Workspace Consistency: A Programming Model for Shared Memory Parallelism

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Question

Do we want just

deterministic program execution,

or a

deterministic programming model?

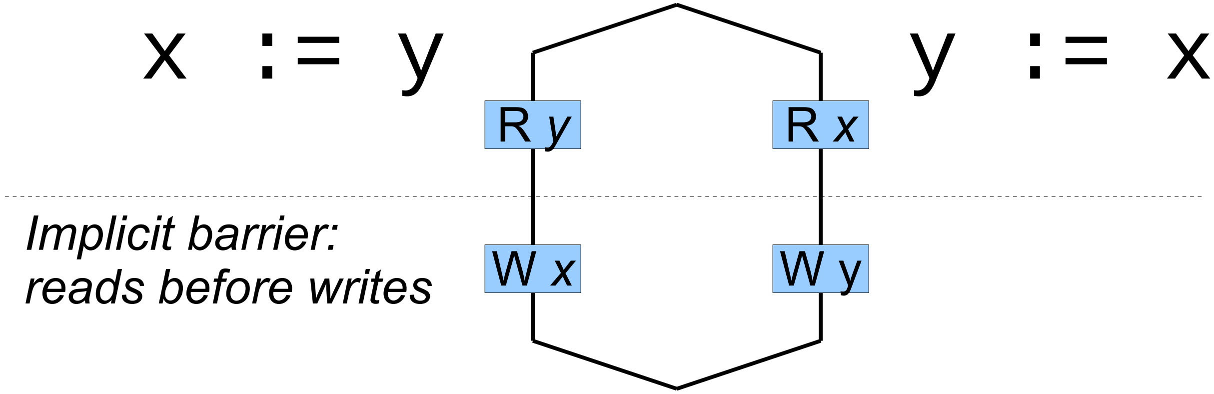
This talk will not answer that question,
but maybe it'll make you think about it.

Ex. 1: Variable Swap

Many languages have "parallel assignment"

```
x,y := y,x
```

Not true parallelism, but similar in spirit to "two assignments in parallel":



Has predictable, **deterministic semantics!**

Workspace Consistency (WC)

Simplistic definition:
A consistency model where parallel threads

1. Read shared state, “check out” a workspace
2. Execute and mutate *private* workspace
3. Write or “check in” changes to shared state

Just like “parallel assignment” semantics
(or version control – see previous talk!)

Ex. 1 (cont): Variable Swap

Suppose we write a “parallel assignment” with *real* threads running assignments in parallel:

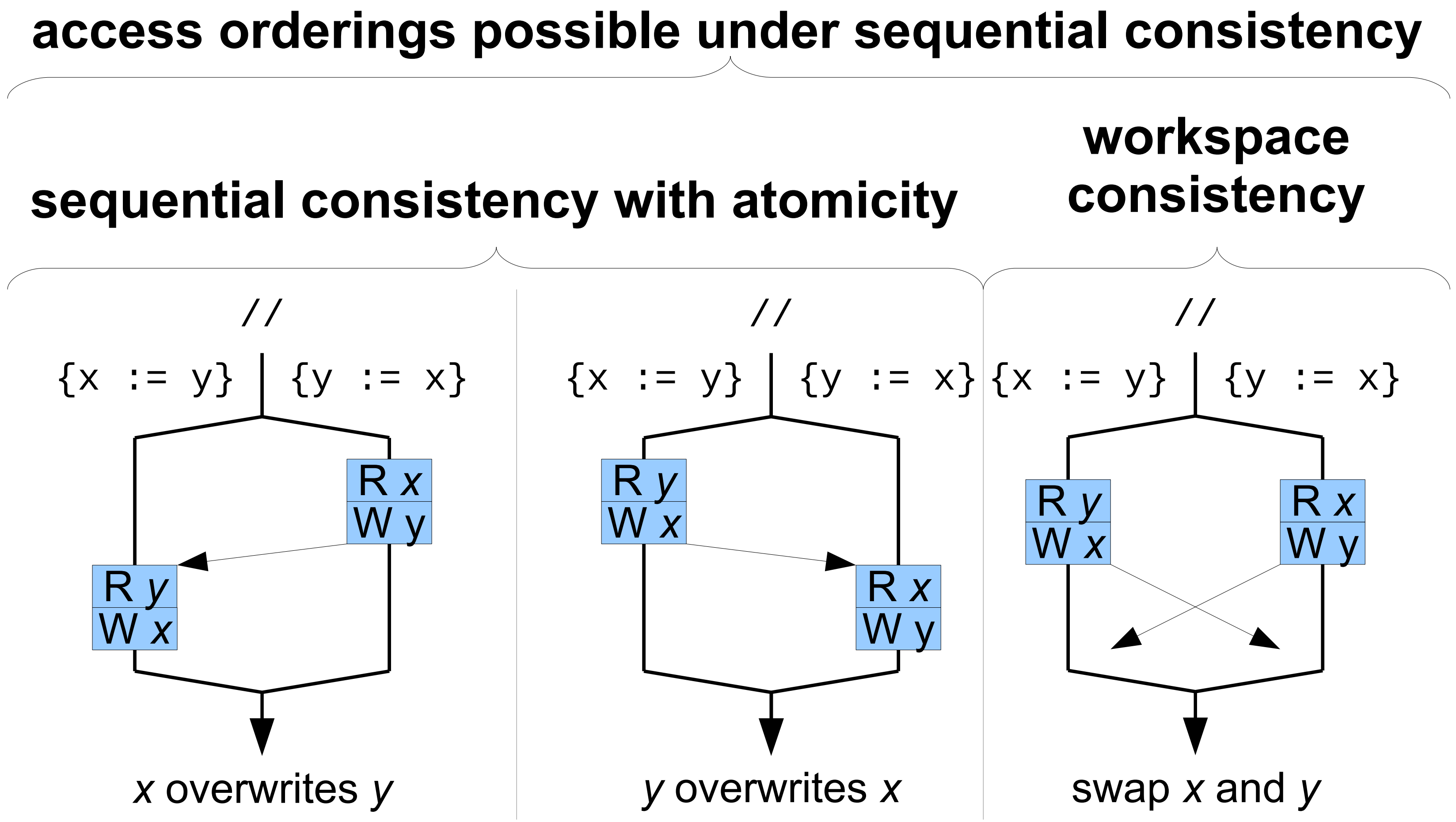
```
{ x := y } // { y := x }
```

Block-structured fork/join operator

How does this code behave under:

- Sequential consistency (SC)?
- SC with assignments in locks/transactions?
- Workspace consistency (WC)?

