Transactions with Nested Parallelism

(Adding Transactions to Cilk)

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TRANSACT

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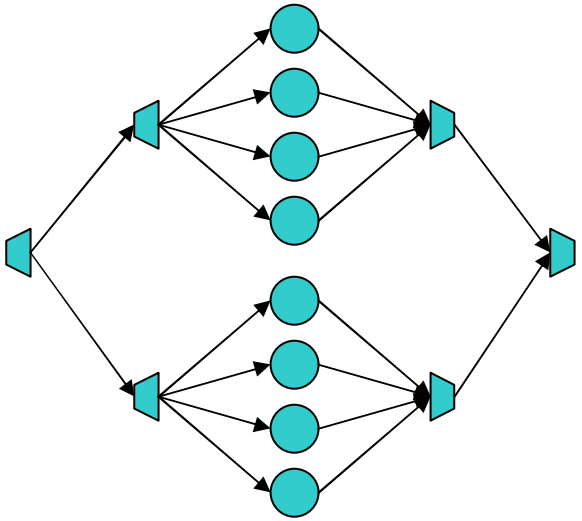
A Sample Cilk Program

```
int supply1[10000];
int supply2[10000];
int N = 4;
cilk int main() {
  spawn buy_computer(supply1);
  spawn buy_computer(supply2);
  sync;
  return 0;
}
cilk void buy_computer(int* c) {
  i = rand() % (10000-N);
  for (j = 0; j < N; j++)
     spawn buy_part(c, i+j);
  sync;
}
cilk void buy_part(int* c,
                   int i)
{  c[i]--;  }
```



A Cilk program which updates inventory after buying two computers.

Purchasing a computer decrements parts from the inventory arrays, **`supply1`** and **`supply2`**, potentially in parallel.

Cilk Runtime and Performance

```
int supply1[10000];
int supply2[10000];
int N = 4;
cilk int main() {
  spawn buy_computer(supply1);
  spawn buy_computer(supply2);
  sync;
  return 0;
}
cilk void buy_computer(int* c) {
  i = rand() % (10000-N);
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cilk void buy_part(int* c,
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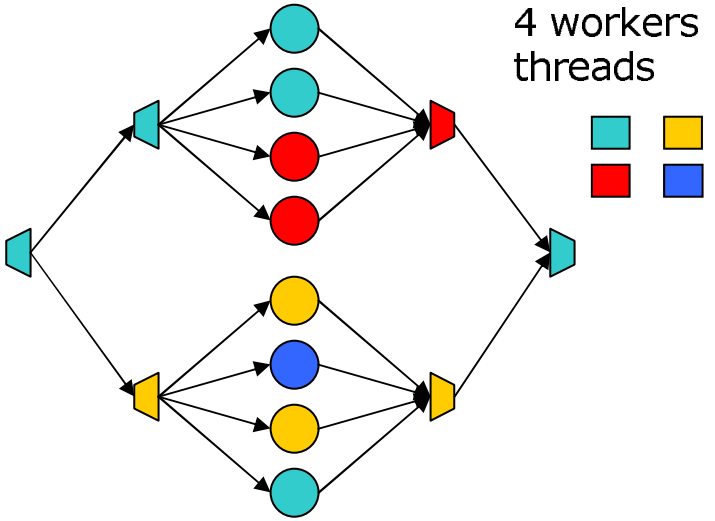


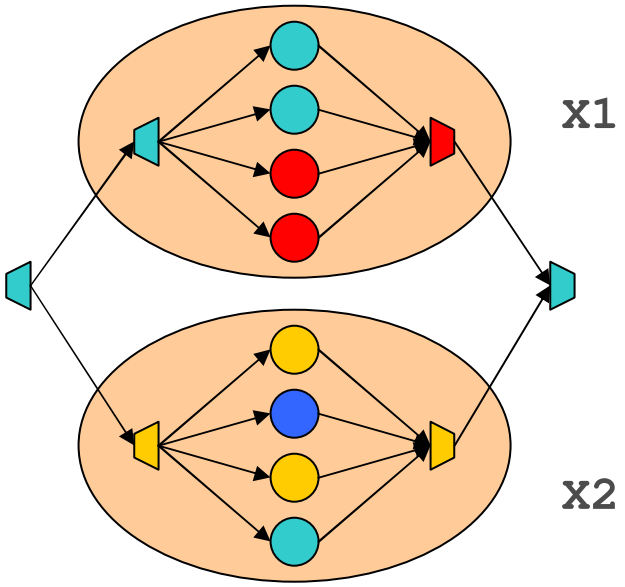
$T_1 = 16,\ T_\infty = 5,\ P=4$

The Cilk runtime schedules the program using work-stealing. Cilk executes a computation with work T_1 and span (critical path) T_∞ on P processors in time $O(T_1 / P + T_\infty)$, w.h.p.

Transactions in Cilk?

```
int supply1[10000];
int N = 4;
cilk int main() {
 spawn buy_computer(supply1); //X1
 spawn buy_computer(supply1); //X2
 sync; return 0;
}
cilk void buy_computer(int* c) {
  atomic {
   i = rand() % (10000-N);
   for (j = 0; j < N; j++)
      spawn buy_part(c, i+j);
   sync;
  }
}
cilk void buy_part(int* c, int i)
{  c[i]--;  }
```

4 workers

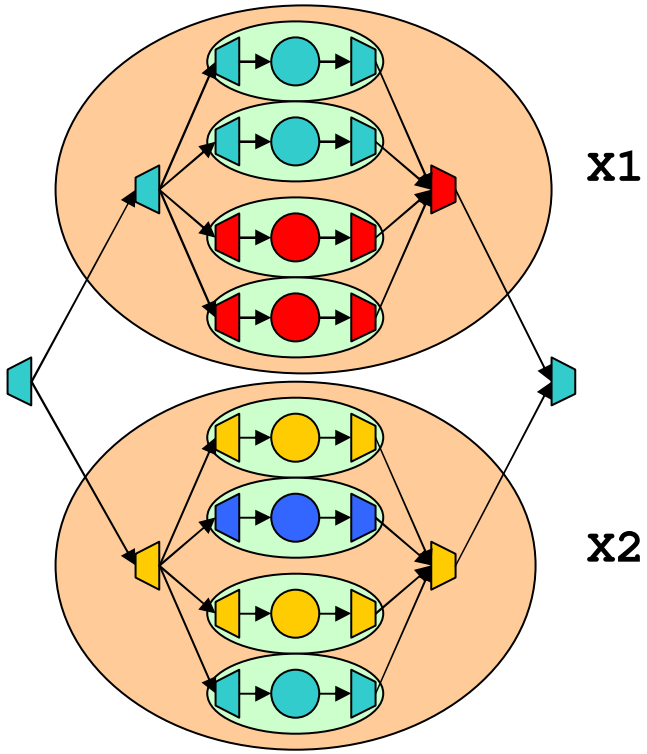


Suppose both computers require parts from the same inventory.
Can we use transactions to ensure both calls to `buy_computer()` are atomic, even though `X1` and `X2` contain nested parallelism?

Transactions with Nested Parallelism and Nested Transactions?

