iCyPhy

Taking Advantage of Clock Synchronization in Distributed Computing

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Invited Keynote Talk

Workshop on Synchronization and Timing Systems (WSTS)

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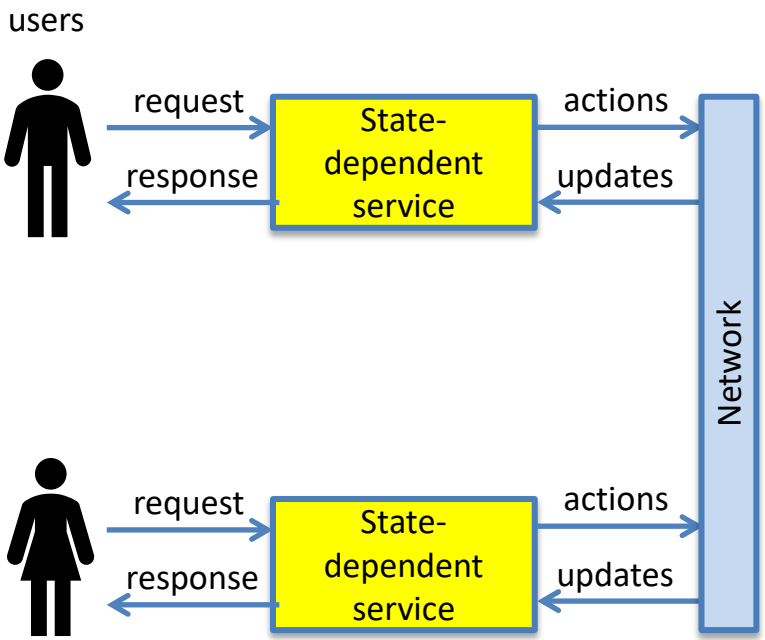
University of California at Berkeley

Distributed System Challenges



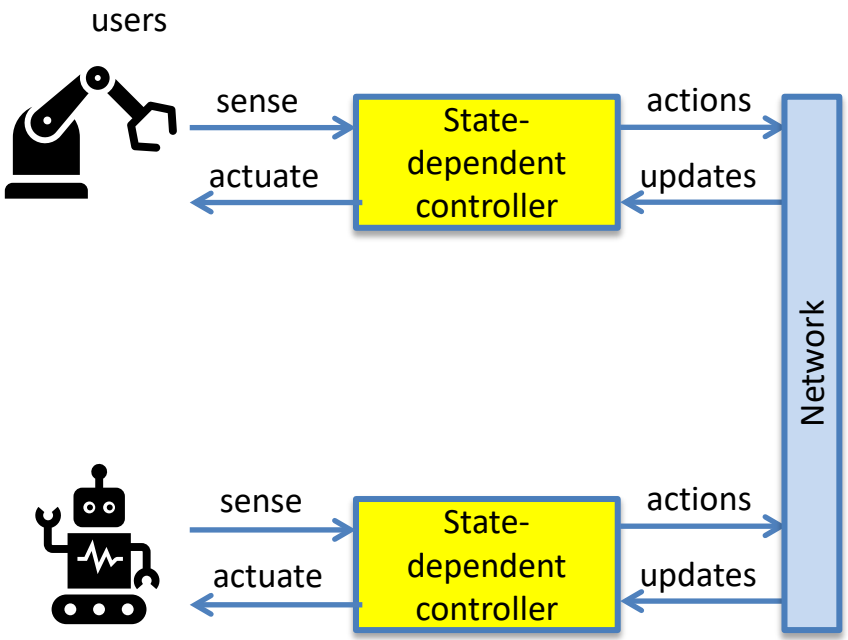
Examples

- Distributed banking
- Financial exchanges
- Auction systems
- Distributed logging

Requirements:

- Consistent balance
- Fair transactions
- Exactly one winner
- Agreement on ordering