Ex. 1 (cont): Variable Swap

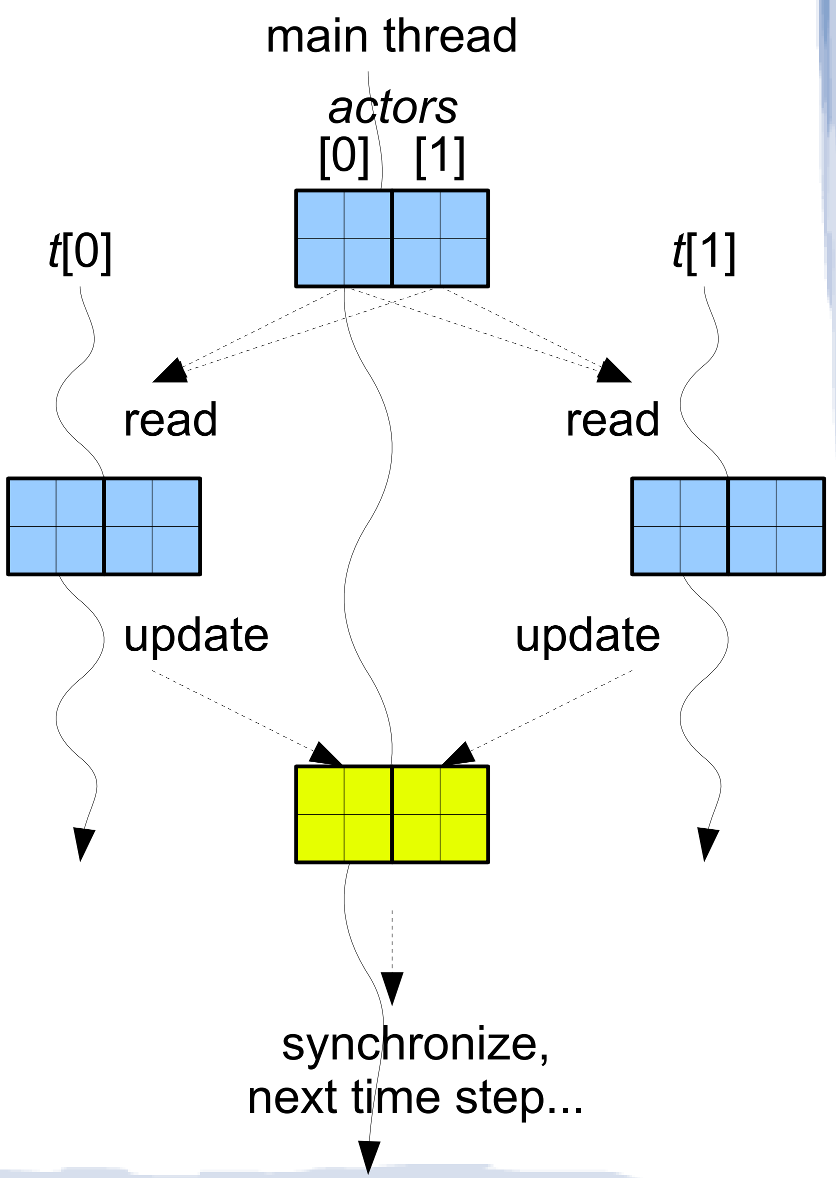


Ex. 2: Gaming/Simulation, Sequential Consistency

```
struct actorstate actor[NACTORS];

void update_actor(int i) {
        ...examine state of other actors...
        ...update state of actor[i] in-place...
}

int main() {
        ...initialize state of all actors...
        for (int time = 0; ; time++) {
                thread t[NACTORS];
                for (i = 0; i < NACTORS; i++)
                        t[i] = thread_fork(update_actor, i);
                for (i = 0; i < NACTORS; i++)
                        thread_join(t[i]);
        }
}
```



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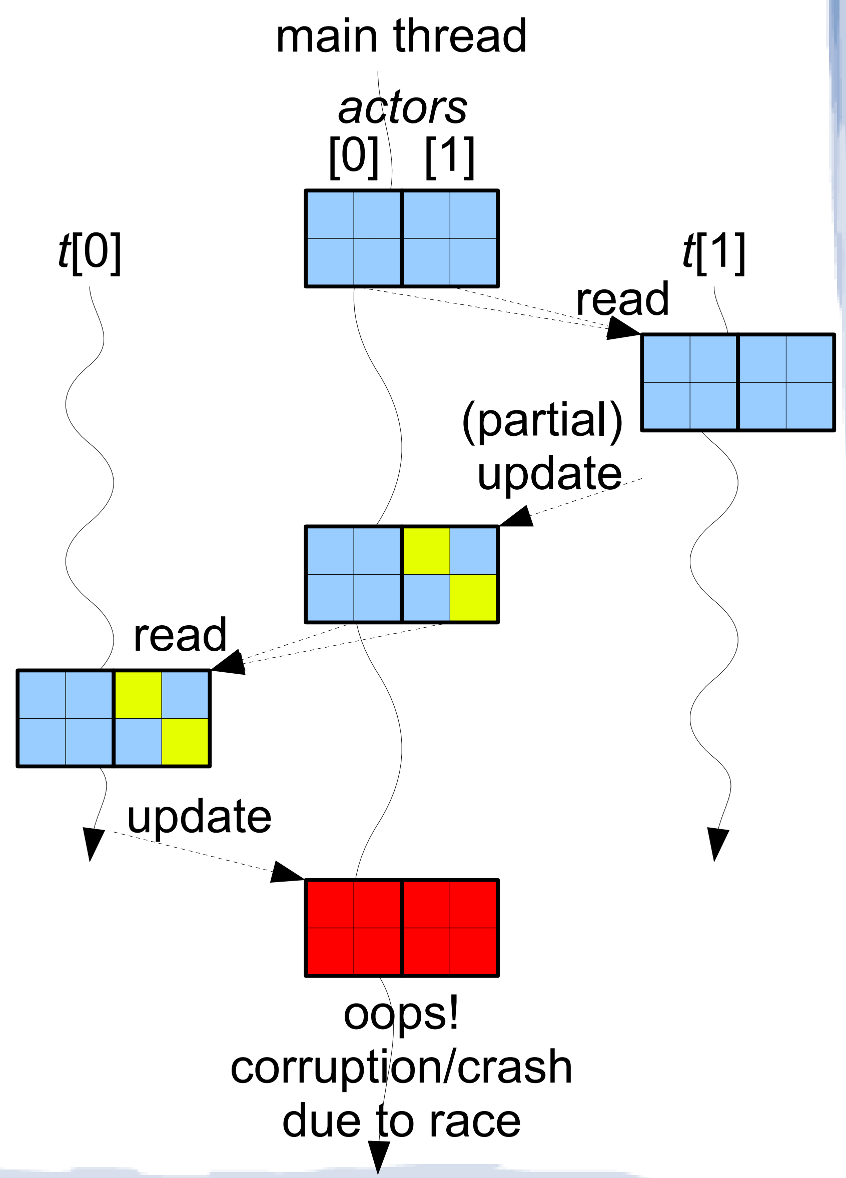

