Deterministic OpenMP For Race-Free Parallelism

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HotPar 2011
Berkeley, CA
26 May 2011

Deterministic Concurrency

Parallel program : same input → same output and behavior

- Reproduce any bug
- Replay computation exactly → Byzantine Fault Tolerance, peer-review accountability
- Address timing channel attacks? (CCSW '10)
- Build an end-to-end verifiable system

The Underlying Problem

- Conventional programming models *inherently nondeterministic*
- Rely on *naturally nondeterministic* synchronization primitives: mutex locks, condition variables, ...

Definition (WoDet '11)

Naturally deterministic synchronization:

Programming logic alone determines

- Which threads synchronize
- Where in each one's respective execution sequence they do so

Consequence:
Timing of arrival at synchronization points does not affect program behavior or output

Synchronization Abstractions

Naturally Deterministic

- Fork/join
- Barrier
- Future

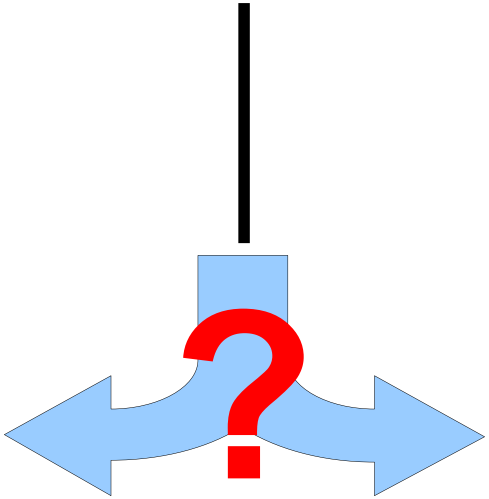
Naturally Nondeterministic

- Mutex lock
- Condition variable
- Semaphore

Naturally Nondeterministic Synchronization Causes Problems

- Burdens the programmer to get synchronization right
- Even when correct, allows high-level data races

High-Level Data Race



A
lock(x)
x := x * 2
unlock(x)

B
lock(x)
x := x + 3
unlock(x)

A gets lock first
x := 2x + 3

B gets lock first
x := 2x + 6

Synchronization Abstractions

Naturally Deterministic

- Fork/join
- Barrier
- Future

Safe

Naturally Nondeterministic

- Mutex lock
- Condition variable
- Semaphore

Risky

Our Goal

- *Naturally deterministic* programming model
- **Let the programmer live in a deterministic world**
- Deterministic programming abstractions expressive enough for most algorithms
- Runtime support that guarantees *race-free* deterministic execution

This Talk

- The Goal √
  A Naturally Deterministic Programming Model
- Background & Related Work
- From OpenMP to DOMP Semantics
- DOMP Runtime
- Efficiency
- Conclusion

Background & Related Work

Previous Approaches

- New languages
  Dataflow languages, SHIM, Jade, DPJ, ...
  - Have to rewrite code
- Deterministic scheduling
  DMP, CoreDet, Grace, Kendo, …
  - Keeps underlying nondeterministic programming model
  - Data races reproducible but not eliminated

Deterministic Scheduling & Races

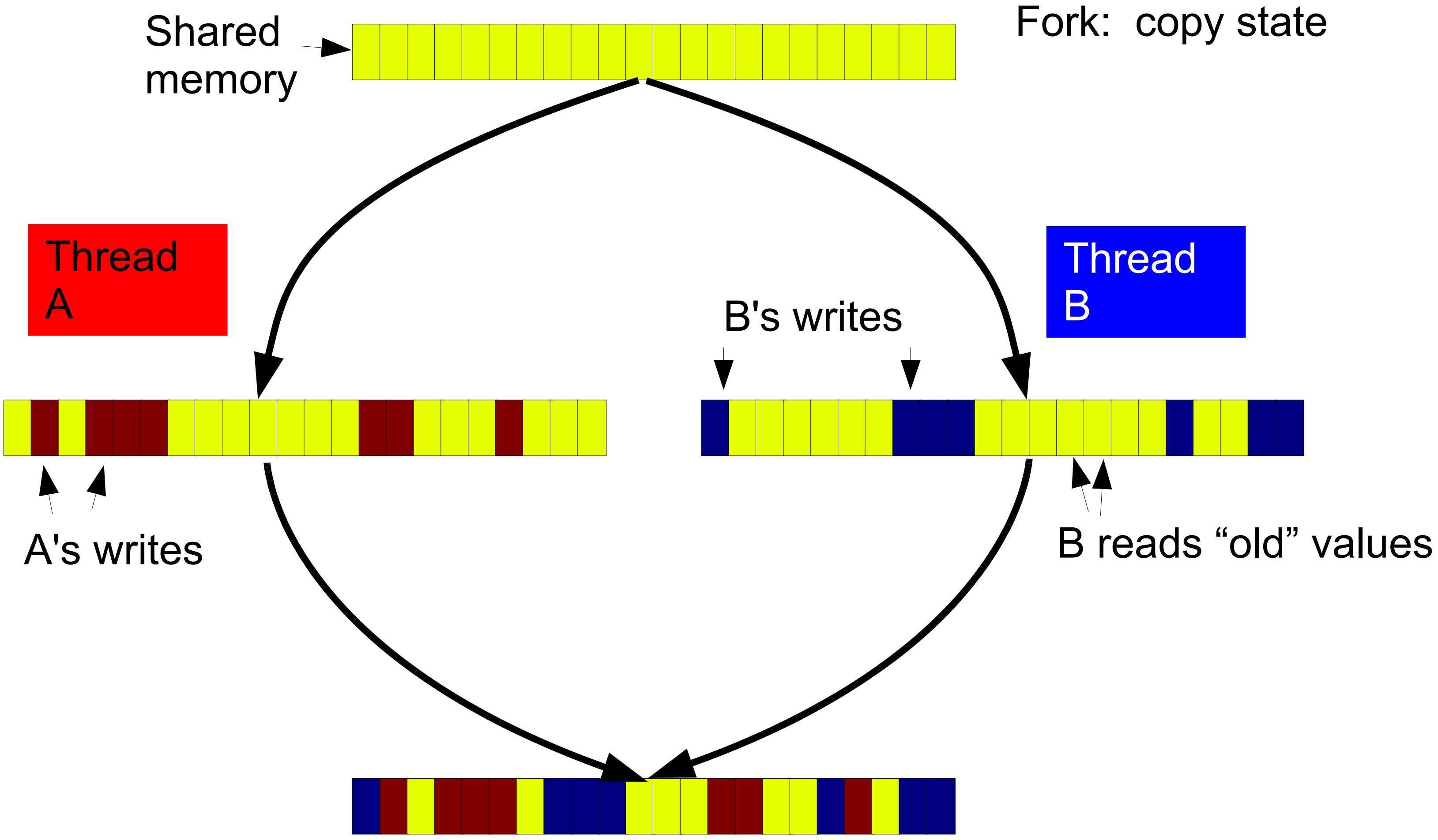
```
int x = 5;

// Start parallel execution here.
{
    // Thread A
    {
        if (input_is_as_usual)
            do_a_lot();
        x++;
    }
    // Thread B
    {
        x++;
    }
}
```

- Programmer forgets to synchronize
- Tests run great!
- On "unusual" input, deterministic scheduler may *always* give 6 ☹
- We want this code *never* to work!

Working-Copies Determinism

(WoDet '11)

- Data like documents in version control system
- Fork-join parallelism model—naturally deterministic semantics
- At fork: runtime gives each concurrent thread a *working copy* of state (like “checkout”)
- Concurrent threads are *isolated*
- At barrier and join: runtime merges copies
- Two writes to same location → ERROR!



Shared memory

Fork: copy state

Thread A

Thread B

B's writes

A's writes

B reads “old” values

Join: merge changes
Conflicting writes → ERROR!

Determinator

- OS kernel based on working-copies determinism (OSDI '10)
- Race-free processes, threads, I/O
- **Naturally deterministic threading API**, but
- Limited to pthread-like fork/join and barrier
- Need for more expressive API

A Better API

Starting point: OpenMP

Attractive because:

- Expressive parallel programming API
- Already well-established
- Most features already naturally deterministic
  - Mostly compatible with working-copies determinism

But, ...

Why OpenMP Is Not the Answer

OpenMP includes naturally nondeterministic synchronization abstractions

- *atomic*
- *critical*
- *flush*

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- *flush*

We would like simply to disallow these, but

Programmers find need to rely on them!