```
int supply1[10000];
int N = 4;
cilk int main() {
 spawn buy_computer(supply1); //X1
 spawn buy_computer(supply1); //X2
 sync; return 0;
}
cilk void buy_computer(int* c) {
  atomic {
   for (j = 0; j < N; j++) {
       i = rand() % 10000;
       spawn buy_part(i);
   }
   sync;
  }
}
cilk void buy_part(int* c, int i)
{  atomic { c[i]--; } }
```

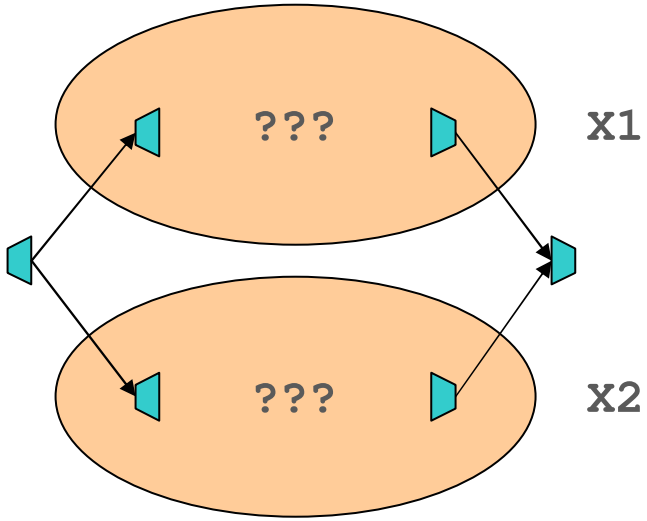
4 workers



Suppose each computer can use more than one of the same part. Can we have parallel transactions nested inside **X1** and **X2**?

Motivation: Library Functions

```
int supply1[10000];
int N = 4;
cilk int main() {
  spawn buy_computer(a); // X1
  spawn buy_computer(a); // X2
  sync;  return 0;
}
cilk void buy_computer(int* c) {
 atomic {
    spawn foo(c);
    sync;
 }
}
cilk void foo(int* c) {
    ???
    // spawn?
}
```



If transactions can have nested parallelism and nested transactions, then we can composably call some library functions written using Cilk inside a transaction without knowing their exact implementation.

XCilk Design

- We describe XCilk, a theoretical design for a software transactional memory system for Cilk which supports transactions with nested parallelism and nested transactions, both of *unbounded nesting depth*.
- XCilk uses an XConflict data structure to efficiently check for transaction conflicts.
- XCilk lazily cleans up memory locations on aborts.

XCilk Bounds on Overhead

XCilk provides a provable bound on the overhead of TM in the following special case:

- For a computation with no transaction conflicts and no concurrent readers to a shared memory location, if the computation has work T_1 and critical path T_∞, XCilk executes the computation on P processors in time

$$O(T_1 / P + PT_\infty).$$

Linear speedup if $P = O(\sqrt{(T_1/T_\infty)})$, vs. $O(T_1/T_\infty)$ for normal Cilk.

- The XCilk runtime system still works correctly in the general case, with conflicts and parallel readers.

Outline

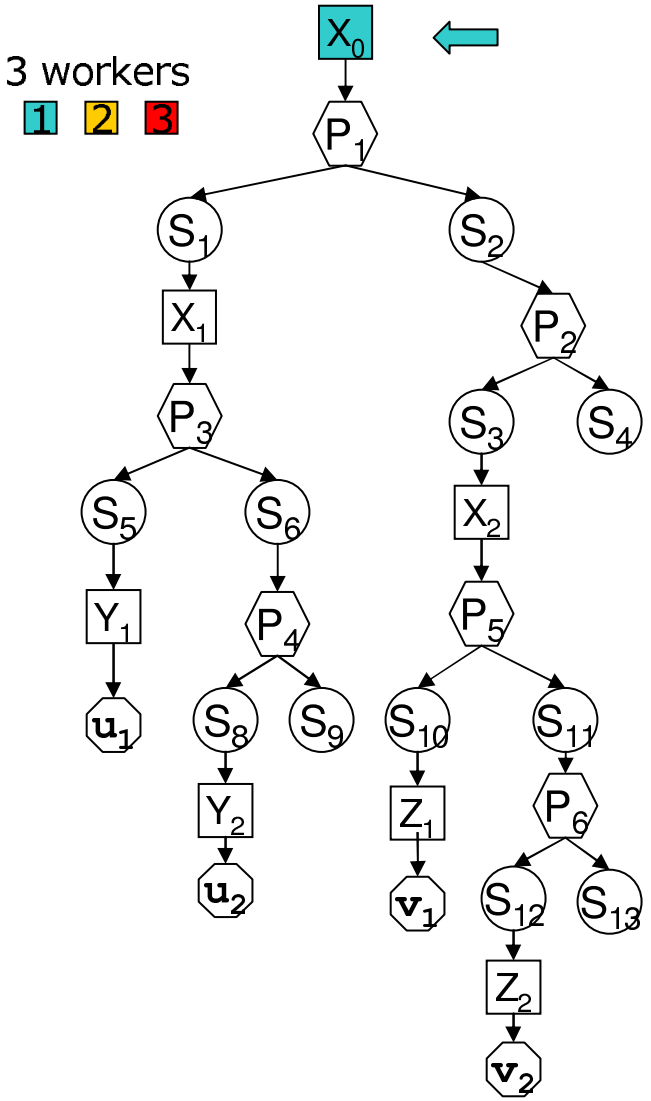
- Definition of Conflict in XCilk
- Efficient XConflict Queries

Summary of XCilk Semantics

- XCilk performs eager conflict detection.
- Transactions in XCilk are closed-nested.
- These two conditions imply a prefix race-free execution [ALS06]. If the effects of aborted transactions can be "ignored", then prefix race-freedom ≈ serializability.

XCilk Computation Tree

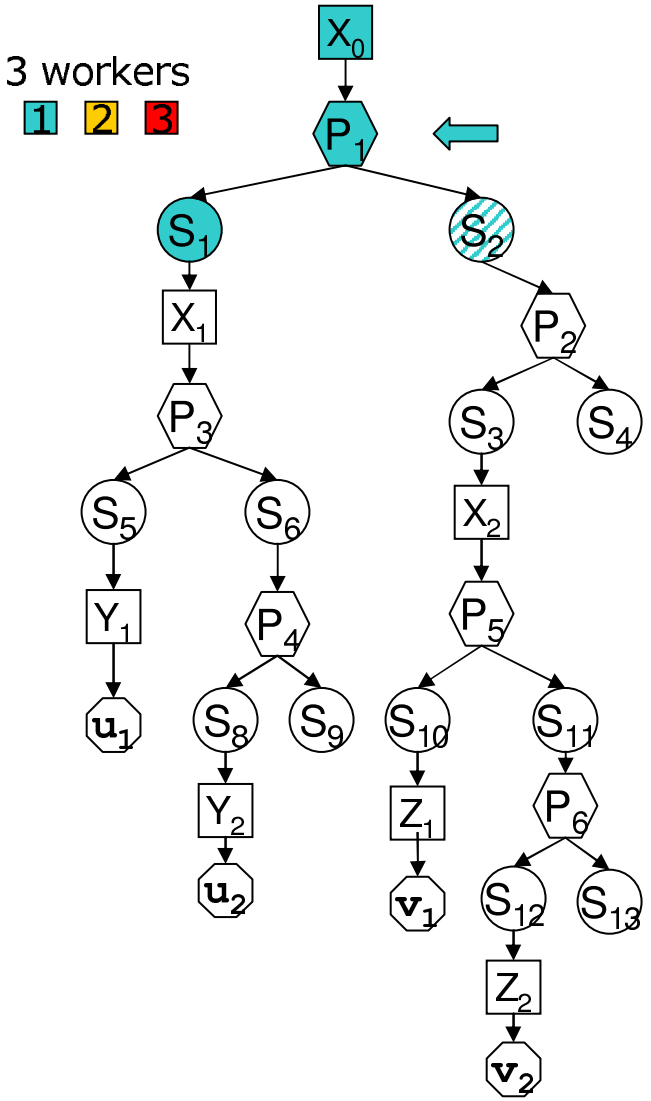
XCilk builds a computation tree as a transactional program executes. A program begins with a single root node ($\mathbf{x}_0$).



XCilk Computation Tree (**spawn**)

XCilk builds a computation tree as a transactional program executes. A program begins with a single root node ($\mathbf{X}_0$).

A **spawn** creates a P-node ($\mathbf{P}_1$) with two S-nodes ($\mathbf{S}_1$, $\mathbf{S}_2$) as children. The worker then starts executing the left child.