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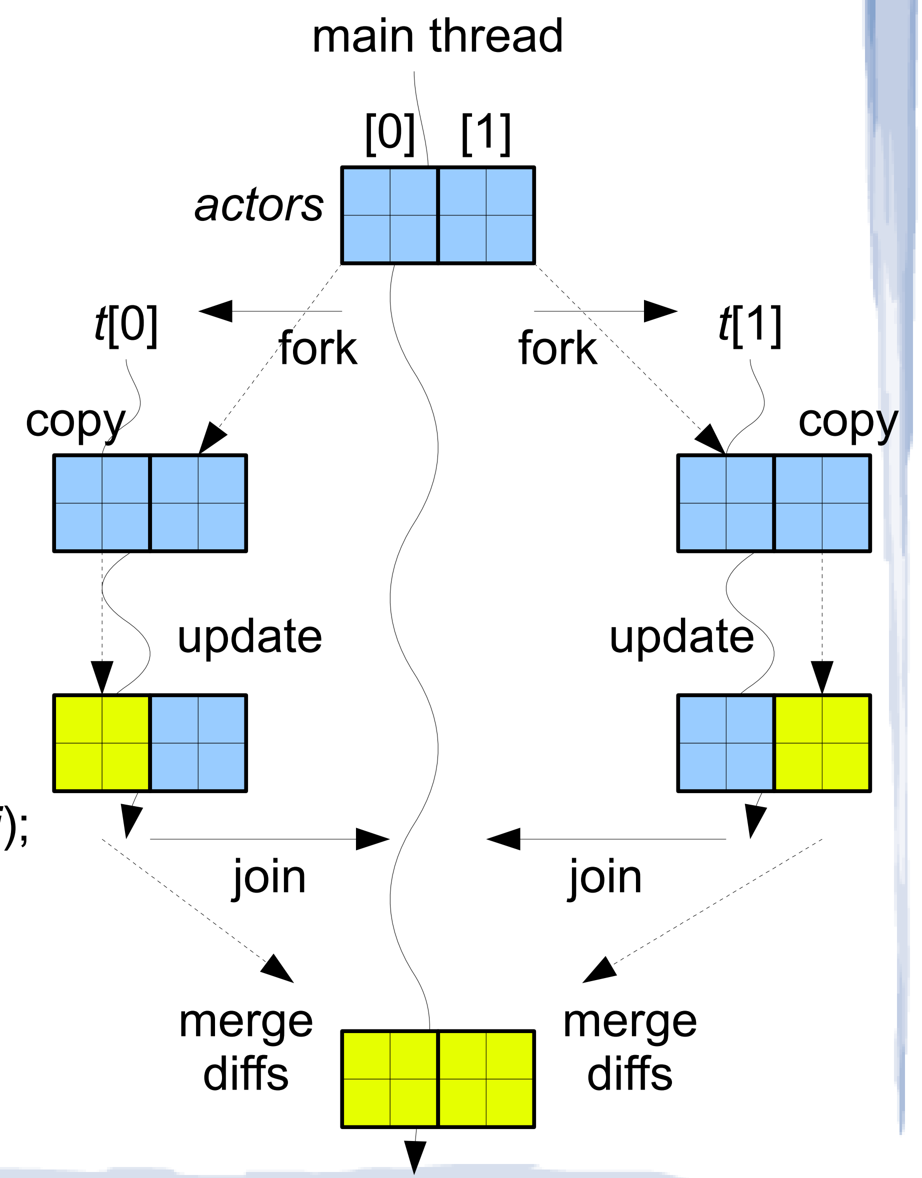


Why Workspace Consistency?

Offers *naturally deterministic* parallel semantics

- Synchronization semantics always *fully define* which prior computed results *do* – and *don't* – affect which blocks of code.
- Behavior depends *only* on structure of code, not on any imposed schedule, *real or artificial.*
- *Less familiar* than sequential consistency, but perhaps equally or *more intuitive*?

(wild subjective claim alert!)

Seen this Before?

In the simple **fork/join** model, this is *not* new

- Early: Parallel Fortran systems
  - Burroughs FMP [Schwartz '80]
  - Myrias Parallel Computer [Beltrametti '88]
- …
- Recent: Language and OS mechanisms
  - Revision/Isolation Types [Burckhardt '10]
  - Determinator OS [Aviram '10]

Many Dimensions of Determinism

	Cilk	Kendo	Grace	CoreDet	Determinator
Deterministic **synchronization semantics**	✓		✓		✓
Deterministic **synchronization behavior**	✓	✓	✓	✓	✓
Deterministic **memory access behavior**			✓	✓	✓
Deterministic **speculation-free execution**	✓	✓		✓	✓

Workspace Consistency

Defining and Generalizing WC

This paper attempts to:

- Give this programming model a name :)
- Define WC more precisely
  - Identify exact conditions for determinism
- Generalize to high-level parallel abstractions
  - Including *non-hierarchical:* pipelines, futures, arbitrary dependency graphs
- Map high-level constructs to simple primitives