Key Insight

- As popular benchmark suites show, programmers rely on nondeterministic primitives—but
- In most cases, they use them to implement *deterministic* higher-level idioms
- We need *deterministic* high-level abstractions to express these idioms
- Need to *extend* OpenMP to fill these gaps

Primitives versus Idioms

- Primitives (in OpenMP, pthreads, etc.)
  - Deterministic: fork/join, barrier, OpenMP work-sharing
  - Nondeterministic: locks, condition variables, *atomic*, *critical*, *flush* …
- Idioms
  - Deterministic: reduction, pipeline ad-hoc work-sharing
  - Nondeterministic: load balancing, task queues, work stealing, user-level scheduling

Primitives versus Idioms

- Primitives (in OpenMP, pthreads, etc.)
  - Deterministic: fork/join, barrier, work-sharing (OpenMP only)
  - Nondeterministic: locks, condition variables, *atomic*, *critical*, *flush* …
- Idioms
  - **~92%** Deterministic: work-sharing, reduction, pipeline
  - **~8%** Nondeterministic: load balancing, task queues, work stealing, user-level scheduling

Code Analysis

- Manually inspect & analyze SPLASH, NPB-OMP, and PARSEC benchmarks
- Count and classify all uses of synchronization primitives
- Classify uses of *nondeterministic* primitives by *idiom* they are used to build

Synchronization in SPLASH

	Deterministic Primitives (56%)		Nondeterministic Primitives (44%)			
	fork/join	barrier	work sharing idioms	reduction idioms	pipeline idioms	load balancing
barnes	1	6	6			
fmm	1	13	28			
ocean	1	40	2	2		
radiosity	3	5	2	8		21
volrend	5	13	8	6		
water-nsquared	1	9	1	7		
water-spatial	1	9	1	4	2	
cholesky	1	4	1			2
fft	1	7	1			
lu	1	5	1			
radix	1	7	1			
	7.11%	49.37%	21.76%	11.30%	0.84%	9.62%

The **only** nondeterministic idioms

Synchronization in NPB-OMP

	Deterministic Primitives (70%)		Nondeterministic Primitives (30%)	
	fork/join	barrier	reduction idioms	pipeline idioms
BT	10		1	
CG	14			
DC	2			
EP	2		1	1
FT	8			
IS	3	2		
LU	9	3	2	10
LU-HP	15		2	
MG	11			
SP	14		2	
UA	59		44	
	68.69%	2.34%	24.30%	4.67%

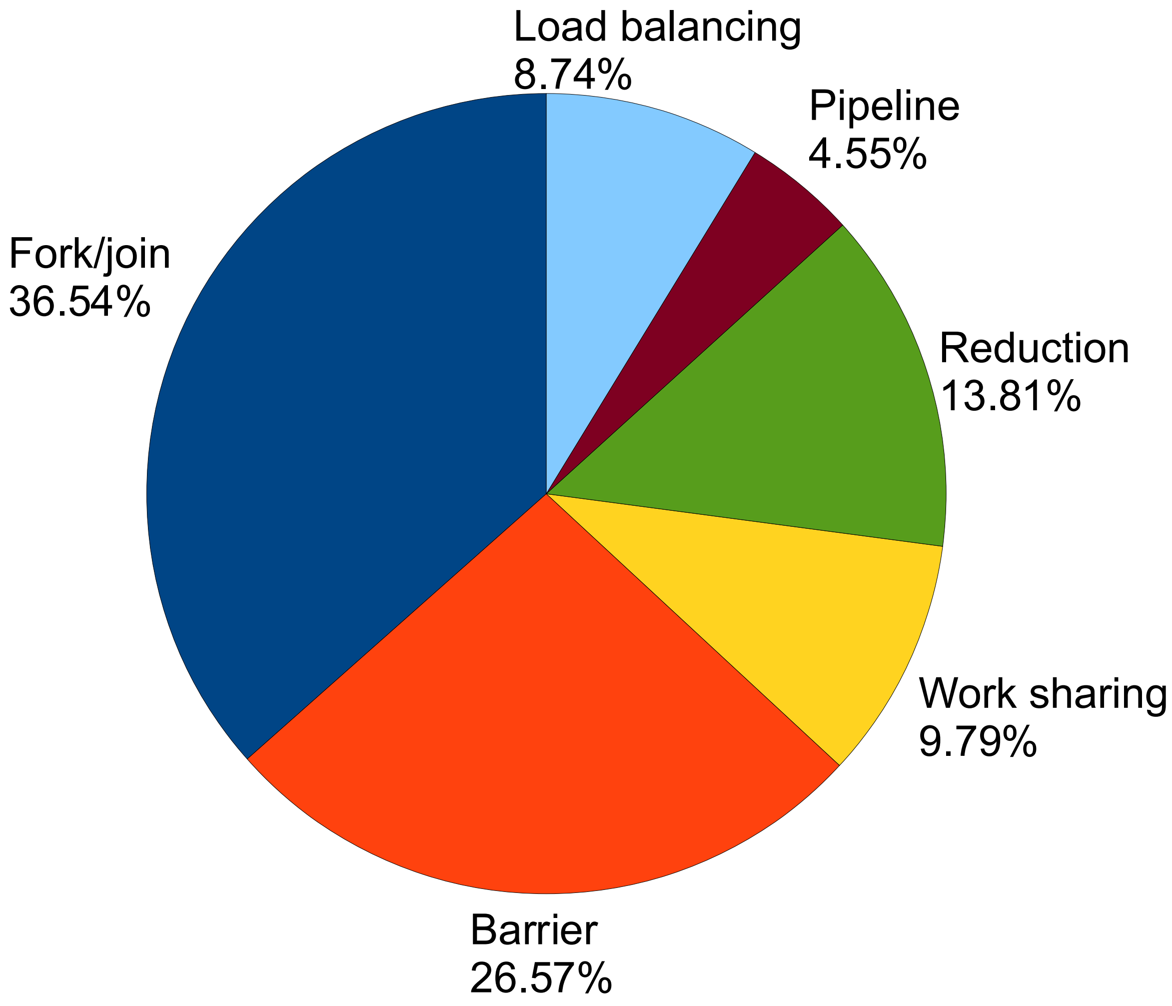
All nondeterministic abstractions used to build deterministic abstractions.

Synchronization in PARSEC

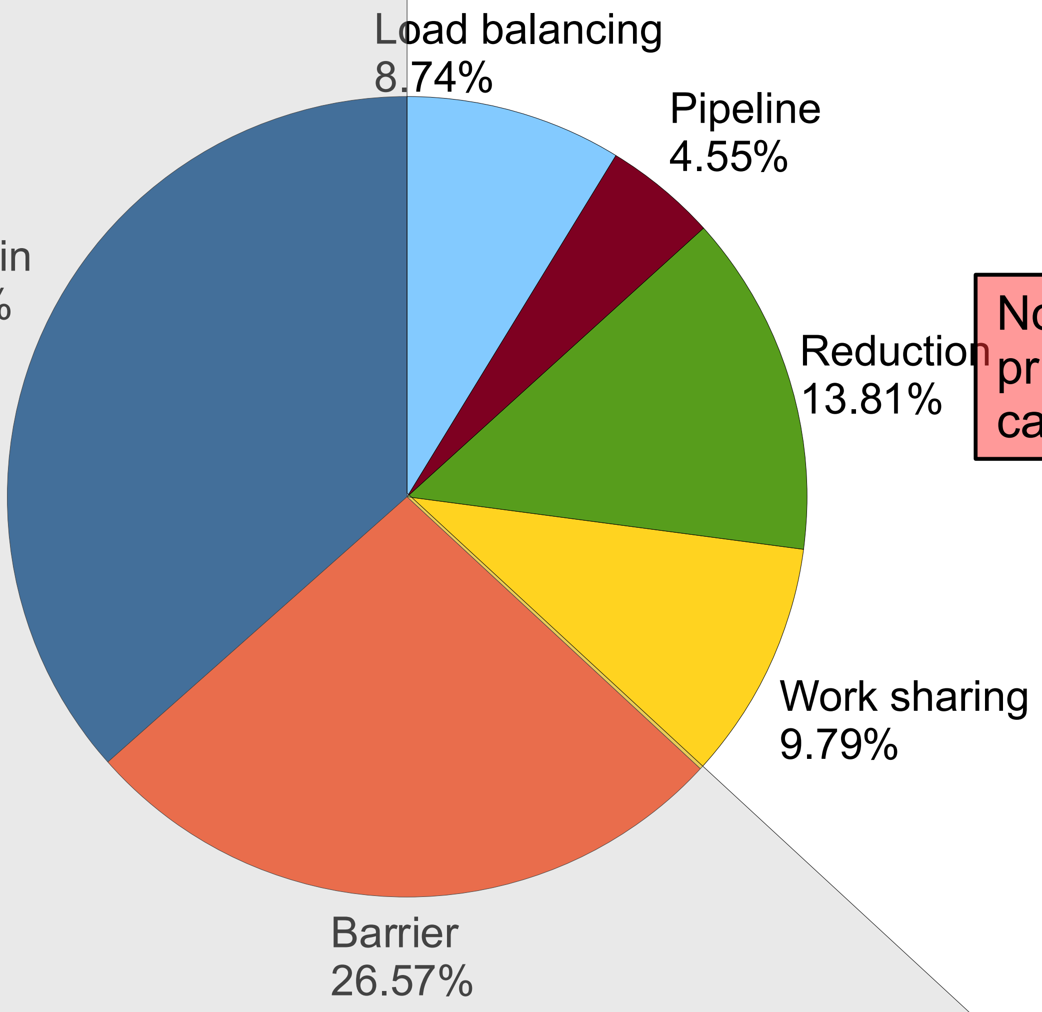
	Deterministic Primitives (62%)		Nondeterministic Primitives (38%)			
	fork/join	barrier	work sharing idioms	reduction idioms	pipeline idioms	load balancing
blackscholes	1					
bodytrack	4					
canneal	1	1	1			
dedup	1	1	1		10	
facesim	2					10
ferret	7					
fluidanimate	13					
freqmine	7					2
raytrace	1	1				
streamcluster	1	27	3			
swaptions						
vips						15
x264	2				4	
	37.82%	24.37%	3.36%	0.0%	11.76%	22.69%