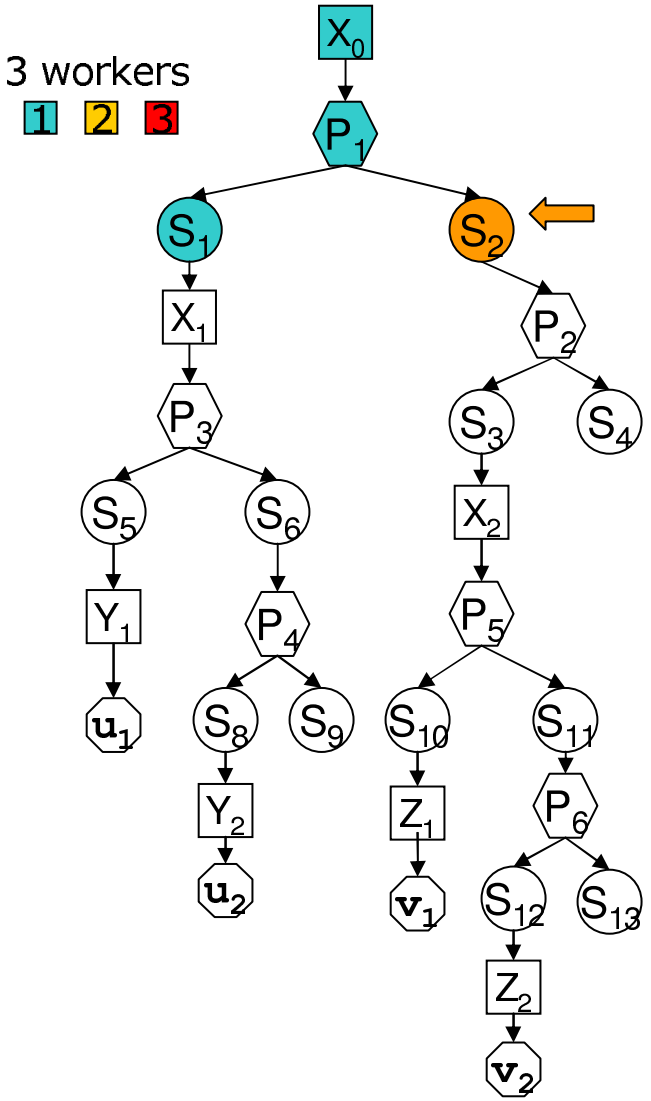


XCilk Computation Tree (`steal`)

XCilk builds a computation tree as a transactional program executes. A program begins with a single root node ($\mathbf{X}_0$).

A **`spawn`** creates a P-node ($\mathbf{P}_1$) with two S-nodes ($\mathbf{S}_1$, $\mathbf{S}_2$) as children. The worker then starts executing the left child.

In XCilk, as in Cilk, a worker can **`steal`** an S-node ($\mathbf{S}_2$) from the deque of another worker.



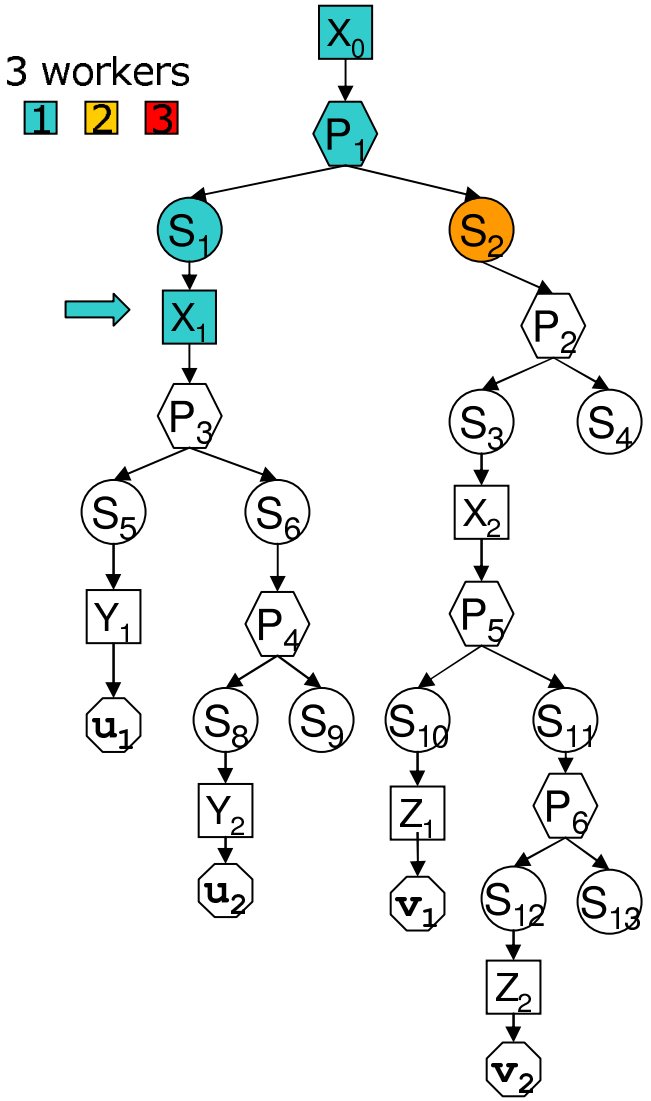
XCilk Computation Tree (**xbegin**)

XCilk builds a computation tree as a transactional program executes. A program begins with a single root node ($\mathbf{X_0}$).

A **spawn** creates a P-node ($\mathbf{P_1}$) with two S-nodes ($\mathbf{S_1}$, $\mathbf{S_2}$) as children. The worker then starts executing the left child.

In XCilk, as in Cilk, a worker can **steal** an S-node ($\mathbf{S_2}$) from the deque of another worker.

An **xbegin** creates a transactional S-node ($\mathbf{X_1}$)

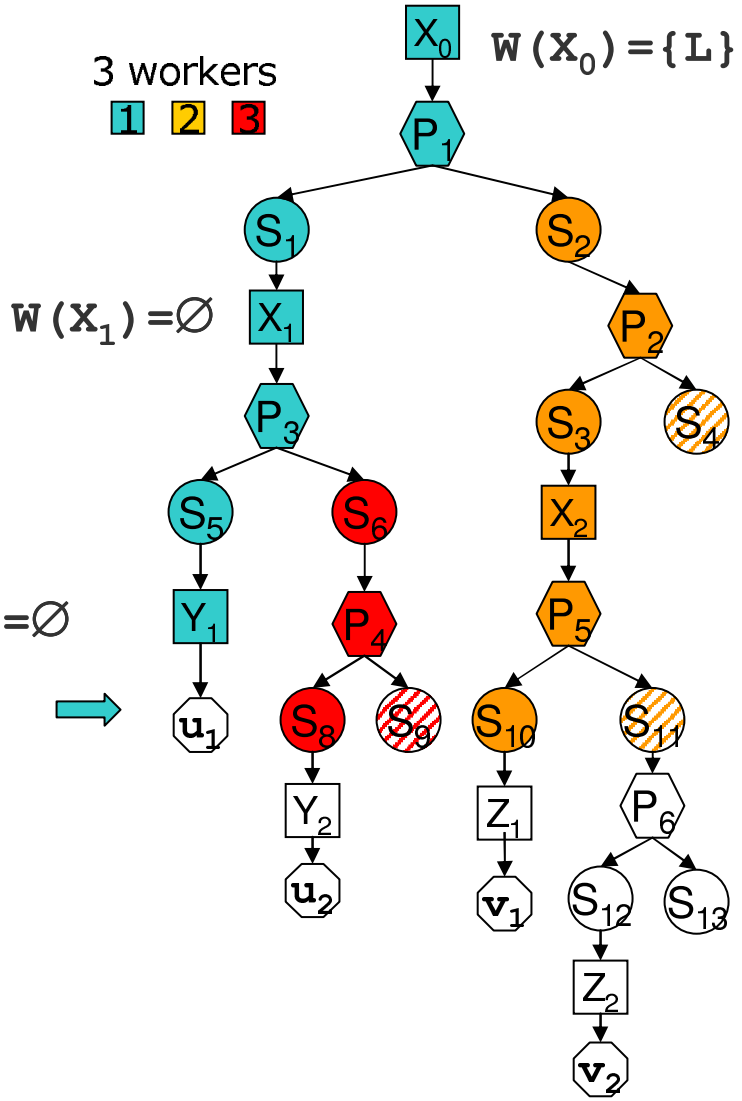


XCilk: Readsets and Writesets

Conceptually, every transaction **X** maintains a set of locations that the transaction read from (the *readset* **R(X)**), and a set of locations that the transaction as written to (the *writeset* **W(X)**).*

The root of the tree represents the world; we assume the writeset of the root contains a value for all memory locations **L**.