Cyber-Physical Examples



Examples

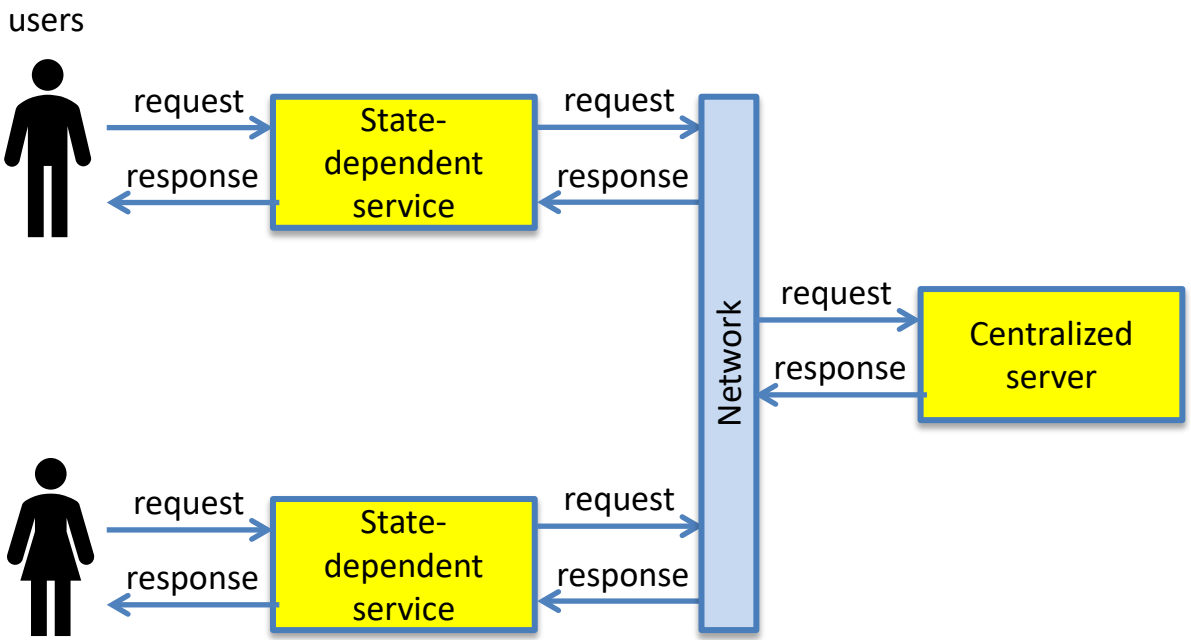
- Factory floor
- Traffic control
- Power systems

Requires a *consistent* view of system state

Requirements:

- Mutual exclusion
- Safe resource sharing
- Operating limits

Classic Centralized Solution



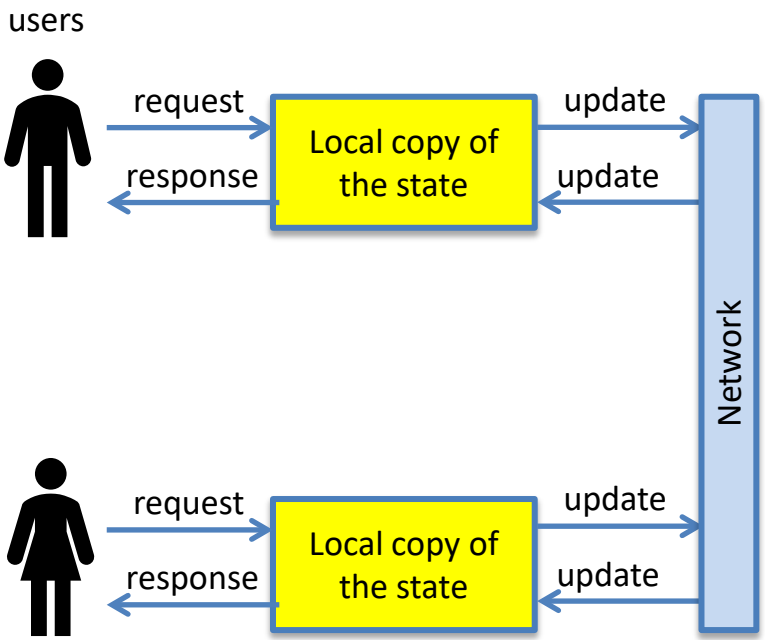
Problems

- Single point of failure
- Unfair (network latency)
- High latency

CAP Theorem: Cannot have

- Consistency
- Availability
- Partition tolerance

Decentralized Solution



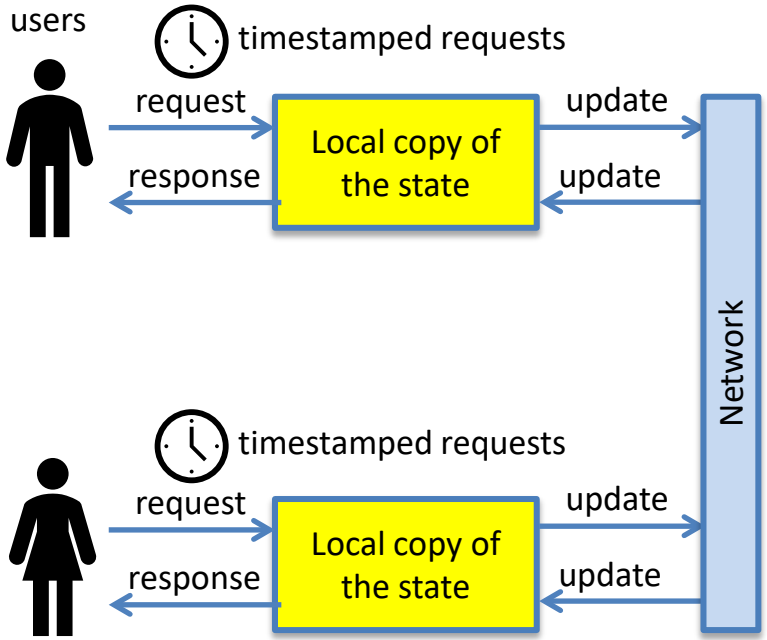
Naïve approaches

- Publish-and-subscribe
- Actors
- Remote procedure calls

Problems

- Inconsistency
- Nondeterminism

Principled Decentralized Solution



Goal:

- Synchronized clocks with bounded error *E*
- Handle events in timestamp order
- Consistency: agreement *at a timestamp*
- Availability: quick responses

Fundamental limit: CAL Theorem:
As ***apparent latency*** increases, either inconsistency or unavailability must increase.
Apparent latency = L + E + X

The Reactor Model of Computation

Reactors:
- Concurrent
- Deterministic
- Distributed
- Time sensitive

https://reactor-model.org

Coordination languages

Programming APIs

https://lf-lang.org

https://lf-lang.org/reactor-uc

https://xronos.com

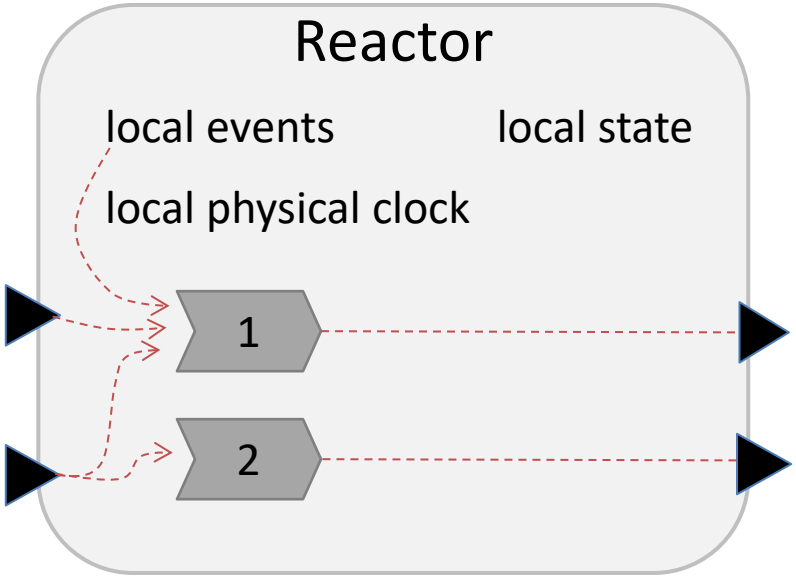
https://rosia.dev

The Reactor Model for Distributed Programs

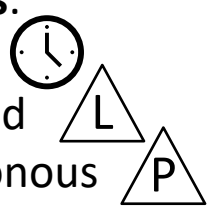
Input ports:
Timestamped events are received in timestamp order at each port.

Reactions:
Triggered by local and/or input events. Manipulate state.

Output ports:
Written to by reactions. Timestamp matches the trigger.