The **only** nondeterministic idioms

How Programs Use Synchronization



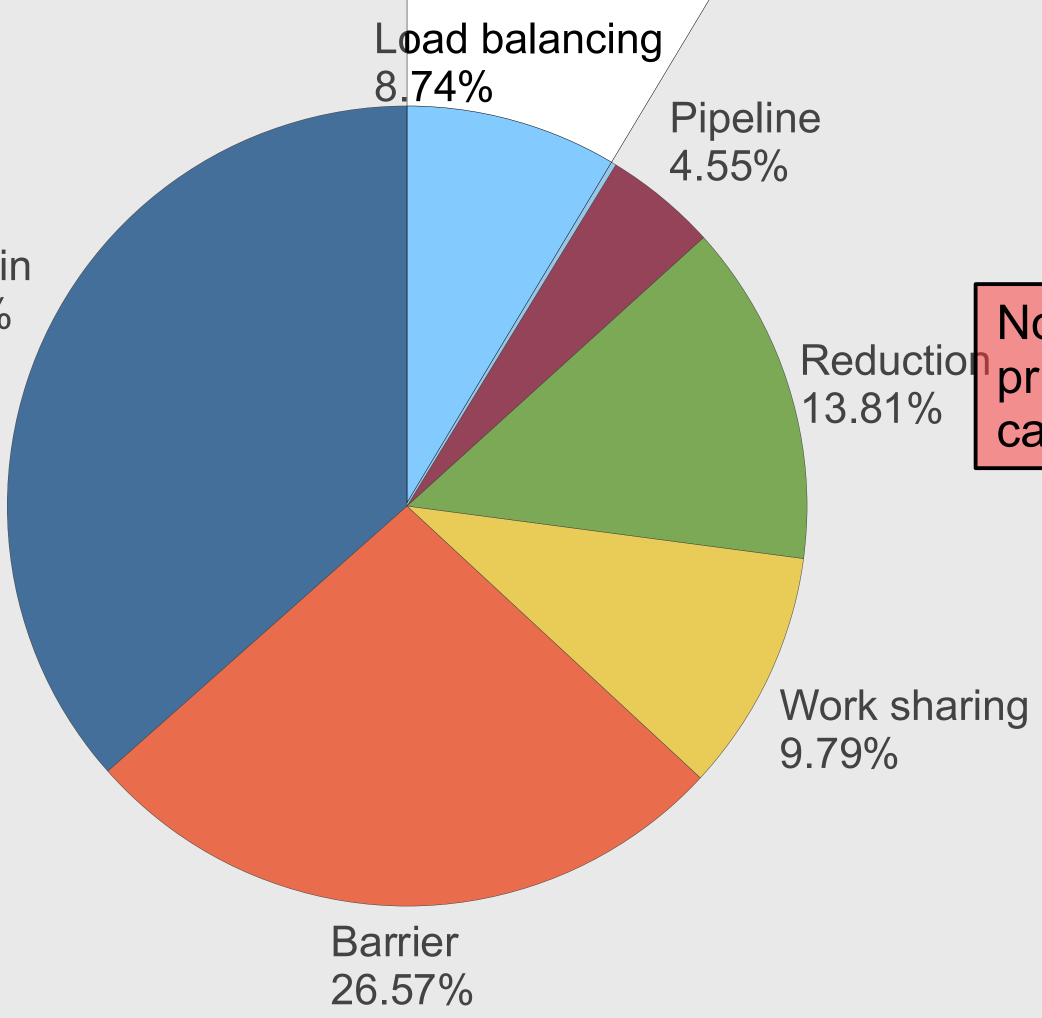
How Programs Use Synchronization



Deterministic primitives

Nondeterministic primitives categorized by use

How Programs Use Synchronization



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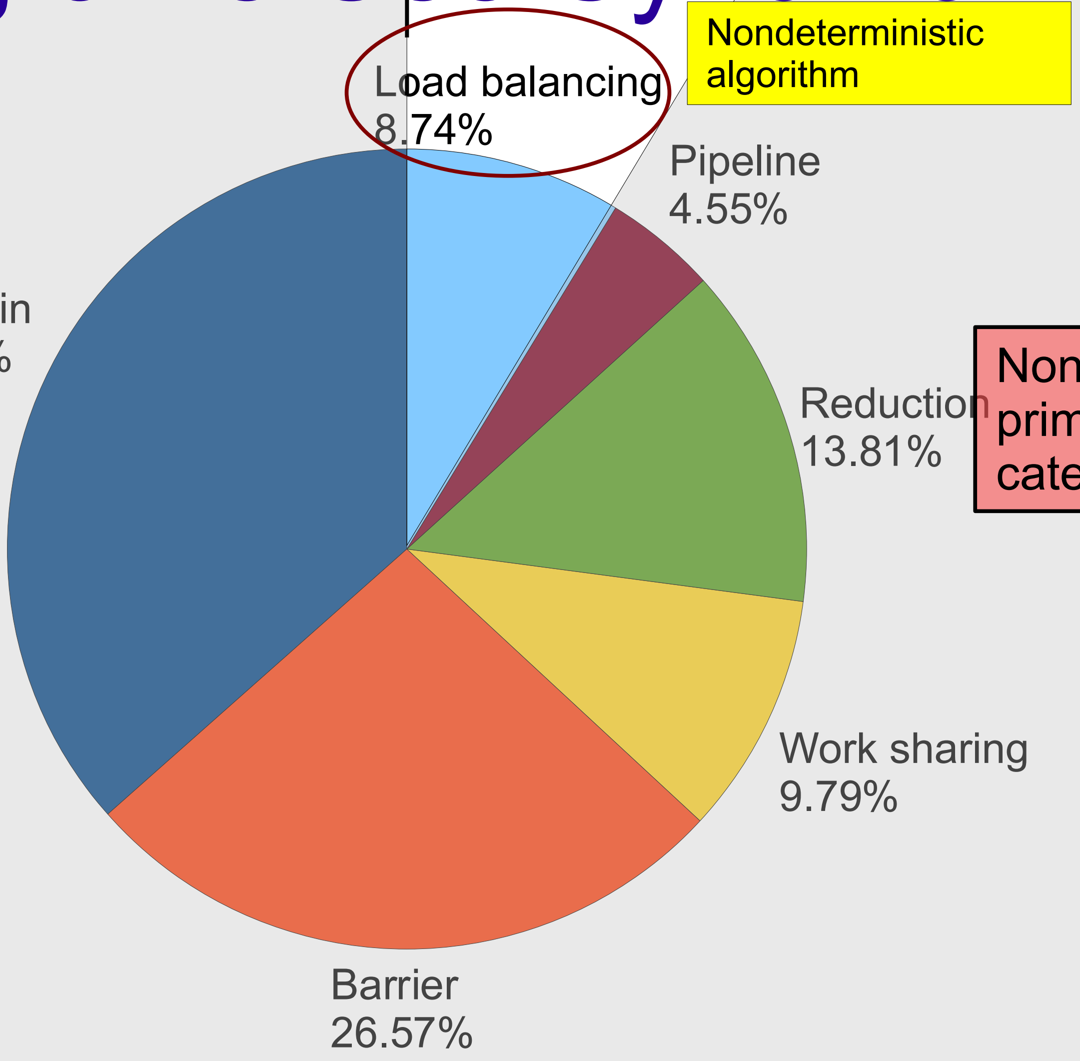
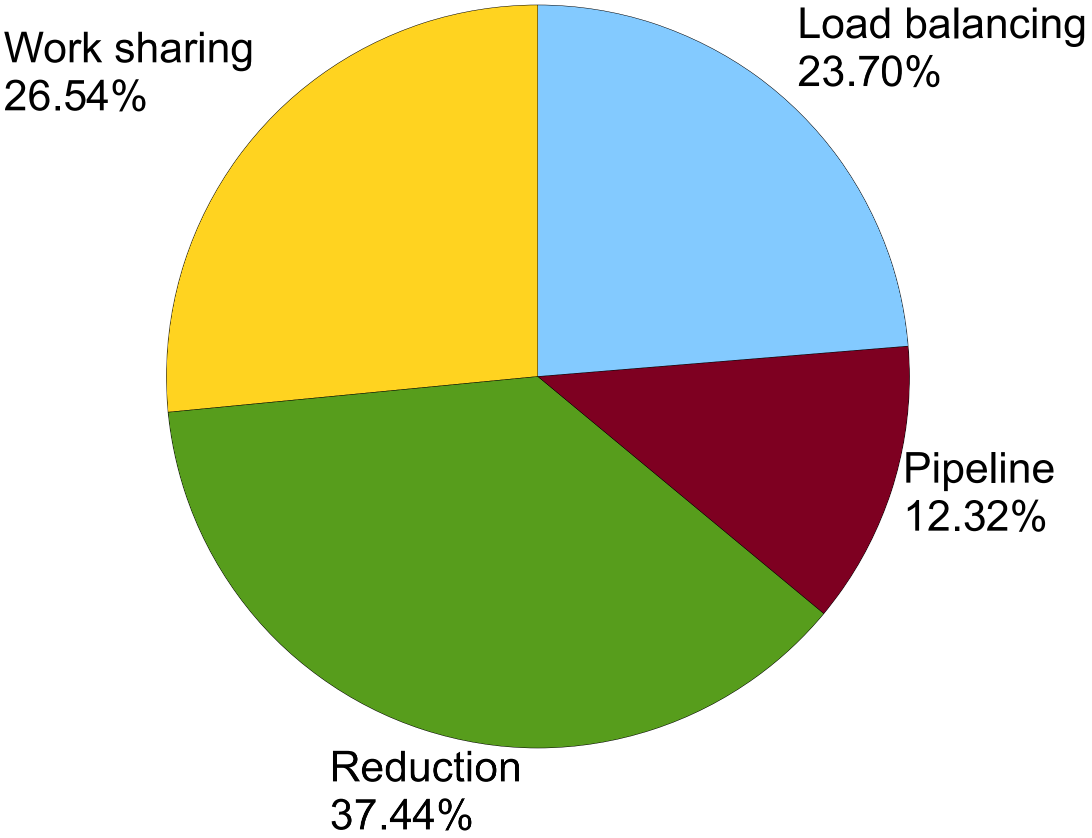