When a memory operation u_1 on a location **L** occurs, it reads the value from the closest ancestor transaction with **L** in its readset.



*We assume **W(X)** is a subset of **R(X)**.

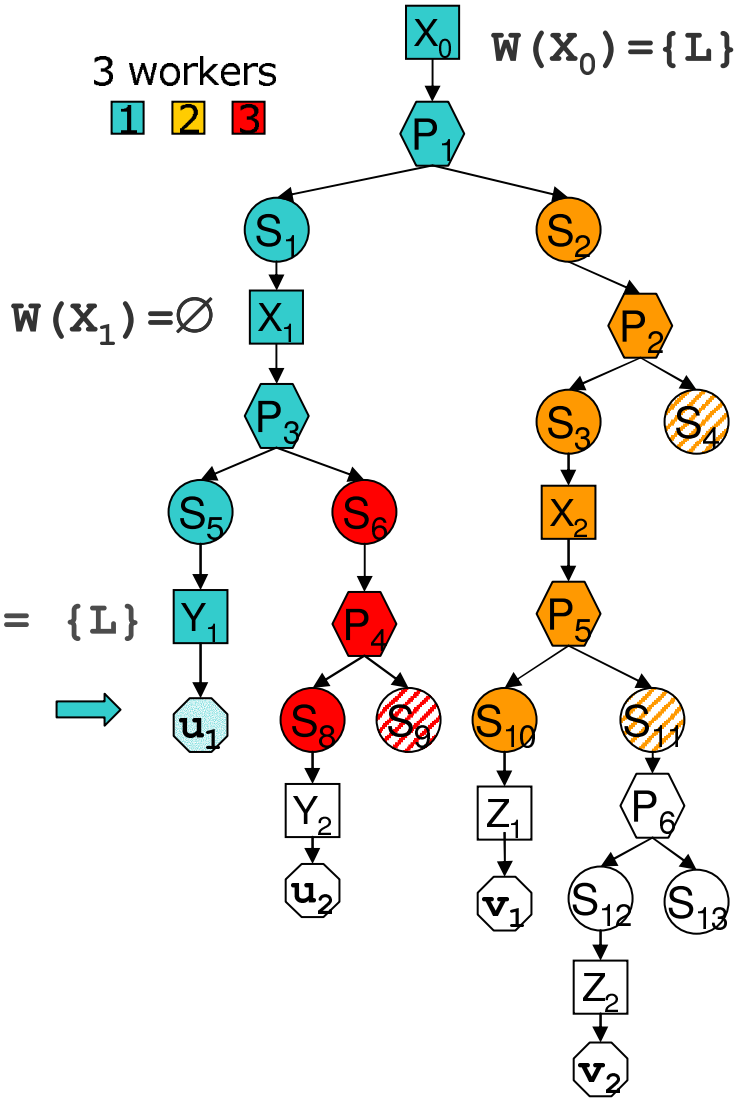
XCilk: `write`

Conceptually, every transaction `X` maintains a set of locations that the transaction read from (the *readset* `R(X)`), and a set of locations that the transaction as written to (the *writeset* `W(X)`).*

The root of the tree represents the world; we assume the writeset of the root contains a value for all memory locations `L`.

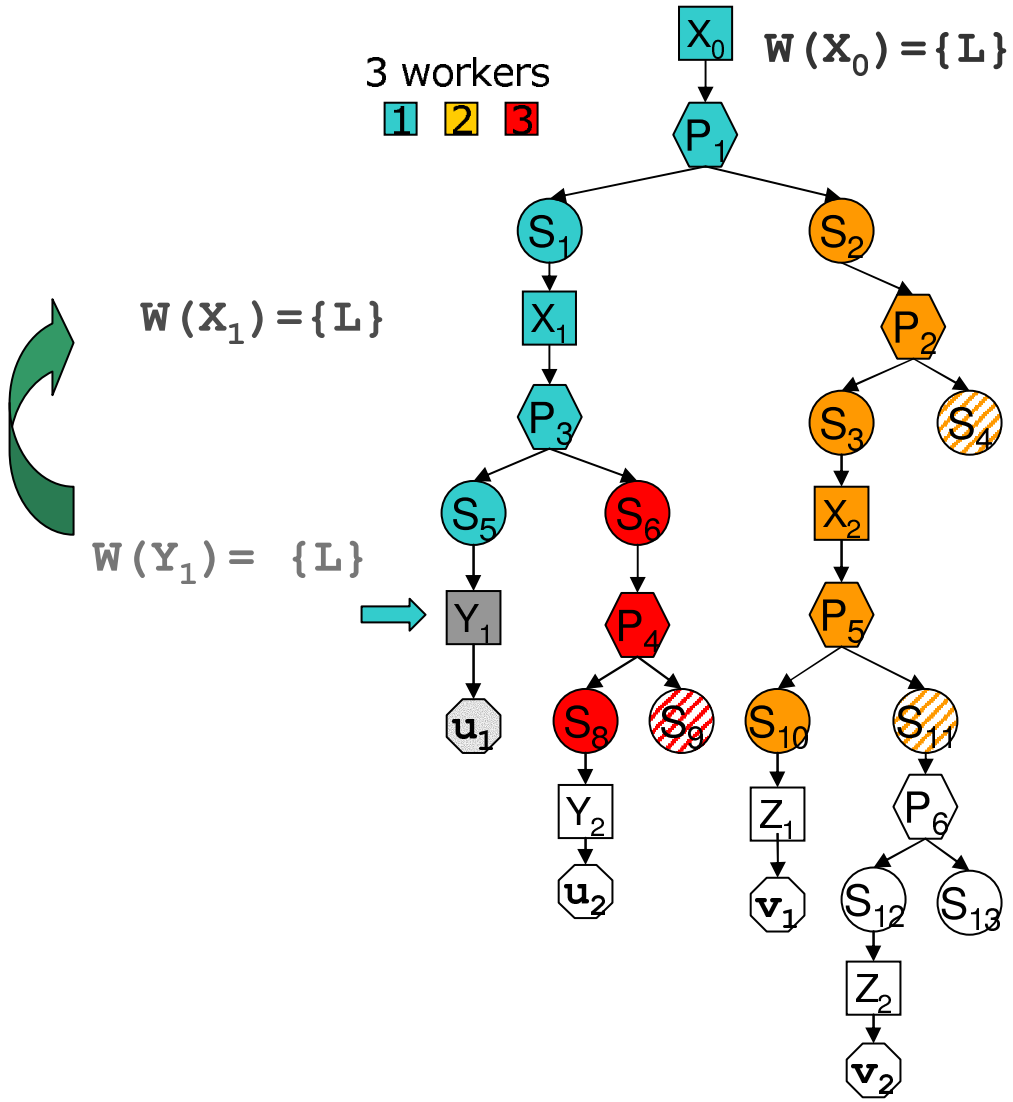
When a memory operation u_1 on a location `L` occurs, it reads the value from the closest ancestor transaction with `L` in its readset.