Local events:
- Periodic
- Scheduled
- Asynchronous



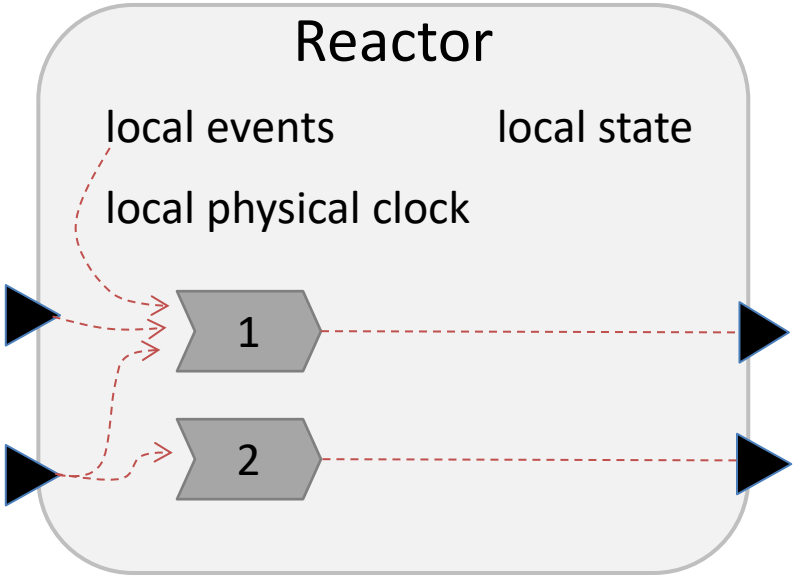
Local physical clock:
Local events are timestamped using this clock.

Goal is to process events in timestamp order.
When events are simultaneous, use reaction order.

Execution

Input ports:
Timestamped events are received in timestamp order at each port.

Reactions:
Triggered by local and/or input events. Manipulate state.



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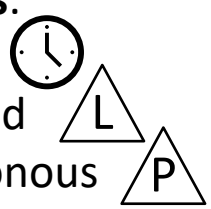

Local physical clock:
Local events are timestamped using this clock.

Output ports:
Written to by reactions.
Timestamp matches the trigger.

Advance local logical time to the timestamp *t* of the earliest next event. Execute triggered reactions in order.

Logical Time Chases Physical Time

Input ports:
Timestamped events are received in timestamp order at each port.

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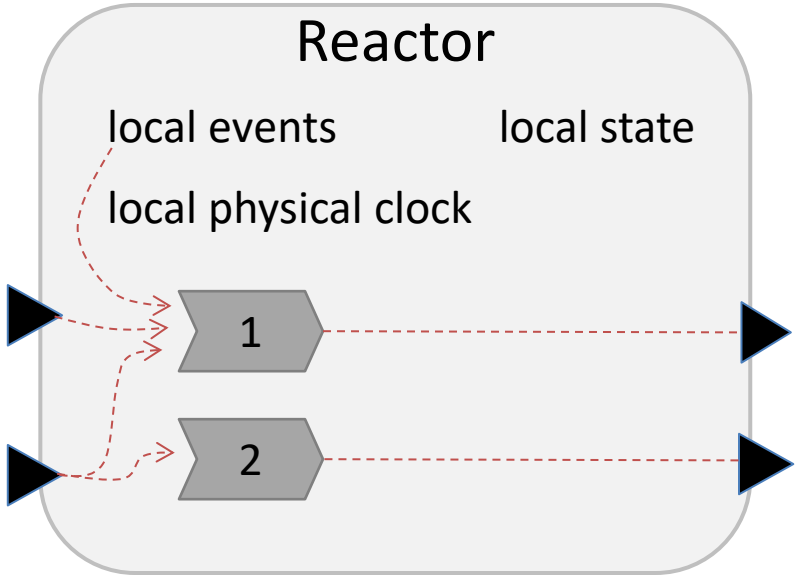
Written to by reactions. Timestamp matches the trigger.



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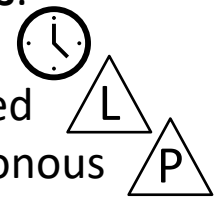

Local physical clock:
Local events are timestamped using this clock.

If local events are timestamped using the local physical clock, advancing to logical time *t* cannot occur before local physical time exceeds *t*.

In-Order Network Delivery

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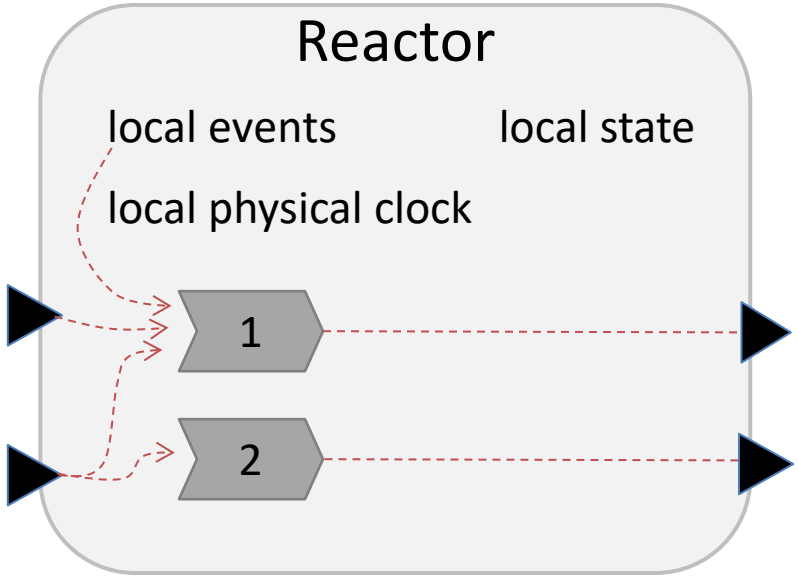