Nondeterministic algorithm

Deterministic primitives

Nondeterministic primitives categorized by use

Uses of Nondeterministic Primitives



Study Conclusion

Many (most) parallel programs could be expressed exclusively in a *naturally determistic* API if it includes abstractions for common high-level deterministic idioms.

OpenMP → DOMP!

- The Goal √
- Background & Related Work √
- From OpenMP to DOMP Semantics
- DOMP Runtime
- Efficiency
- Conclusion

From OpenMP to DOMP

Deterministic OpenMP (DOMP)

- Redefine compatible OpenMP constructs to be explicitly deterministic
- Offer deterministic alternatives to nondeterministic OpenMP constructs

OpenMP

- *Annotations* to parallelize a sequential program
- Legacy languages—little (no) rewriting
- Directives annotate structured blocks
    - *parallel*—general fork/join
    - *for*—parallel loop execution
    - *sections*—parallel tasks
- Optional clauses modify default behavior
    - *shared*, *private*, etc. for variables
    - *reduction* (sum, product, ...) across threads

Sequential Version

```
// Multiply an n x m matrix A by an m x p matrix B
// to get an n x p matrix C.
void matrixMultiply(int n, int m, int p,
        double ** A, double ** B, double ** C) {

        for (int i = 0; i < n; i++)
            for (int j = 0; j < p; j++) {
                C[i][j] = 0.0;
                for (int k = 0; k < m; k++)
                    C[i][j] += A[i][k] * B[k][j];
            }
}
```

OpenMP Version

```
// Multiply an n x m matrix A by an m x p matrix B
// to get an n x p matrix C.
void matrixMultiply(int n, int m, int p,
        double ** A, double ** B, double ** C) {
        #pragma omp parallel for
        for (int i = 0; i < n; i++)
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                C[i][j] = 0.0;
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OpenMP Semantics

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// Multiply an n x m matrix A by an m x p matrix B
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Starts with
single parent
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Starts with single parent thread

Creates new threads, distributes work

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                    for (int k = 0; k < m; k++)
                         C[i][j] += A[i][k] * B[k][j];
               }
}
```

Starts with
single parent
thread

Creates
new threads,
distributes work

Joins threads
to parent

DOMP Semantics

```
// Multiply an n x m matrix A by an m x p matrix B
// to get an n x p matrix C.
void matrixMultiply(int n, int m, int p,
        double ** A, double ** B, double ** C) {
        #pragma omp parallel for
        for (int i = 0; i < n; i++)
            for (int j = 0; j < p; j++) {
                C[i][j] = 0.0;
                for (int k = 0; k < m; k++)
                    C[i][j] += A[i][k] * B[k][j];
            }
}
```

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```

Distributes copies of shared state

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            }
}
```

Distributes copies of shared state

Merges copies of shared vars into parent's vars (if no data race)

OpenMP Reductions

- Sum, product, ... on the *same variable* across threads
- Lock-free safety from data races
- Results available only after relevant parallel block
- NATURALLY DETERMINISTIC!

OpenMP Reduction

```
int x = 5;
#pragma omp parallel sections reduction(+: x)
{
    #pragma omp section
    {
        if (input_is_as_usual)
            do_a_lot();
        x++;
    }
    #pragma omp section
    {
        x++;
    }
}
printf(“x = %d\n”, x) // Always prints 7!
```

OpenMP Reduction

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    #pragma omp section
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}
printf("x = %d\n", x) // Always prints 7!
```

sections assigns each *section* to a different thread

reduction aggregates the + on *x* across sections/threads

Unfortunately, ...

Not general enough

- Arithmetic or logical operations only
- Scalar types only
- Commutative and associative only

… Forcing the programmer to resort to hand-rolling reductions out of *naturally nondeterministic* primitives

DOMP General Reduction

```
// Assume: dimensions n, m, p have been set globally.
// Returns the product of two matrices.
extern matrix * matrix_multiply(matrix * A, matrix * B);

matrix * I = new_identity_matrix(n, m);
matrix * C = matrices[0];

#pragma omp parallel for reduction(matrix_multiply : I : C)
for (int i = 1; i < NUM_MATRICES; i++)
      C = matrix_multiply(C, matrices[i]);
// C now points to the product of all the matrices in the array matrices.
```

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$f : (a,b) \to c \mid a,b,c \in T$

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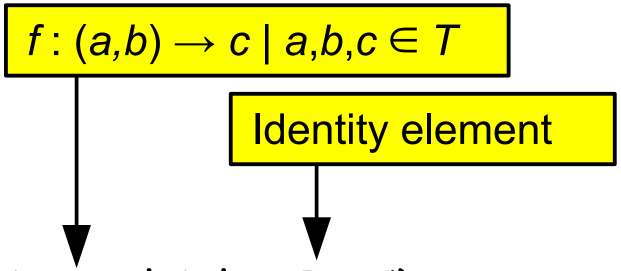

$f : (a,b) \rightarrow c \mid a,b,c \in T$

Identity element

DOMP General Reduction

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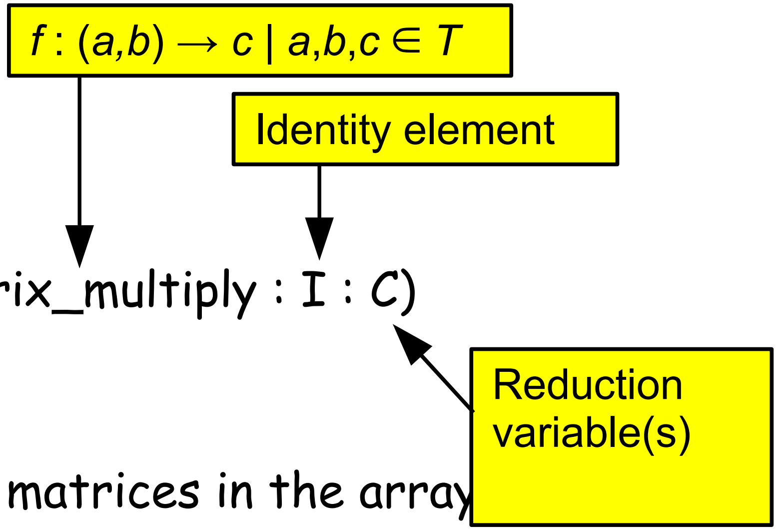

$f : (a,b) \rightarrow c \mid a,b,c \in T$

Identity element

Reduction variable(s)

Pipelines

Another deterministic idiom programmers hand-roll from naturally nondeterministic primitives for lack of high-level abstractions

E.g. LU (NPB-OMP): Uses ad hoc synchronization (*flush* memory barrier) to busy-wait on a flag

DOMP Pipelines

```
#pragma omp sections pipeline
while x = (more_work(x)) {
        #pragma omp section
        {
                x = do_step_a(x);
        }
        #pragma omp section
        {
                x = do_step_b(x);
        }
        /* … */
        #pragma omp section
        {
                x = do_step_n(x);
        }
}
```