u_1: `write to L`



XCilk: **xend**

An **xend** commits a transaction. With closed nesting, when a transaction (Y_1) commits, it conceptually merges its readset and writeset into the readset/writeset of its transactional parent (X_1).

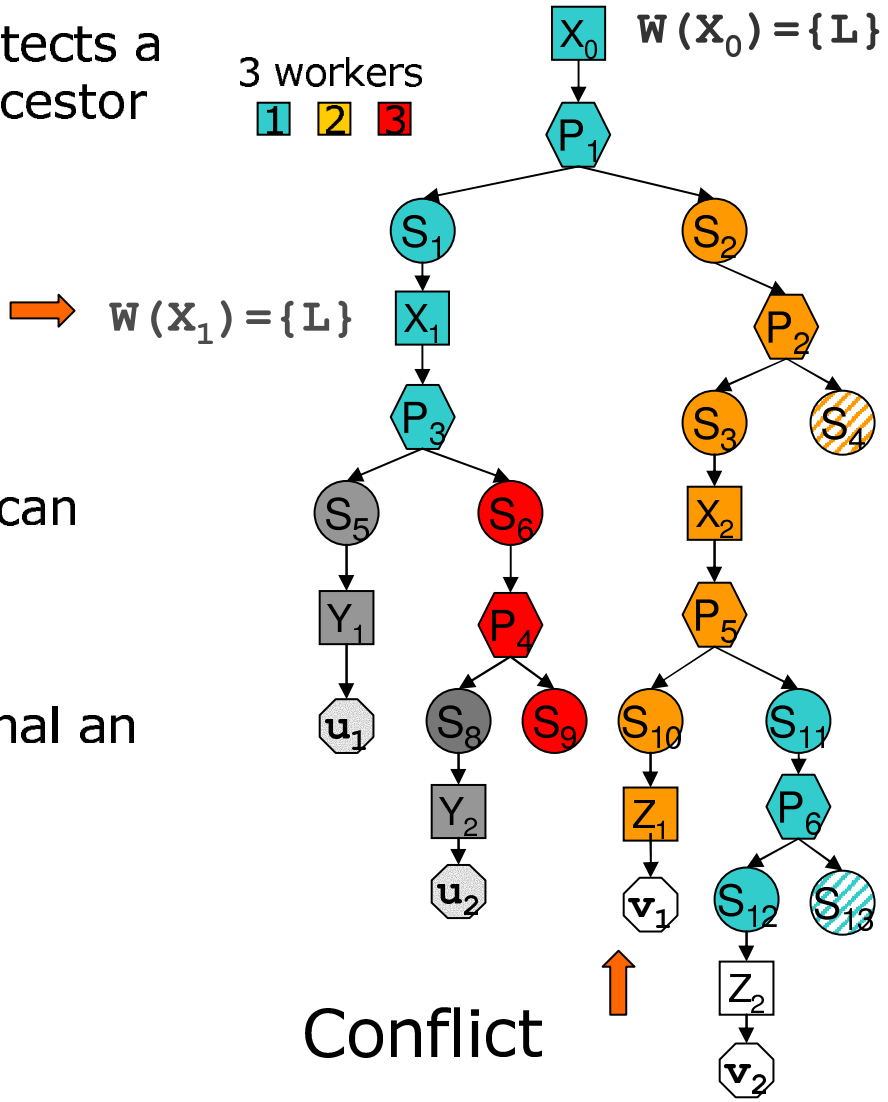


XCilk: Conflicting `write`

If $\mathbf{v}_1$ tries to write to `L`, XCilk detects a conflict, because $\mathbf{x}_1$ is not an ancestor of $\mathbf{v}_1$.

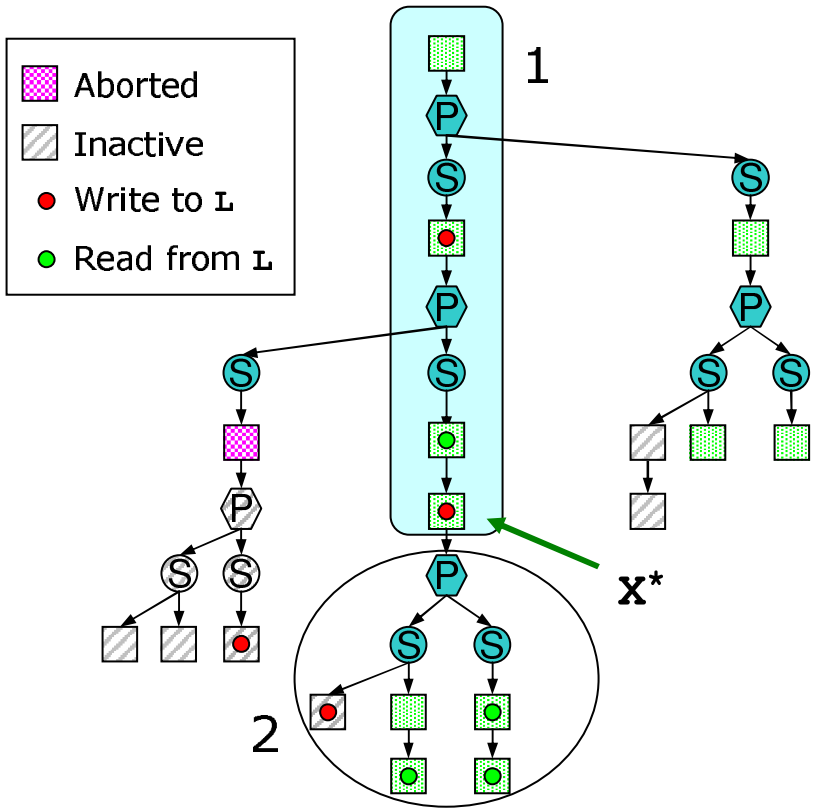
Since $\mathbf{v}_1$ conflicts with $\mathbf{x}_1$, XCilk can choose to abort $\mathbf{z}_1$ immediately.

Alternatively, XCilk can also signal an abort of $\mathbf{x}_1$, wait for worker 1 to notice, and then finish $\mathbf{v}_1$.



Invariant: Conflict-Free Execution

XCilk performs eager conflict detection, and guarantees that the execution is always conflict-free.

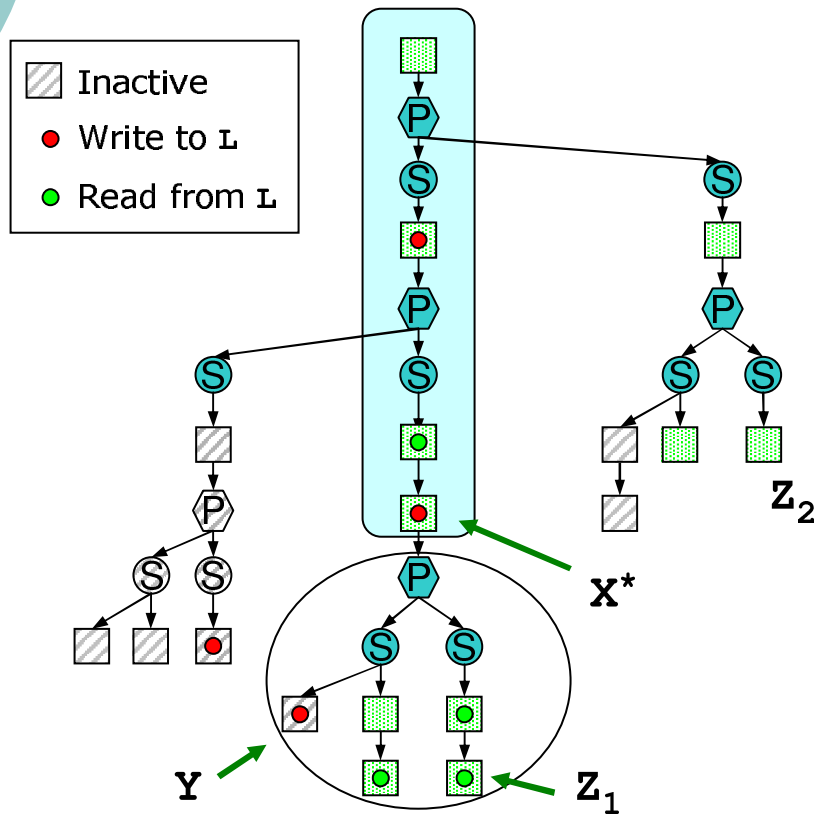


At any time, for any given memory location `L`:

1. All active transactions that have `L` it their writeset fall along a chain.
2. All active transactions with `L` in their readset are either along the chain or are descendants of the end of the chain.