Local events:
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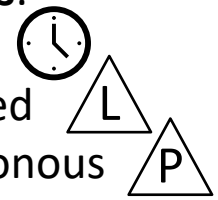
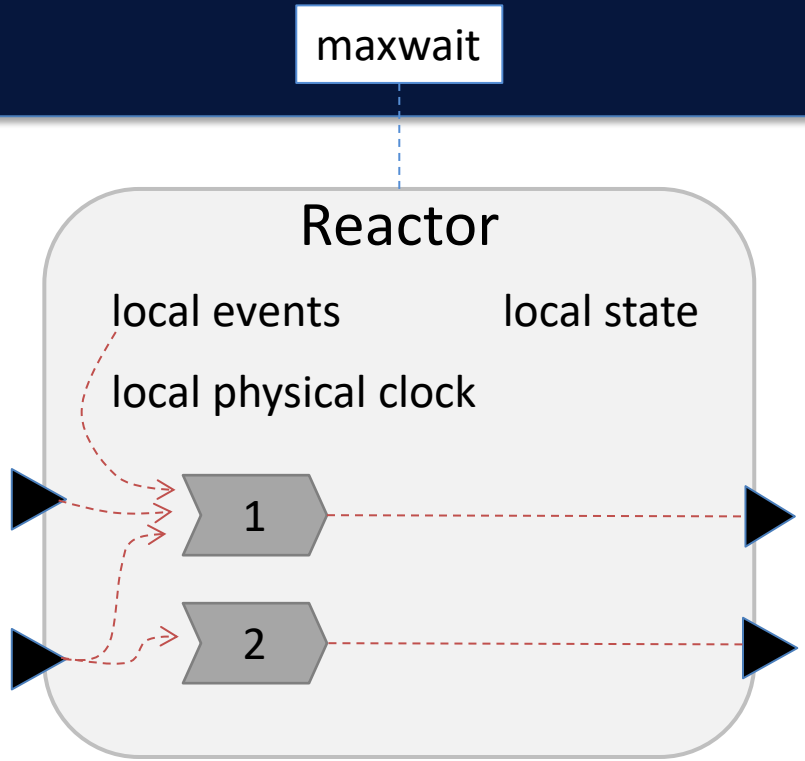


Local physical clock:
Local events are timestamped using this clock.

It is safe to advance to logical time *t* when local physical time exceeds *t* and inputs have been received on each input port with timestamp *t* or greater.

maxwait



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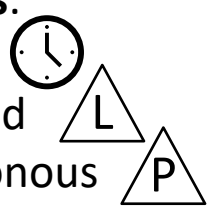
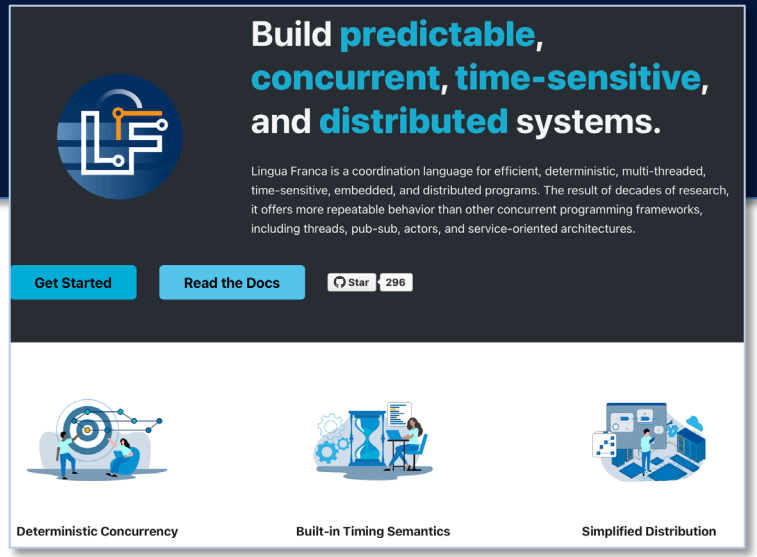


Local physical clock:
Local events are timestamped using this clock.