DOMP Pipelines

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while x = (more_work(x)) {
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        {
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        }
        /* … */
        #pragma omp section
        {
                x = do_step_n(x);
        }
}
```

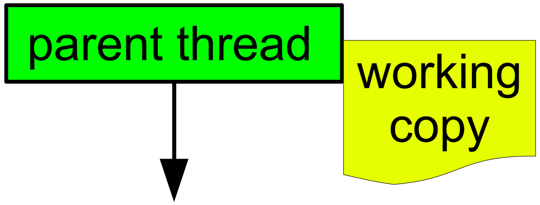
One thread per *section*

Each *section* starts executing when the one before has finished

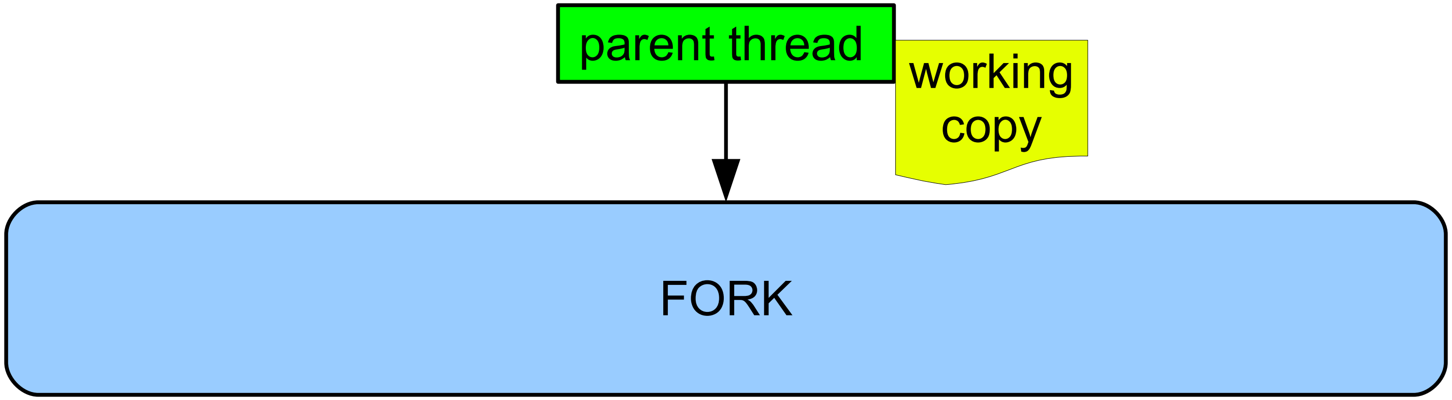
Var *x* gets its value each time from the previous *section* and then is thread-private

- The Goal √
- Background & Related Work √
- From OpenMP to DOMP Semantics√