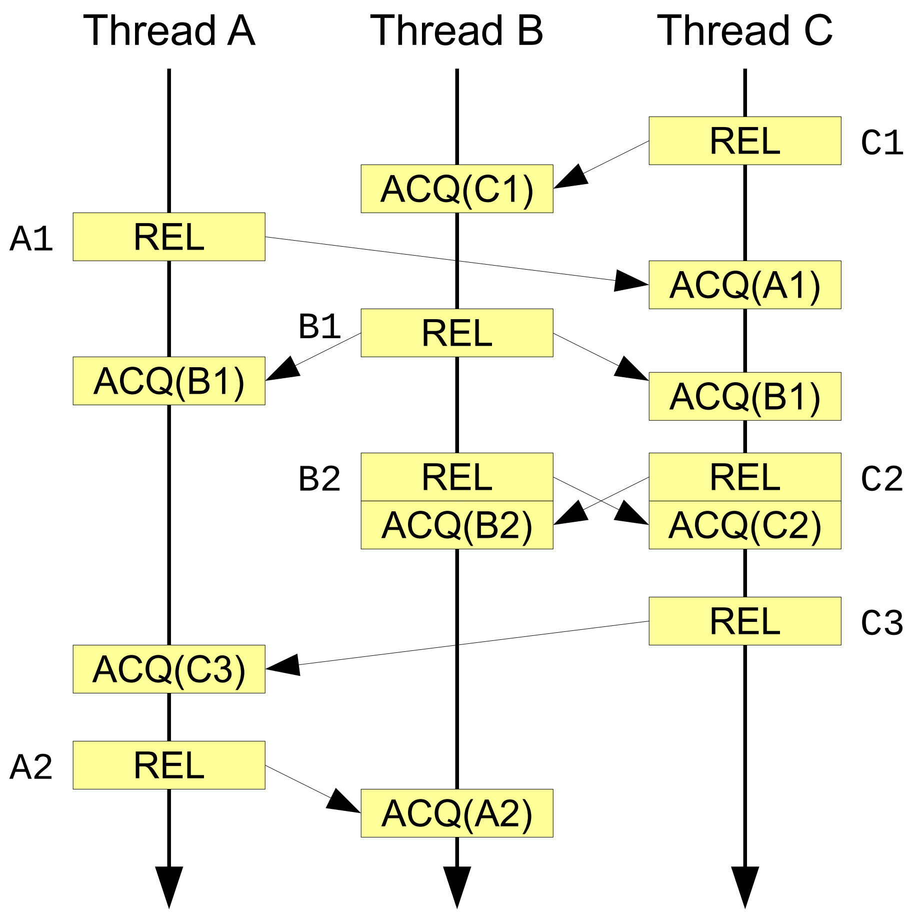
Defining Workspace Consistency

1. Deterministic *synchronization semantics:*
   - Synch occurs at **release** and **acquire** events
   - Program logic alone *uniquely* defines:
     - At what points **release**, **acquire** events occur
     - Which **release** event “feeds” each **acquire**
2. Deterministic *memory behavior:*
   - Updates propagate between threads when, and *only* when, *mandated* by synchronization
   - Conflicting parallel writes handled deterministically at relevant **acquire**

Synchronization in WC

"Primitive" approach:

- Label each **release** (threadID, release#)
- Each **acquire** explicitly names specific **release**
- **acquire** waits for, merges updates from that **release**



Why is WC deterministic?

Inductive argument (informal):

- *Assuming:*
  - Sequential code is deterministic
  - No cyclic dependencies (deadlock-free)
- Program state at each **release** determined uniquely by *causally prior* code, data, events
- State feeding into each **acquire** determined uniquely by own state + paired **release**

Yields *unique* synchronization graph

Example Primitive Thread API

Primitive thread/synchronization operations:

- $t \leftarrow$ **fork**(fun): create new thread *t* at version 0
- **rel**(): release current thread's next version #
- **acq**(*t*, *v*): acquire version *v* from thread *t*
- **exit**(): stop thread and release version ∞

First **release**() in thread *t* releases version 1, etc.

High-level Synchronization

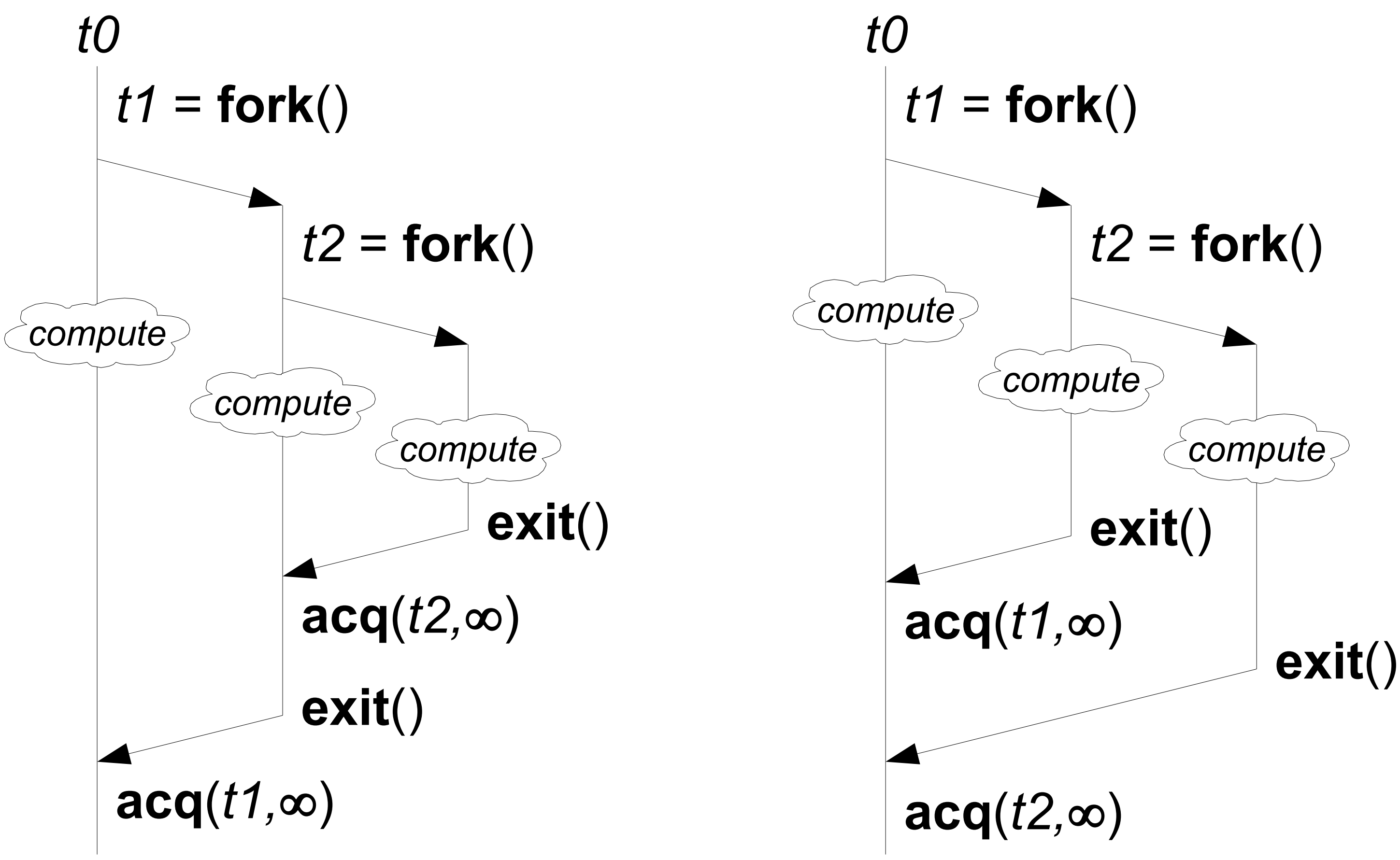
What is interesting about this primitive API?