Advance to logical time *t* when either:
1. Inputs are known up to *t* and *T* > *t* (*T* = local physical time)
2. *T* > *t* + maxwait

Lingua Franca

Concurrent, distributed, timed, & deterministic by default

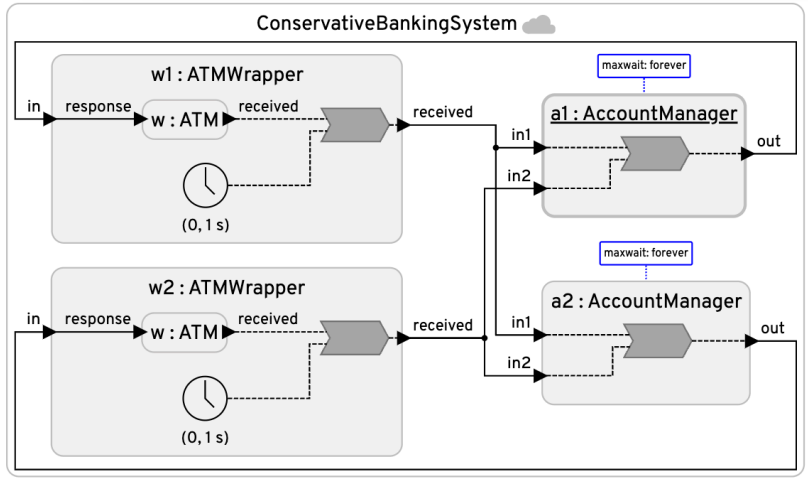


- A polyglot coordination language for high performance, secure, distributed, real-time, safety-critical software.
- An open source tool chain supporting development in C, C++, Python, Rust, and TypeScript: https://github.com/icyphy/lingua-franca
- Shows that time-stamped deterministic discrete-event models can execute efficiently.

- *Deterministic concurrency*
- Automatic multicore utilization
- Federated, distributed execution
- Real-time scheduling

https://lf-lang.org

Visualization of architecture is automatically generated from source.

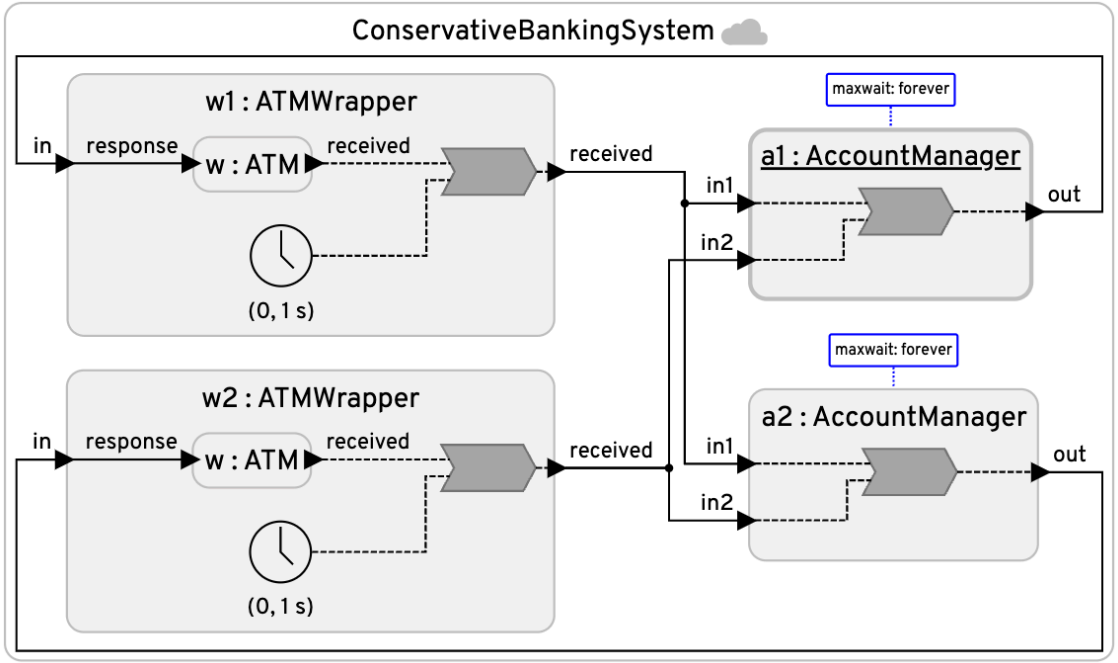


Strong Consistency: maxwait == forever

```
federated reactor {
  w1 = new ATMWrapper()
  w2 = new ATMWrapper()
  @maxwait(forever)
  a1 = new AccountManager()
  @maxwait(forever)
  a2 = new AccountManager()

  w1.received -> a1.in1
  w2.received -> a2.in2
  w1.received -> a2.in1
  w2.received -> a1.in2

  a1.out -> w1.in
  a2.out -> w2.in
}
```