Conflicts with the Last Writer to `L`

In the case where no transactions abort, XCilk reduces conflict detection to queries checking for conflicts against the id of the last transaction to write to `L`.

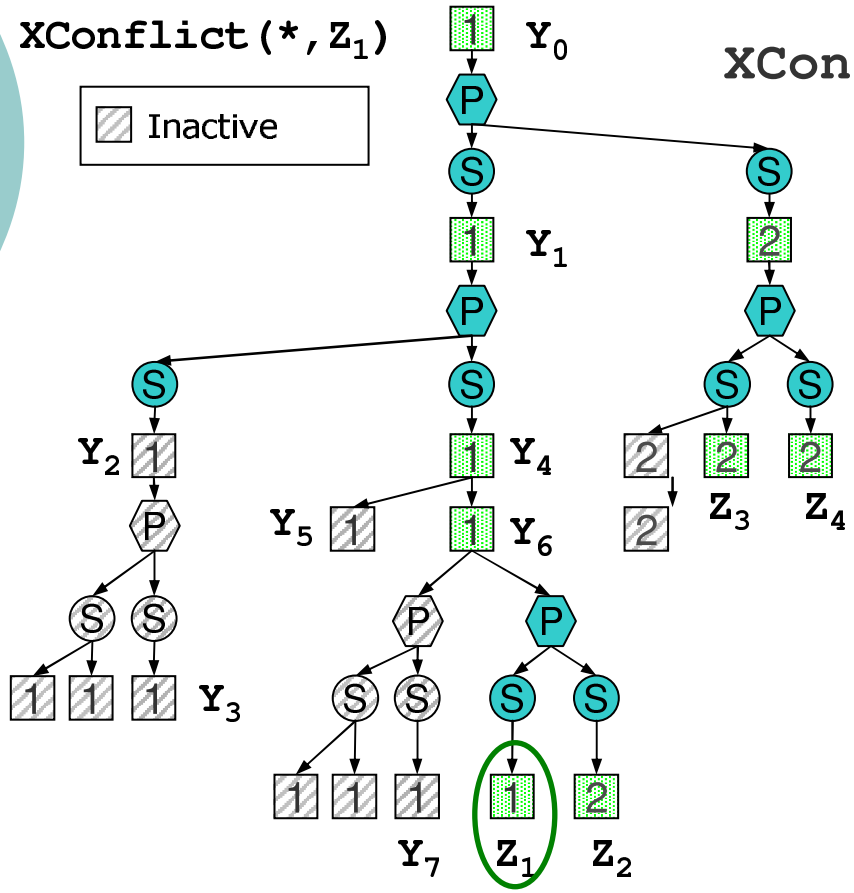


Let `Y` be the last transaction which last wrote to `L`. `X*` must be an ancestor of `Y`, i.e., `Y` has "merged" into `X*` because of transaction commits.

If a transaction `Z` wants to perform a read from `L`,

1. Determine if `X*` is an ancestor of `Z`.
2. If no, report a conflict.

The XConflict Oracle



`XConflict(Y, Z)` answers this query:

For any *running* node Z,

```
int XConflict_Oracle(Y, Z) {
  X ← Y's closest active
      ancestor transaction
  if (X is an ancestor of Z)
    return "no conflict"
  else
    return "conflict";
}
```

Case 1: No conflict
Case 2: Conflict

The XConflict data structure is able to answer the query of **`XConflict_Oracle`** in O(1)-time.

Outline

- Definition of Conflict in XCilk
- Efficient XConflict Queries

Sources of Overhead in XCilk

Assume we keep a history of accesses to each memory location `L`. The overhead in XCilk comes from two sources:

- Updates to the XConflict data structure / histories after a transaction `Y` commits.
- Queries to XConflict to check for conflicts on (potentially) every memory access.

Explicit Merges on Commit

Option 1: Explicit Merge
When we commit a transaction `Y` into its parent `X`, for every location `L` in `Y`'s readset and writeset, we change the id from `Y` to `X` in `L`'s history.

Advantage: Faster queries.

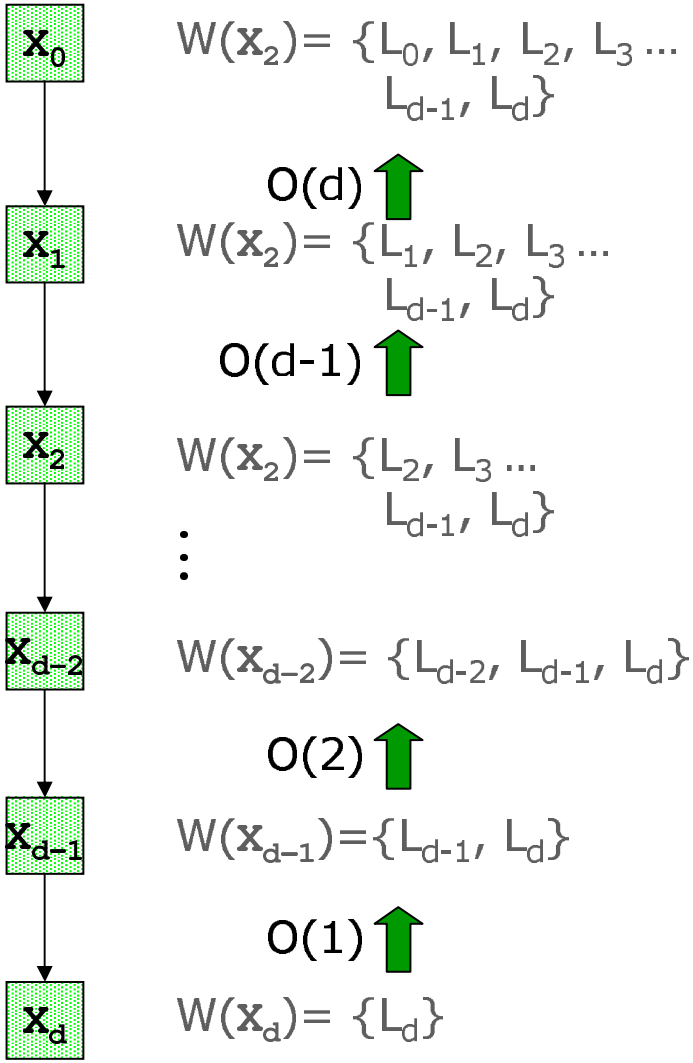
On a query, the last transaction to write to `L` is always active.