- DOMP Runtime
- Initial Results
- Conclusion

DOMP Runtime


parent thread

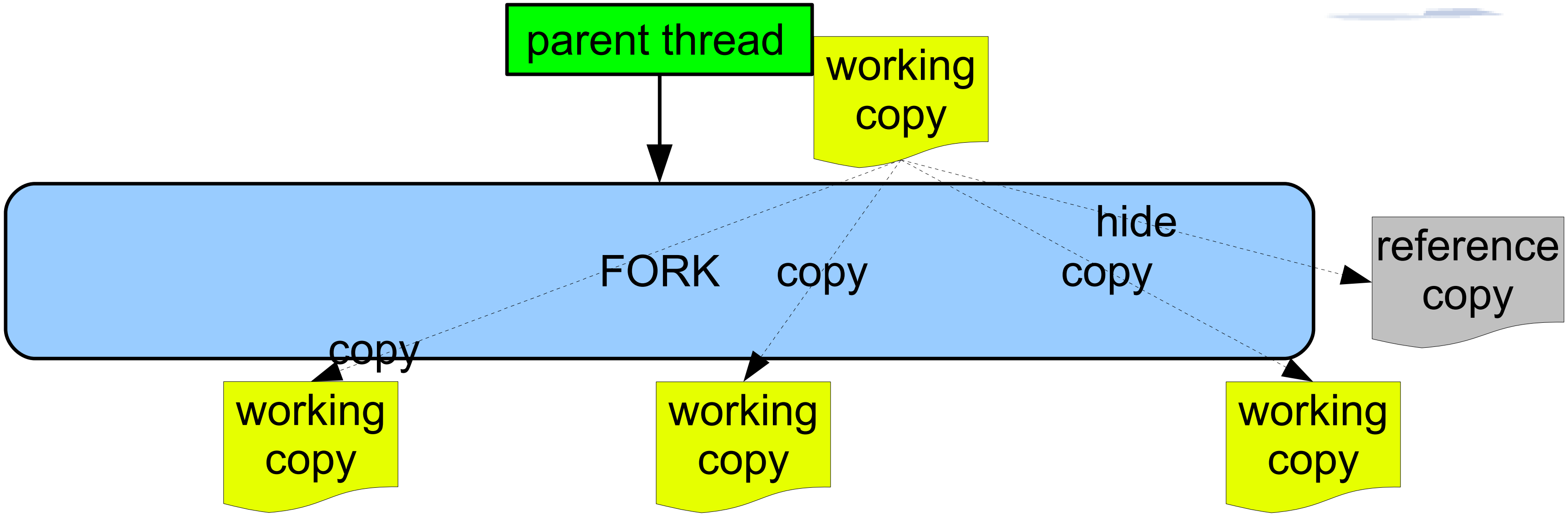
working copy



parent thread

working copy

FORK


parent thread
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FORK
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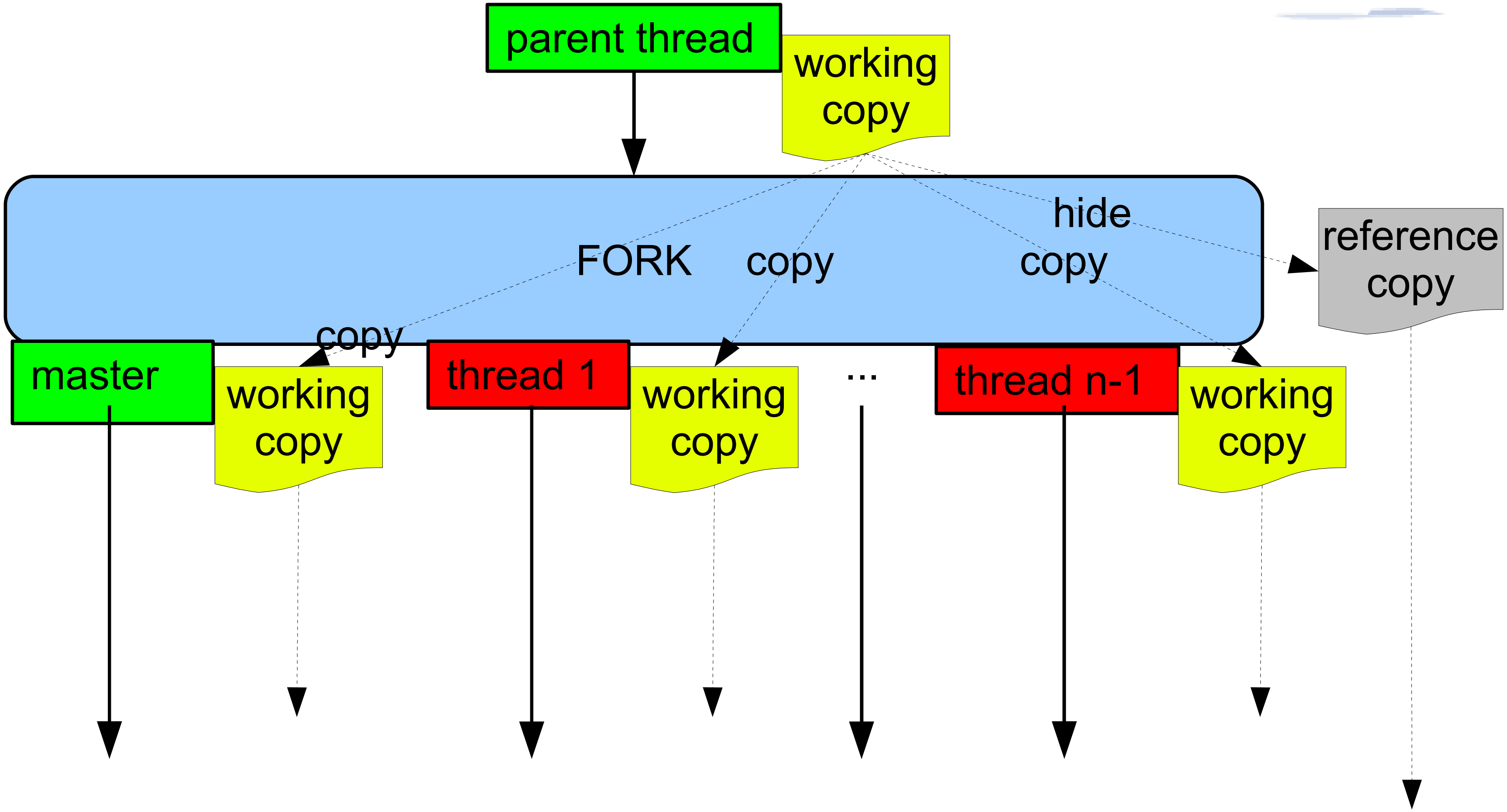
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thread 1
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thread n-1
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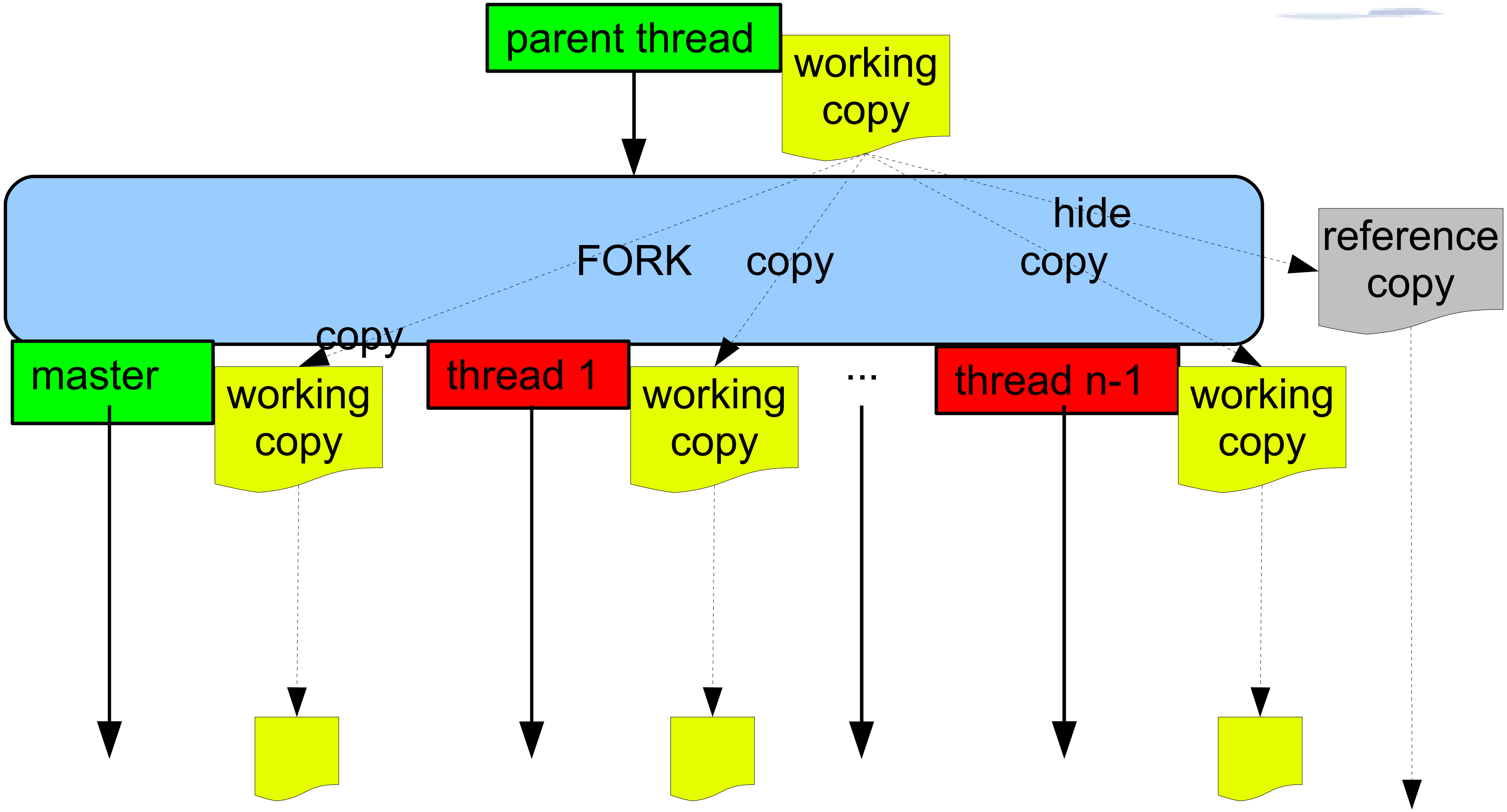
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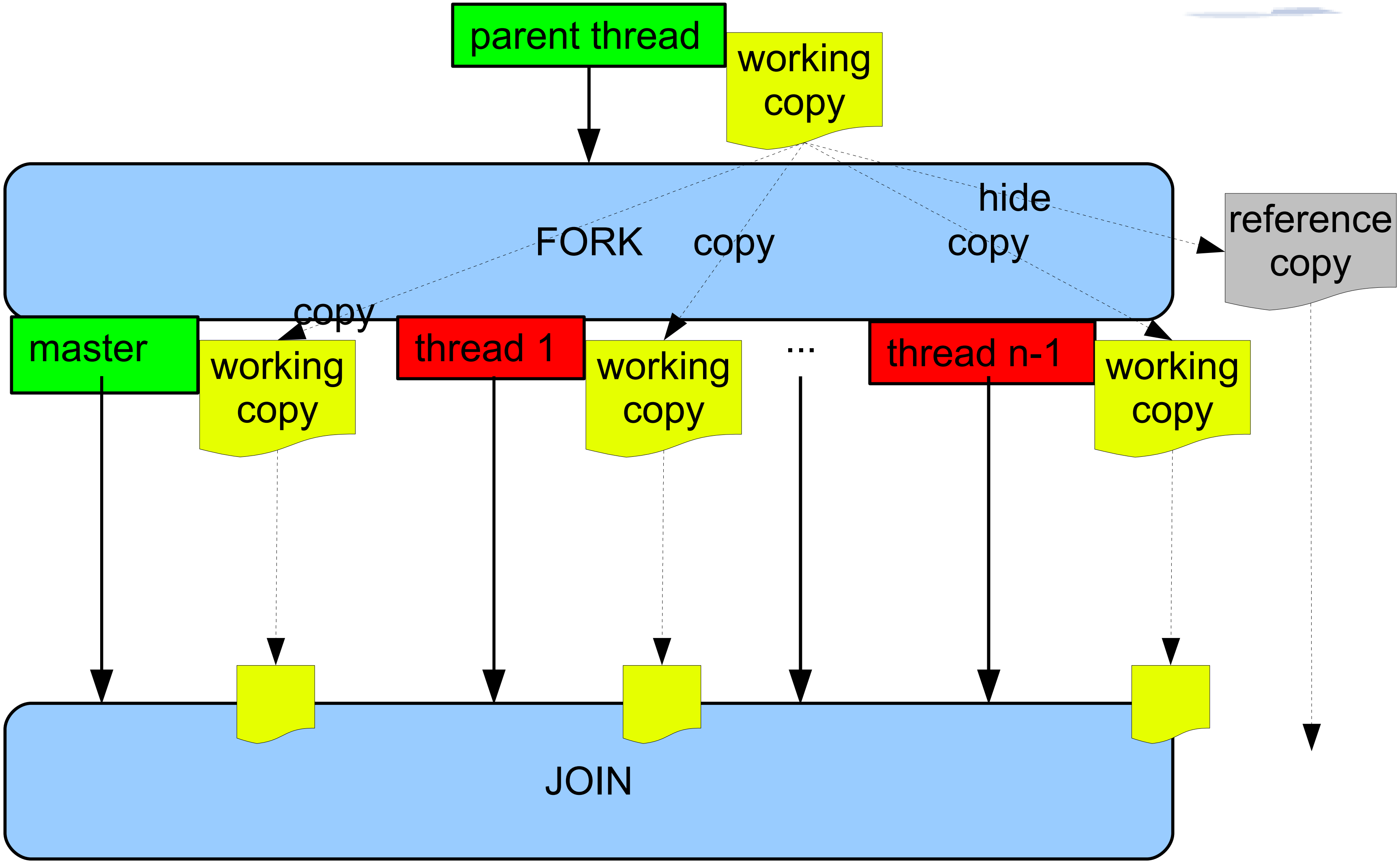