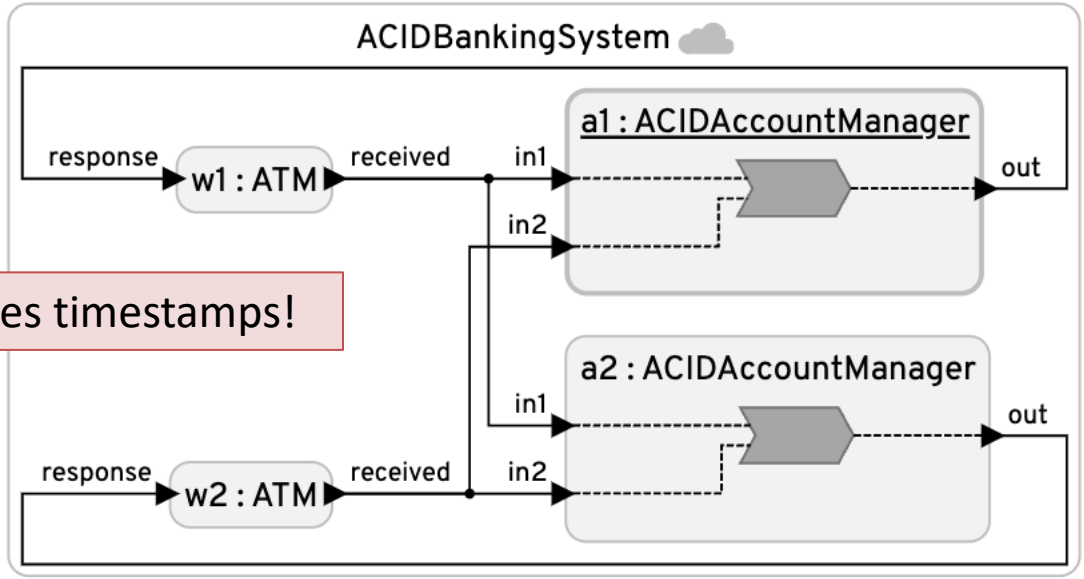


Chandy and Misra [1988] with NULL messages.

Alternative: Bounded maxwait to detect missing NULL messages (heartbeat).

Eventual Consistency Without Coordination

```
reactor ACIDAccountManager {
  input in1: int
  input in2: int
  output out: int
  state balance: int = 0
  reaction(in1, in2) -> out {=
    if (in1->is_present)
      self->balance += in1->value;
    if (in2->is_present)
      self->balance += in2->value;
    lf_set(out, self->balance);
  =} tardy
}
```