1. It satisfies WC's conditions for determinism
2. Many high-level synchronization abstractions are easily constructed atop it.

Examples:

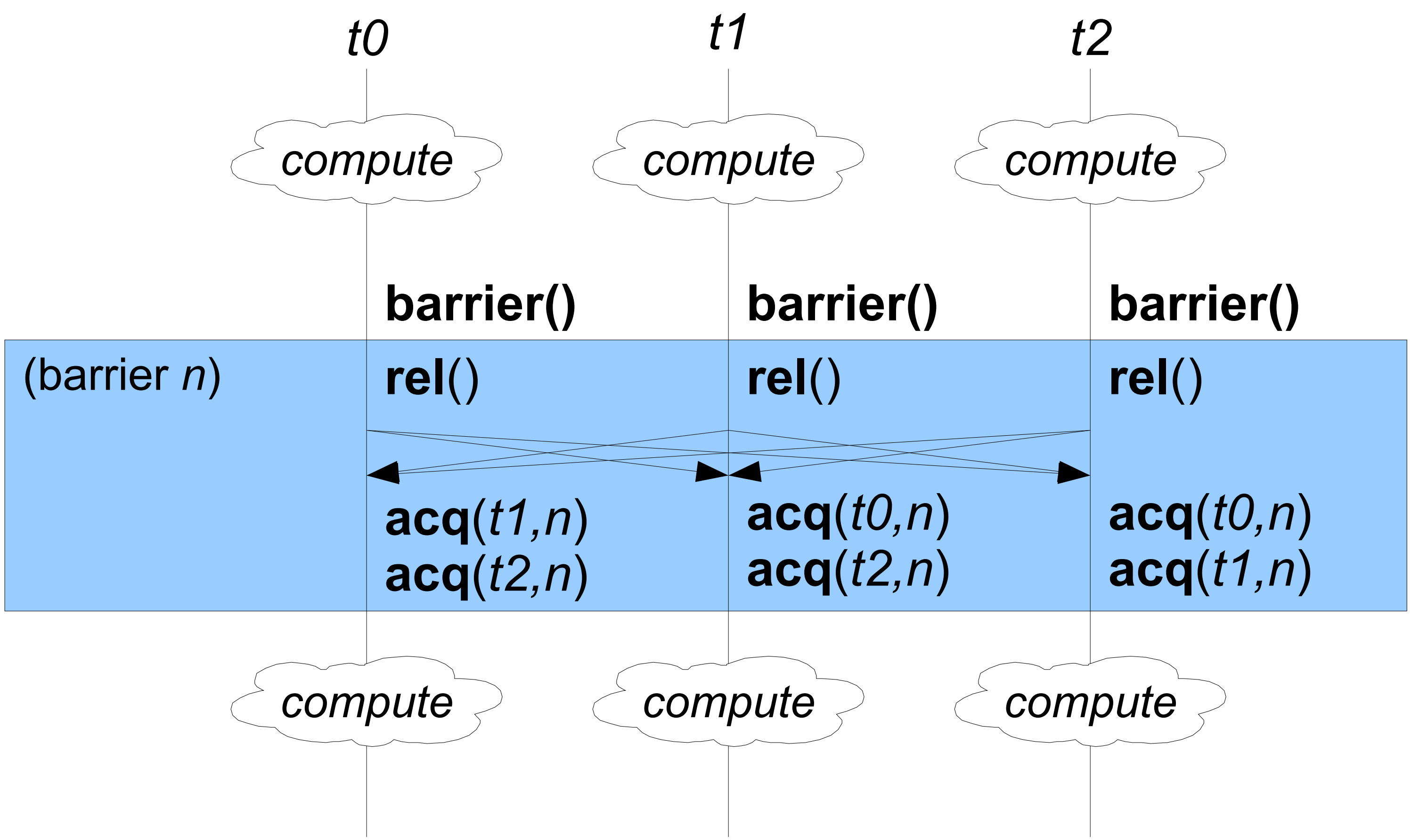
- Hierarchical: fork/join, barrier, task, reduction
- Non-hierarchical: pipeline, future

Example: Fork/Join, Futures



(as in Revision/Isolation Types model)