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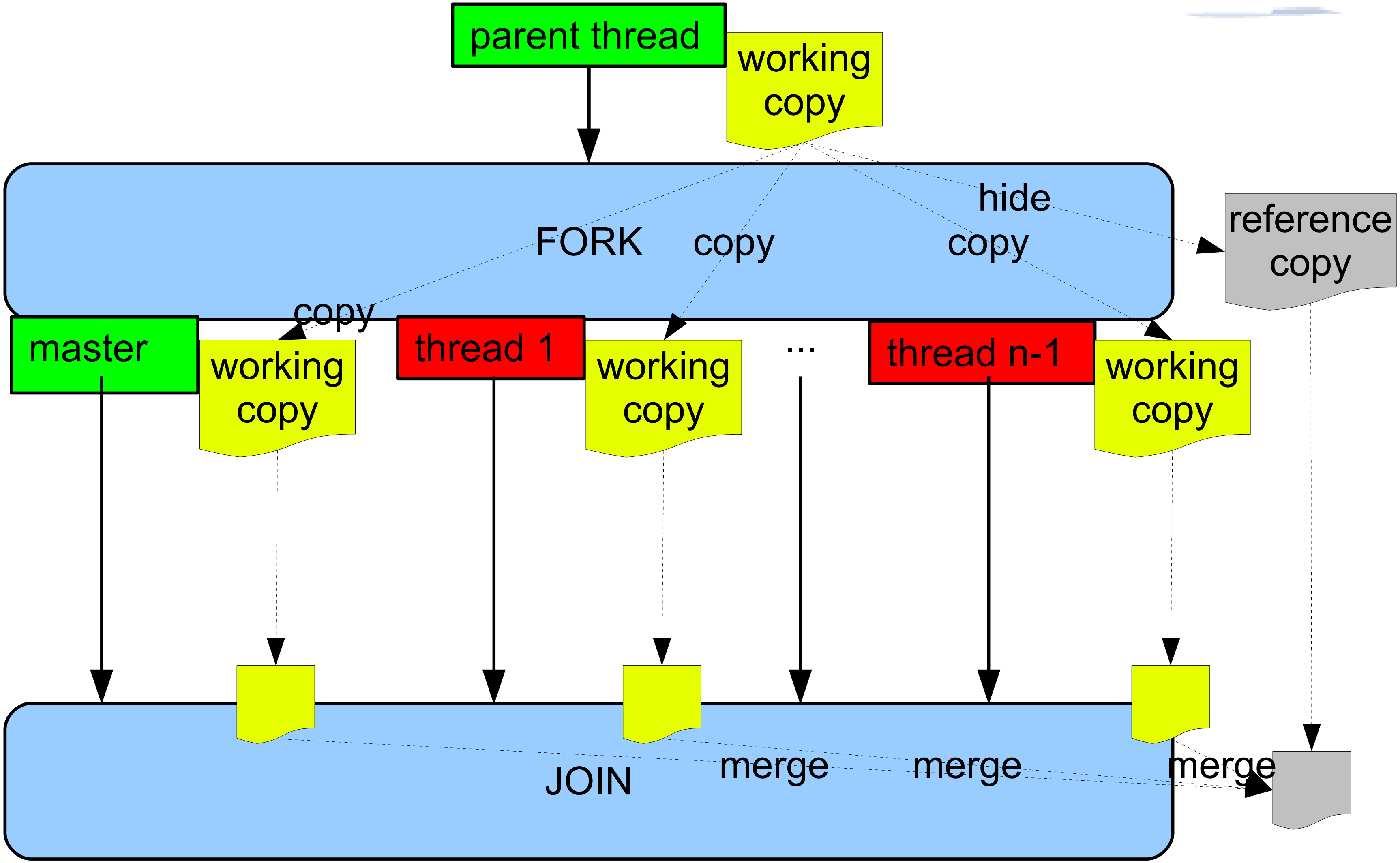
JOIN


parent thread
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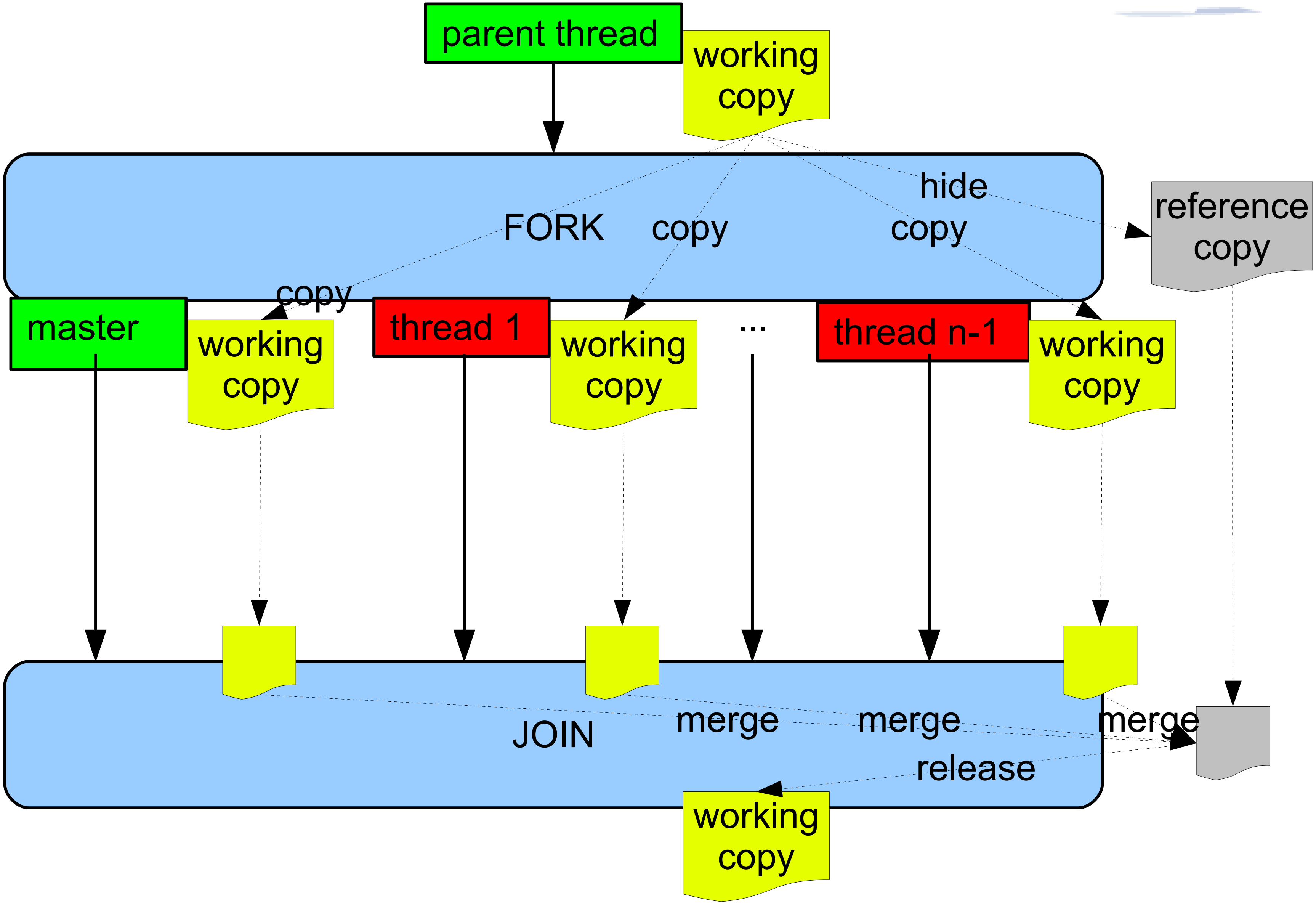
working copy
...
thread n-1
working copy
JOIN
merge
merge
merge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FORK
copy
copy
hide
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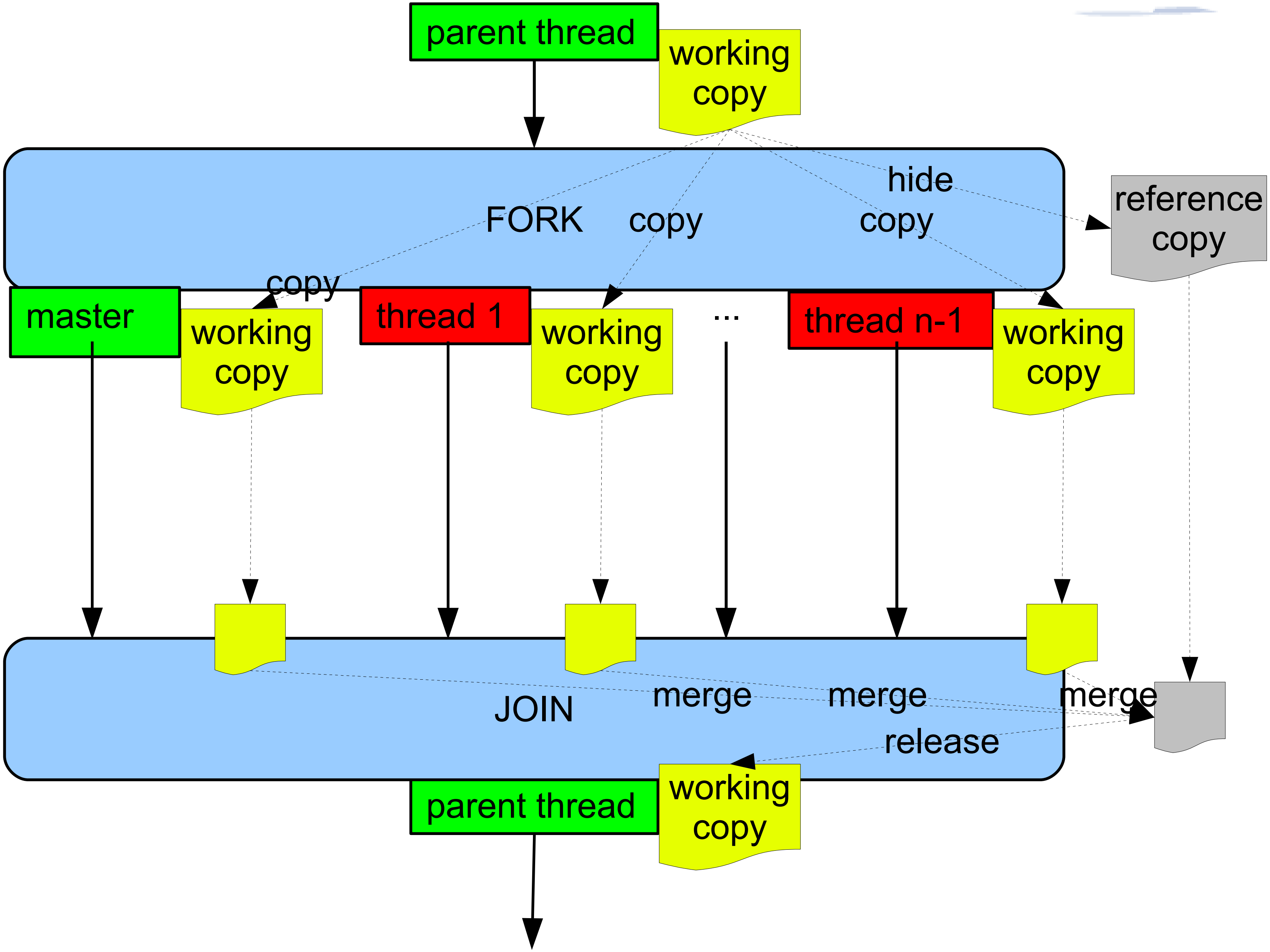
master
working copy
thread 1
working copy
...
thread n-1
working copy
JOIN
merge
merge
merge
release
working copy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merge
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working copy