Slow Commit with Explicit Merging

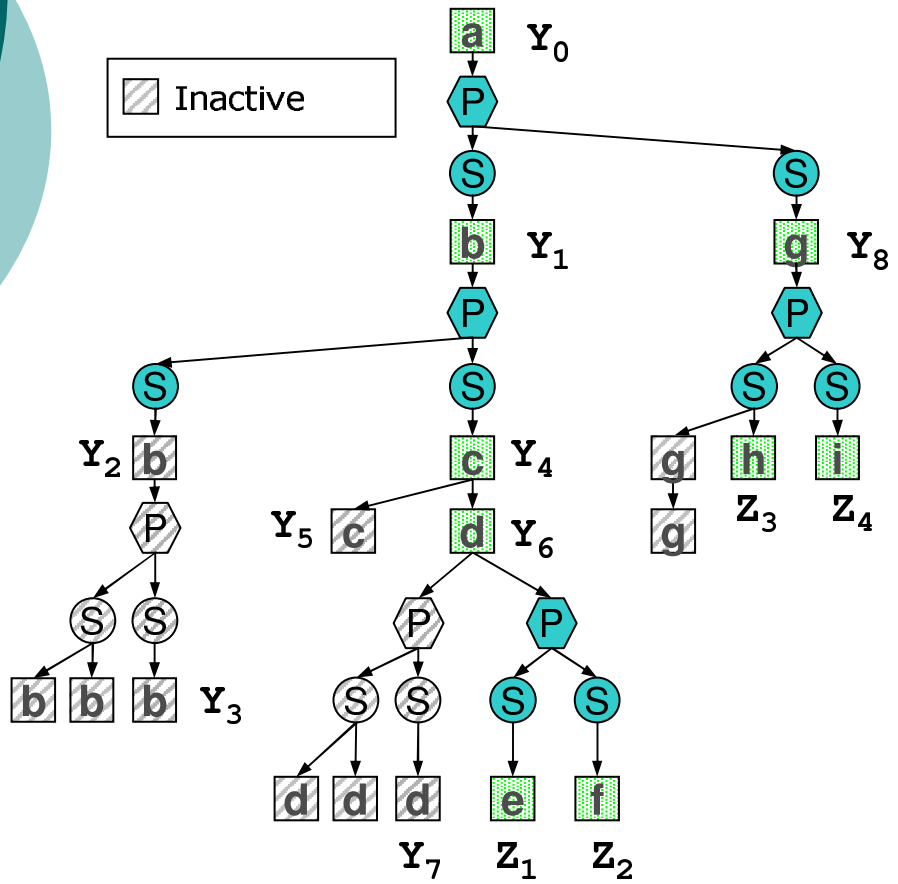
Explicitly merging writesets immediately on transaction commits can blow up work by a factor proportional to the nesting depth.

For example, consider a chain of nested transactions with depth *d*, with each transaction x_i accessing a different memory location L_i.

No nesting: $O(d)$ work.
Closed nesting: $O(d^2)$ work.



Implicit Merges



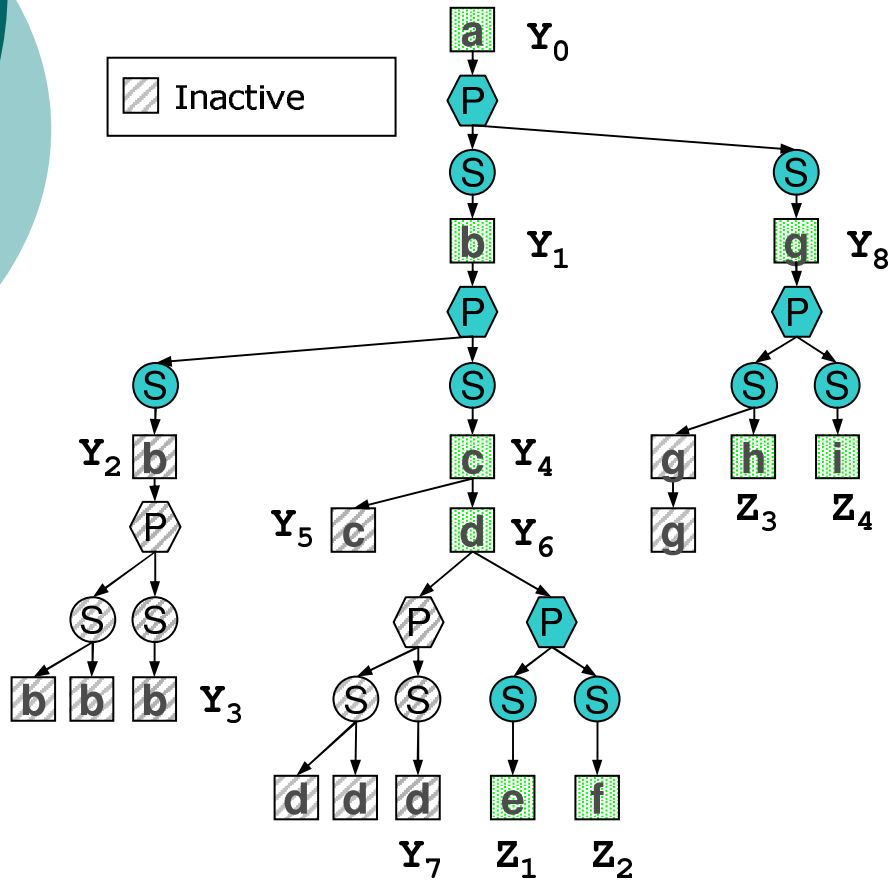
Sets **a** through **i** represent groups of transactions which have merged together.

Option 2: Implicit Merge

Implicitly merge `Y` into its closest active transactional ancestor. On commit, do nothing to histories for `L`.

Advantage: Fast updates.

Implicit Merges with Slow Queries?



Option 2: Implicit Merge

Implicitly merge `Y` into its closest active transactional ancestor. On commit, do nothing to histories for `L`.

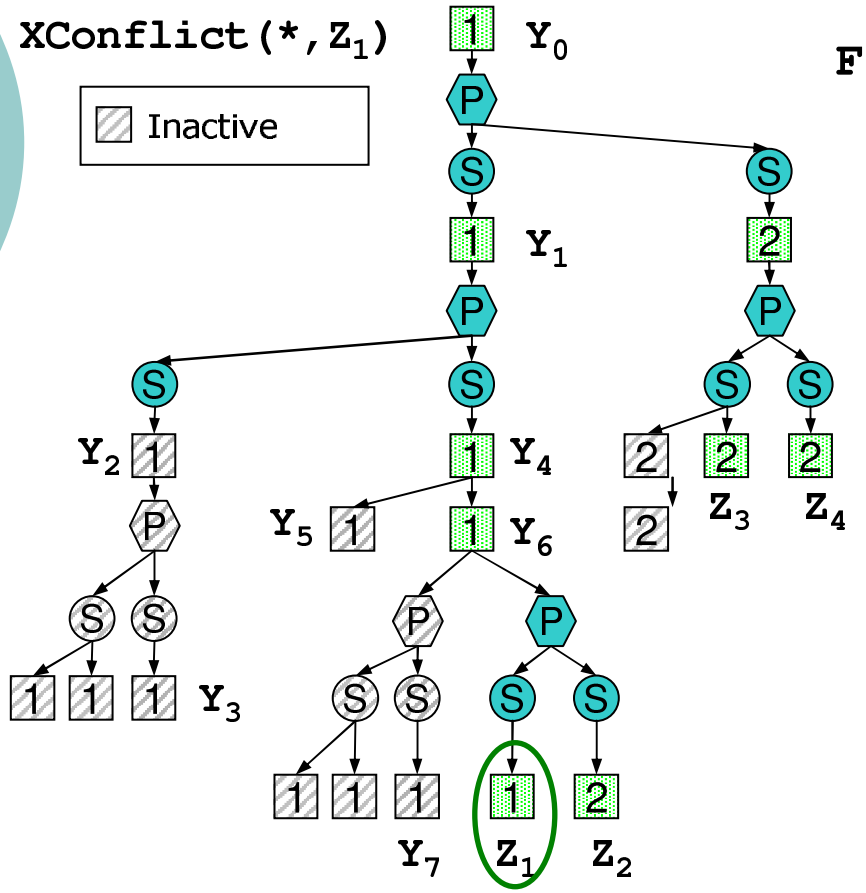
Advantage: Fast updates.

Disadvantage: Slow queries?

If the XConflict query must walk up the tree to determine which transaction `Y` has merged into, the query might require $\Omega(d)$ time.

XCilk potentially performs an XConflict query on every memory access. Therefore, we need queries to take O(1) time!