Example: Barrier Synchronization

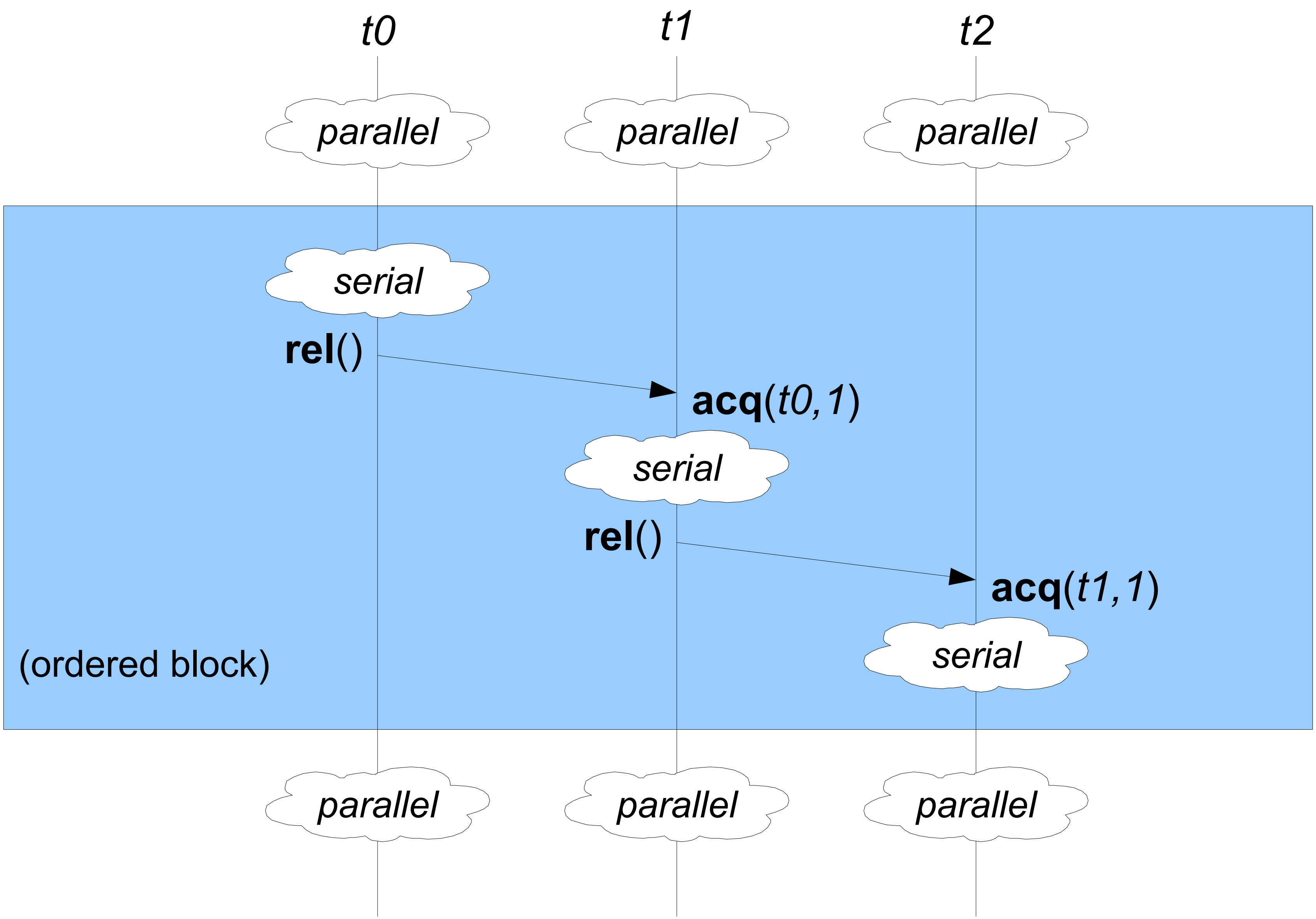


Example: Partially Ordered Loops

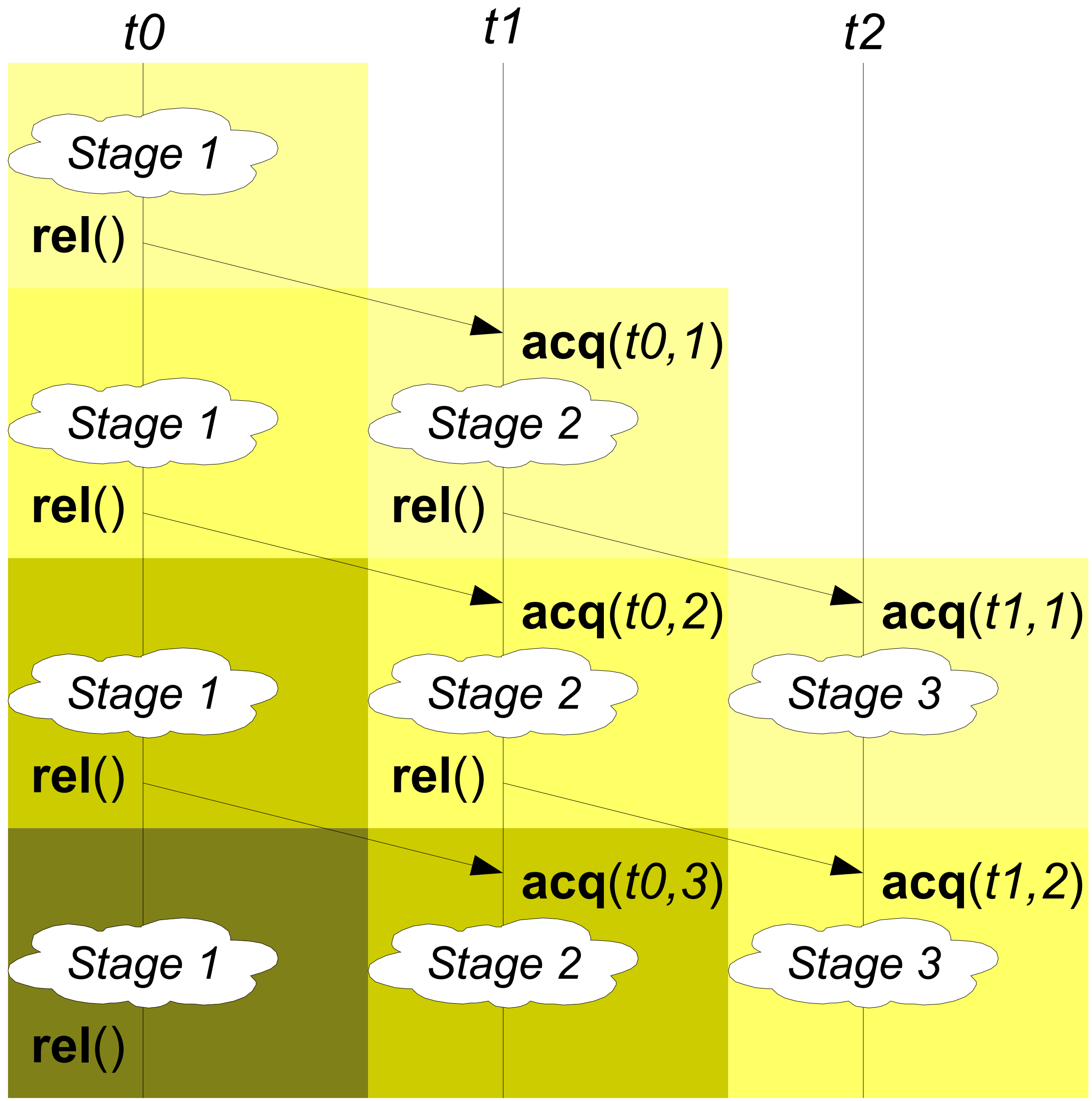
OpenMP feature:
parallelize a loop body across iterations, *but* order an interior block by iteration count

```
#pragma omp parallel for
for (i = 0; i < 3; i++) {

   parallel block

   #pragma omp ordered
   {
      serial block
   }

   parallel block
}
```