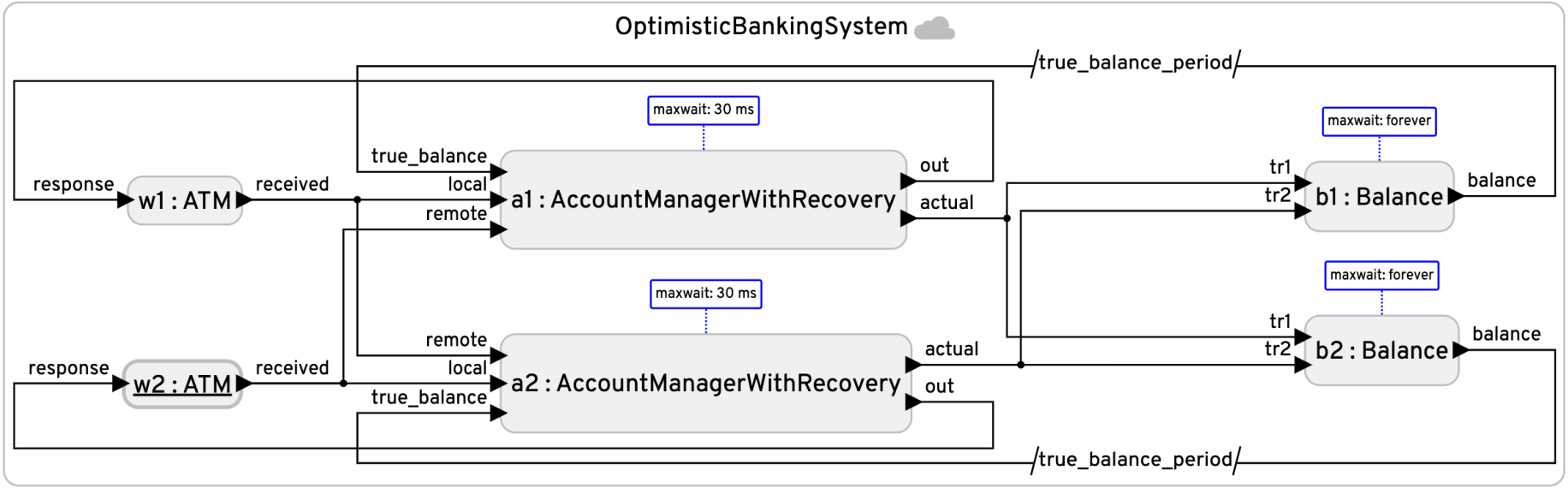


Ignores timestamps!

```
@maxwait(0)
a1 = new ACIDAccountManager()
@maxwait(0)
a2 = new ACIDAccountManager()
```

ACID 2.0 [Helland, 2021], CRDTs [Shapiro, et al., 2011], CALM [Hellerstein & Alvaro, 2021]

Optimistic Execution with Rollback



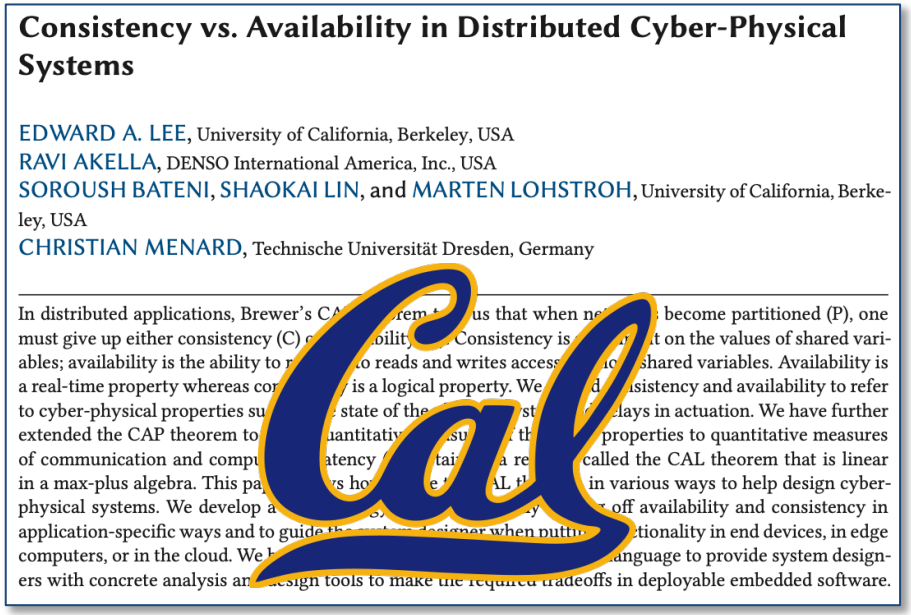
Guarantee 30 ms unavailability, taking measured business risk, and ensure perfect consistency (assuming eventual delivery).

TimeWarp [Jefferson, 1985]

Fundamental Limits

Consistency fundamentally comes with a cost in availability, where the cost is proportional to apparent latency ($L + E + X$).

Reactors with maxwait (and absent_after) enable explicitly managing this tradeoff and detecting faults as early as possible.



Consistency vs. Availability in Distributed Cyber-Physical Systems

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Lee, E. A., et al. (2023). "Consistency vs. Availability in Distributed Cyber-Physical Systems." ACM Transactions on Embedded Computing Systems (TECS) **22**(5s): 1-24.

Conclusion

All of this depends on clock synchronization with bounded error.

Reactors with maxwait handle a surprising variety of distributed computing patterns:

- Chandy-and-Misra [1988]
- Fault tolerant Chandy-and-Misra
- Logical Execution Time (LET)
- ACID/CRDT/CALM
- Optimistic with or without rollback
- Remote procedure calls (RPC) with futures
- Pub-Sub (maxwait == 0, output port is a topic)
- Actors (maxwait == 0)

Maxwait: A Generalized Mechanism for Distributed Time-Sensitive Systems, by Francesco Paladino, Shulu Li, Edward A. Lee, arXiv:2601.21146, Jan. 2026.