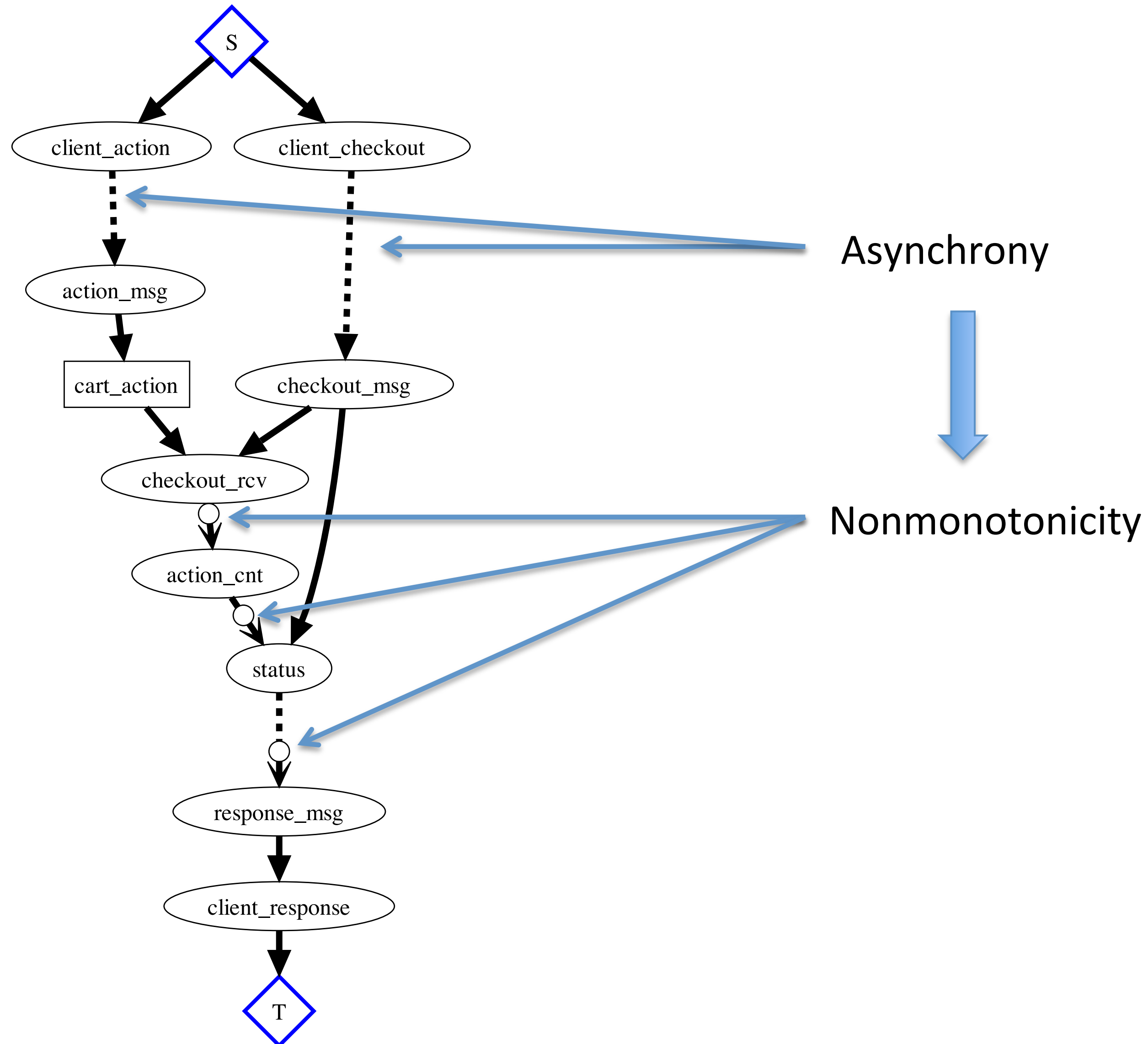
# Disorderly Cart Analysis



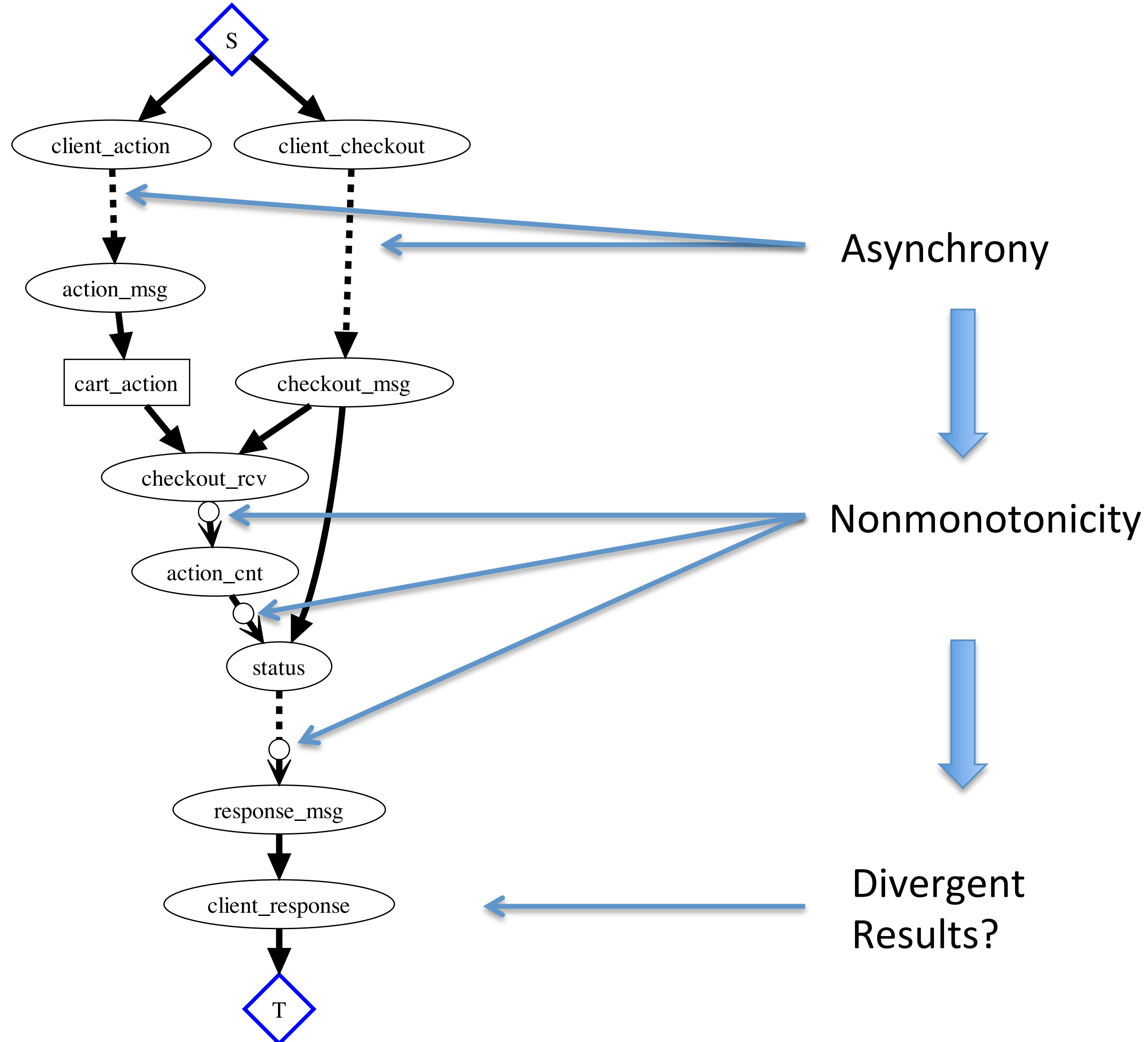
# Disorderly Cart Analysis



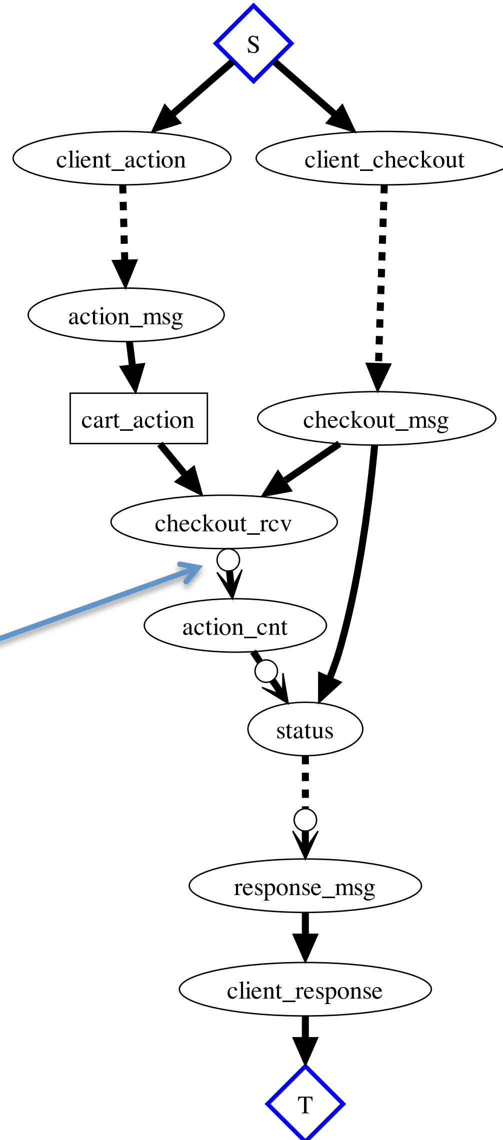
# Disorderly Cart Analysis



# Disorderly Cart Analysis



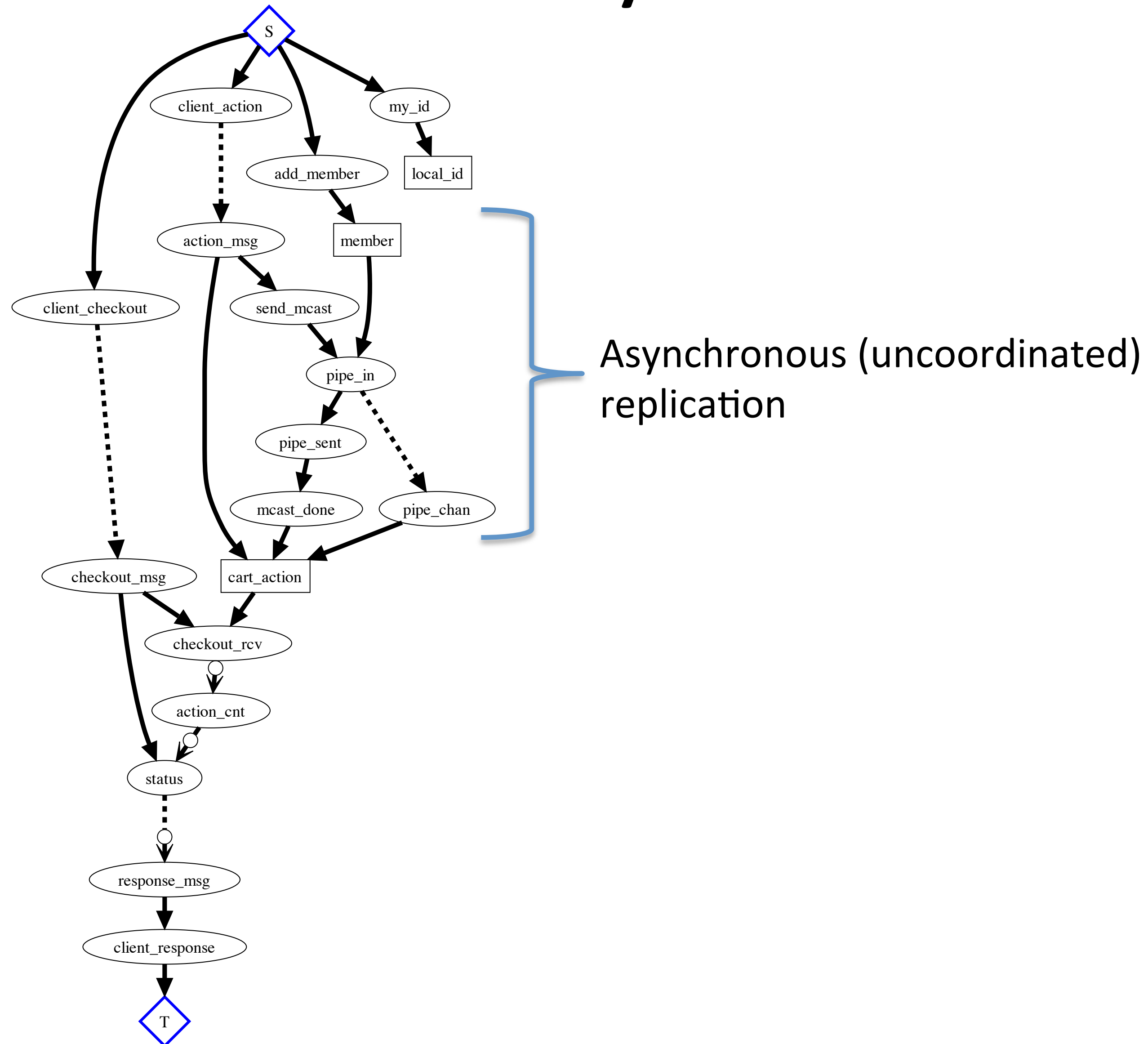