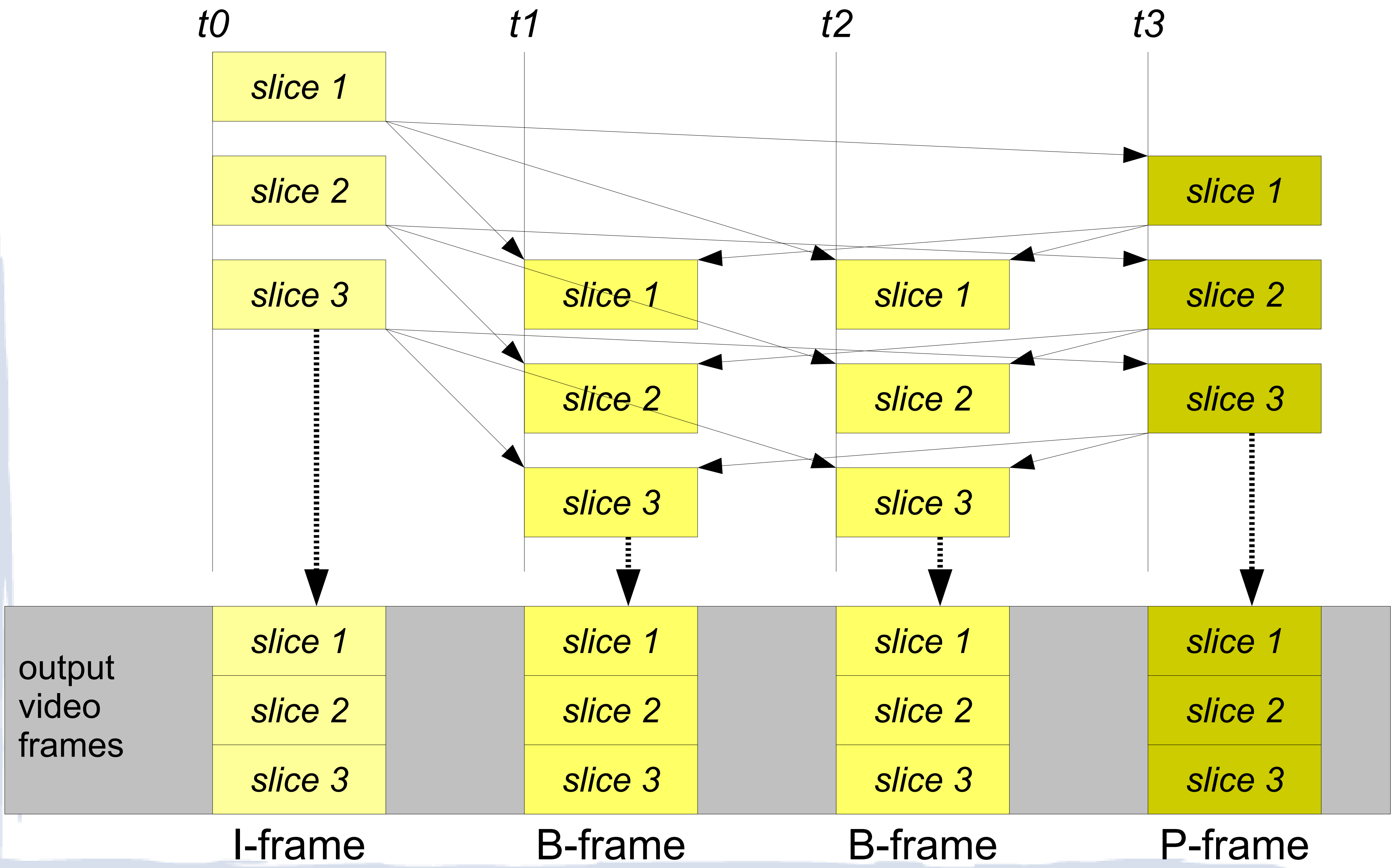
Example: Partially Ordered Loops



Example: Simple Pipelines

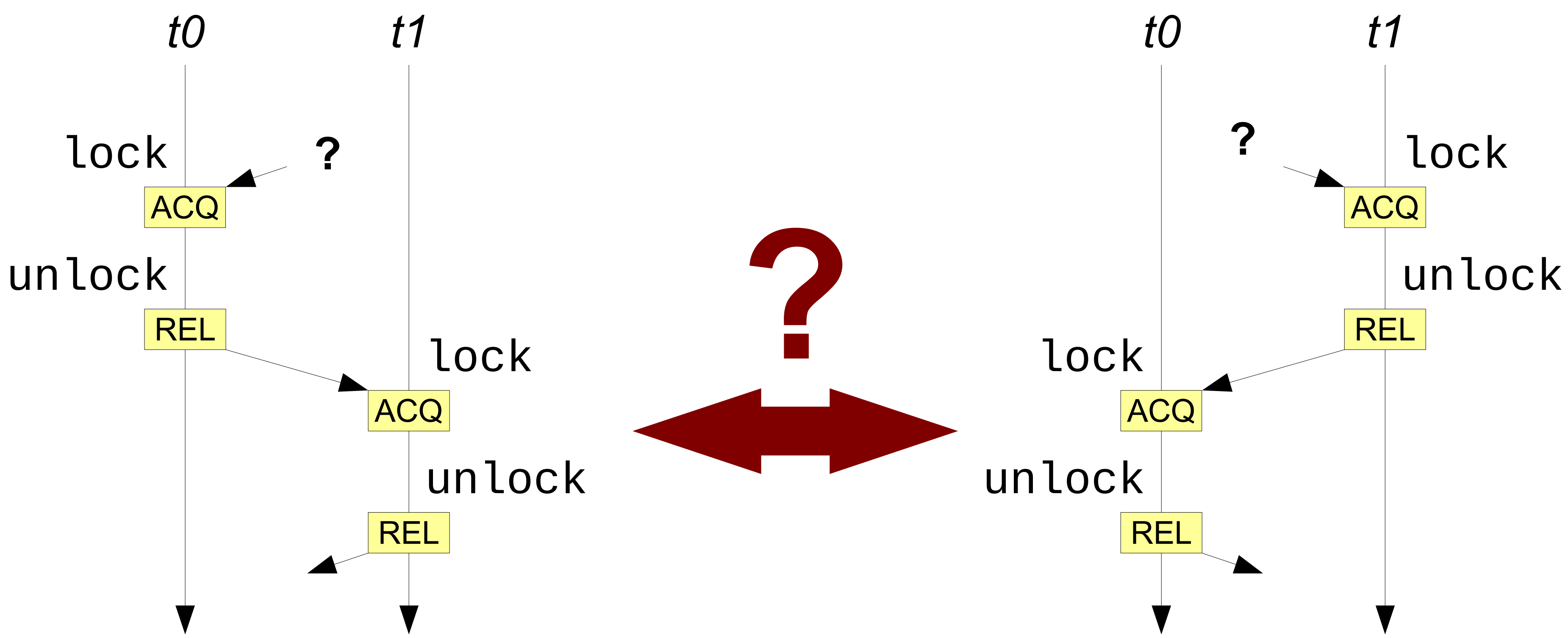


Tasks with Explicit Dependencies



What does WC *not* support?

Nondeterministic synchronization: e.g., mutexes



What *else* does WC not support?

Not sure – Future Work!

Determinizing Memory Access

WC assumes *serial code* is deterministic

Only true if we either:

- Assume code is race-free (weak determinism)
- Determinize regular memory accesses too

For strong determinism, we must “diff-&-merge” memory over *arbitrary* synchronization graphs

- Not necessarily straightforward!

Determinizing Memory Access

Build on Lazy Release Consistency (LRC)

- Created for distributed shared memory (DSM)
- Supports version-based update propagation via **release/acquire** pairing, as WC requires
- **Key change for WC:** propagate updates at – *and never before* – acquire/release pairs
  - No "eager update pushes" as in usual LRC
- Practical? Remains to be seen!

Implementation Work In Progress