The XConflict Query



For any *running* node Z,

```
int XConflict_Oracle(Y, Z) {
  X ← Y's closest active
      ancestor transaction
  if (X is an ancestor of Z)
    return "no conflict"
  else
    return "conflict";
}
```

Case 1: No conflict
Case 2: Conflict

XConflict can run in O(1) time *because it does not always need to find* **x** to answer the oracle query.

Trace Construction: Updates

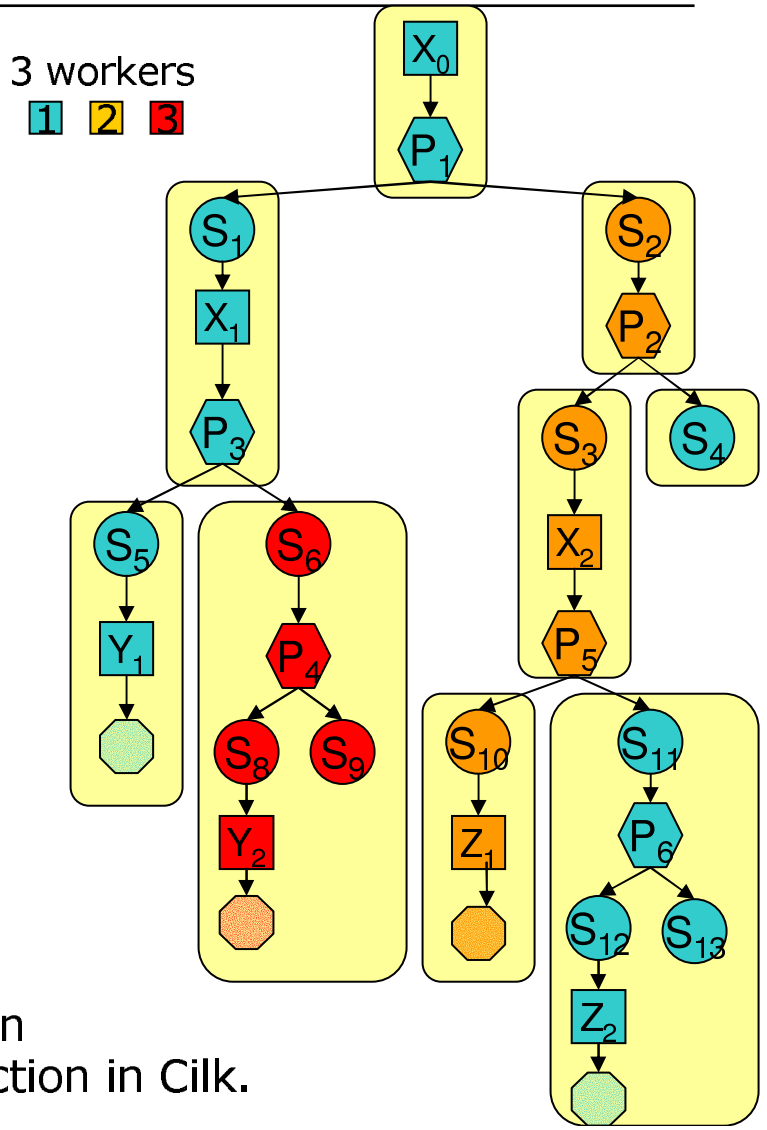
XCilk speeds up XConflict queries, by dividing the computation tree into traces, with each trace executed by a single worker.*

In Cilk, traces are created by splitting on steals.

$$\#\ \text{traces} = O(\#\ \text{steals}) = O(PT_\infty)$$

Thus, we can afford to acquire a global lock on steals, and perform O(1) amortized work per trace.

Nested transactions are merged together by merging traces together when traces complete.



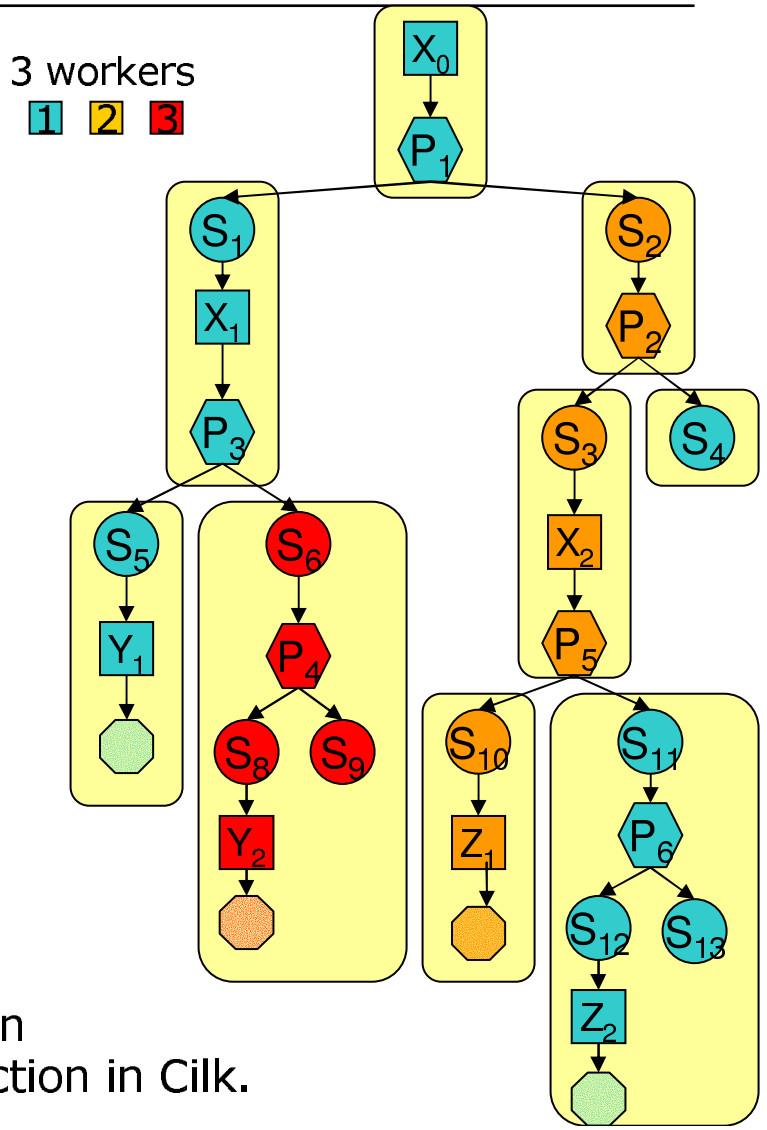
*Trace construction is similar to the construction in [BFGL04, Fineman05], used for parallel race detection in Cilk.

Trace Construction: Queries

XCilk speeds up XConflict queries, by dividing the computation tree into traces, with each trace executed by a single worker.*

An XConflict query involves a constant number of O(1)-time operations at two tiers: a global tier (queries between traces), and a local tier (between tree nodes).

When there are no transaction conflicts and no parallel readers to the same memory location, XCilk performs (at most) one `XConflict` query per memory access.



*Trace construction is similar to the construction in [BFGL04, Fineman05], used for parallel race detection in Cilk.

XCilk Performance Bound

- In the special case of a computation with no transaction conflicts and no concurrent readers to a shared memory location, XCilk performs (at most) one O(1)-time XConflict query per memory access.
- Maintaining the XConflict data structure introduces overhead of $O(T_1 / P + PT_\infty)$.
- Therefore, the entire program runs in time $O(T_1 / P + PT_\infty)$.
- Linear speedup if $P = O(\sqrt{(T_1/T_\infty)})$, compared to $P = O(T_1/T_\infty)$ for normal Cilk.

Open Questions

- Can we provide any performance guarantees on programs which are conflict-free, but also allowing parallel reads to the same location? What if there are conflicts?
- Can we "garbage-collect" XCilk's metadata (e.g., transaction ids) in a provably-efficient manner?
- Can we simplify the XCilk data structures in special but possibly "common" cases? For example, what if the nesting depth is bounded by *d*?