# Disorderly Cart Analysis



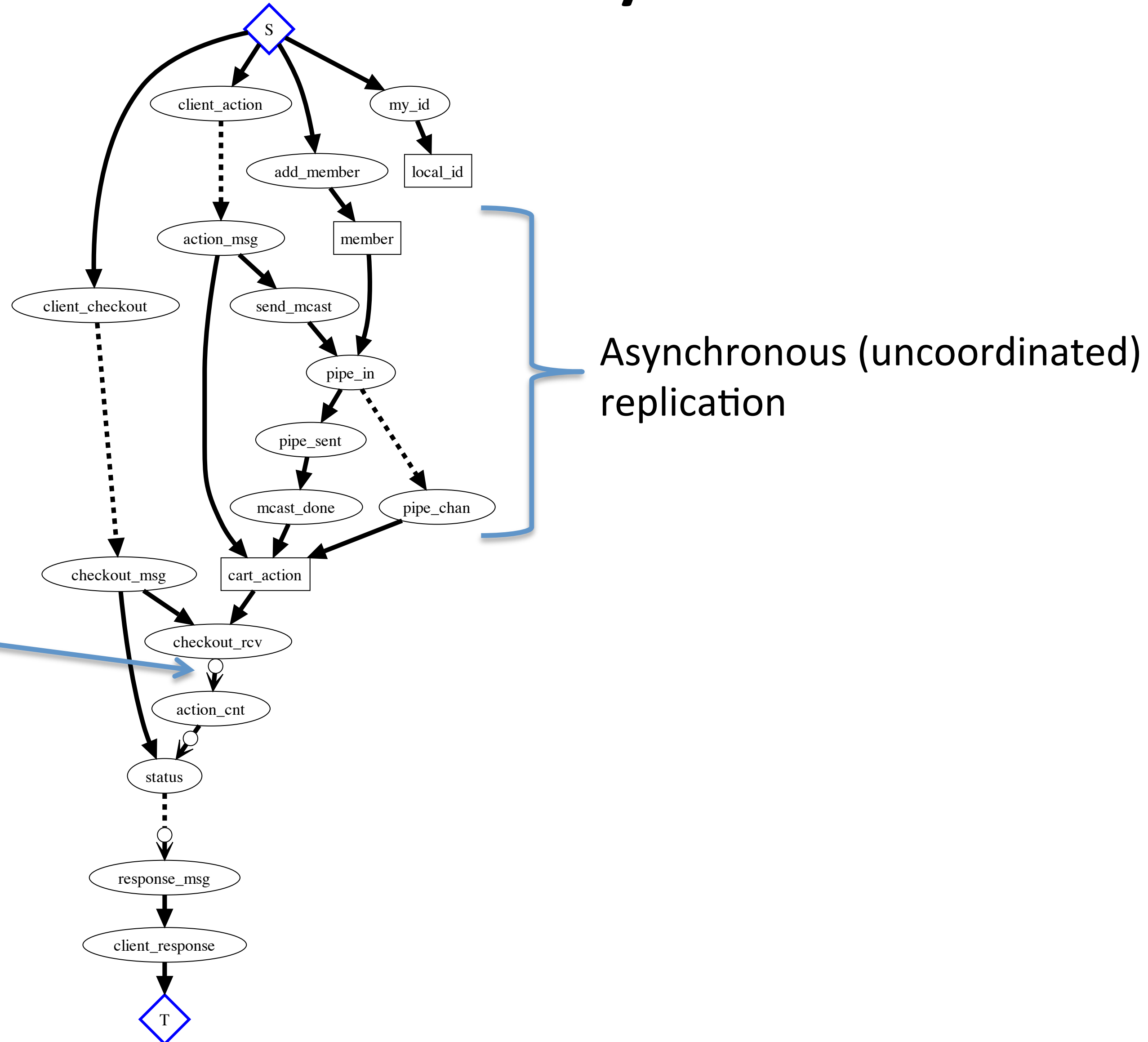

$n$ = |client_action|
$m$ = |client_checkout| = 1

***1* round of coordination**

# Replicated Disorderly Cart



# Replicated Disorderly Cart




Still just 1 round of coordination

# Summary

- Why *dis*orderly?
  - Order is expensive and sometimes distracting
- When is order really *needed*?
  - When nomonotonicity makes the computation order-dependent
- What is coordination *for*?
  - Re-establishing order, to guarantee consistency.
- CALM <~ Bloom
  - A disorderly programming language
  - Tools to identify points of order

# More

Resources:

http://bloom.cs.berkeley.edu

http://bloom-lang.org

Writeups:

- Consistency Analysis in Bloom: A CALM and Collected Approach (CIDR’11)
- Dedalus: Datalog in Time and Space (Datalog2.0)
- The Declarative Imperative (PODS’10 Keynote address)
- Model-theoretic Correctness Criteria for Distributed Systems (in submission)

# Queries?