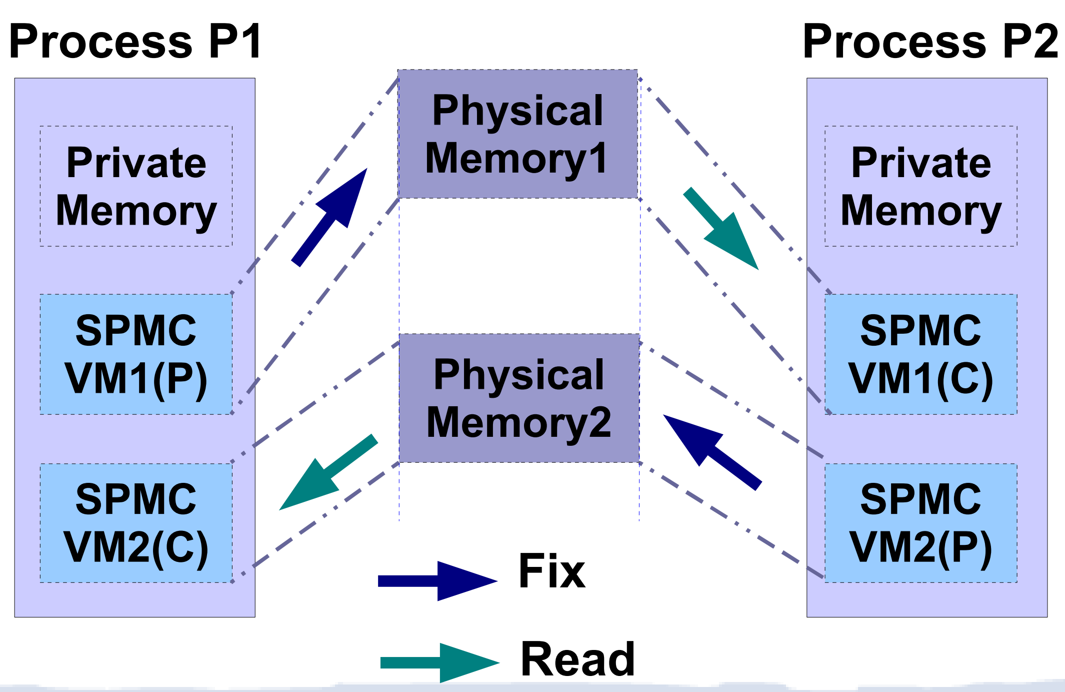
High-level: **Deterministic OpenMP (DOMP)**

- Builds on OpenMP for familiarity, convenience
- Enriches OpenMP's deterministic abstractions
  - General user-defined **reductions**
  - **Pipelines** and multiple **ordered** blocks
  - Explicit, dynamic **task synchronization**
- Reduce programmers' need to “escape” to non-deterministic synchronization
  - Further details to appear in HotPar '11

Implementation Work In Progress

Low-level: **Determinator OS** [OSDI '10]

- Add *non-hierarchical synchronization* via **producer/consumer virtual memory**



Conclusion

Workspace Consistency gives programs deterministic **semantics**, not just **execution**

- Simple memory state propagation model
  - As in parallel assignment, version control
- Can support interesting high-level abstractions
  - Fork/join, future, barriers, pipelines, etc.
- Reduce to powerful **release/acquire** primitives

Determinator-based prototype in progress

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