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Efficiency

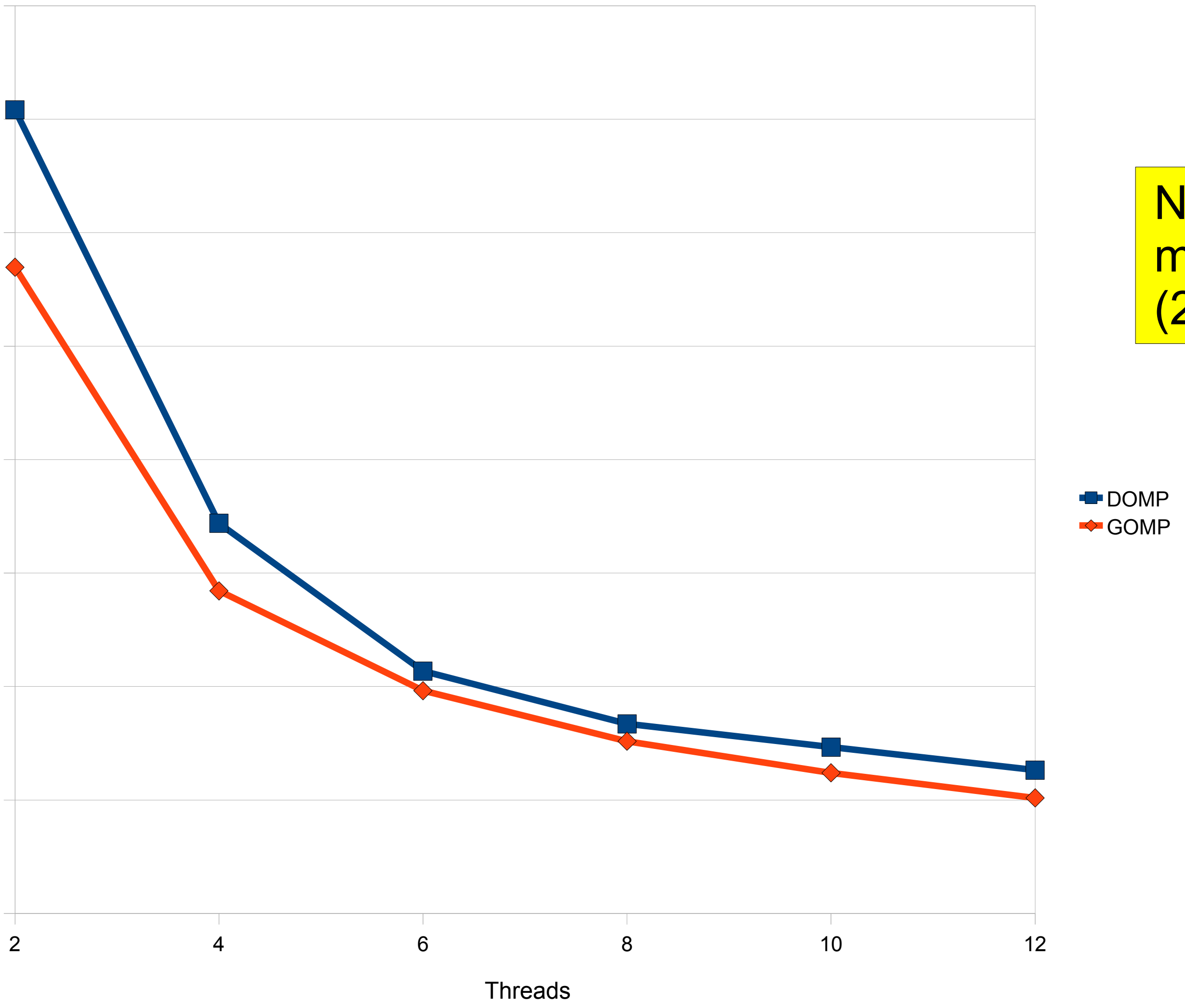
Can DOMP be Efficient?

- Problem:
  Cost of copying and merging data:
  $O(\mathit{num\_threads} \times \mathit{bytes\_of\_data})$
- Solution:
  Lazy per-page copy-on-write
  Lazy page-granularity merge

Previous Experience

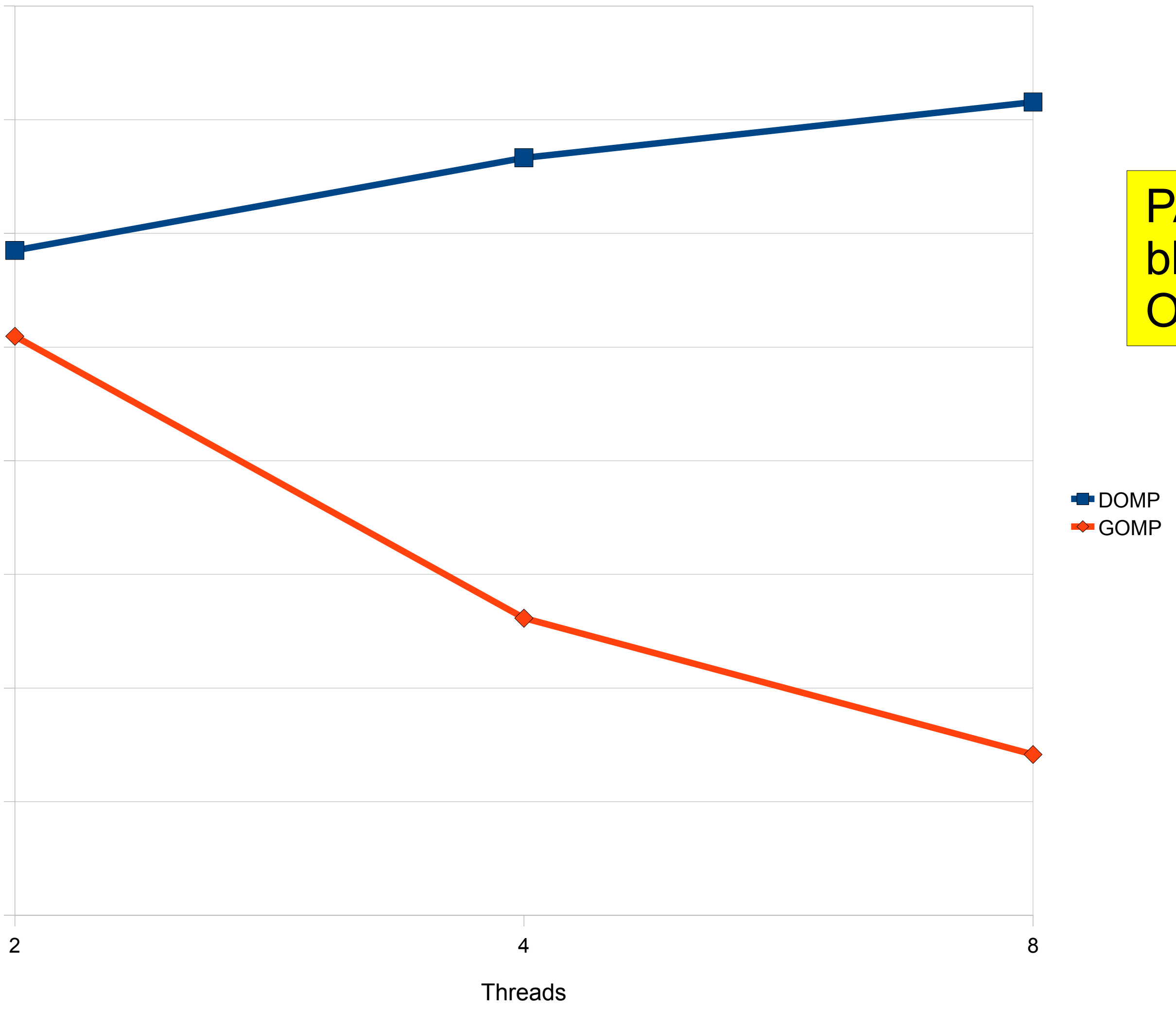
- *Dthreads*, *Determinator*—both naturally deterministic
- Good results for some benchmarks
- Great for “embarrassingly parallel” applications
- Fine-grained parallelism can be expensive

The Good News``



Naïve matrix multiplication (2048 x 2048)

The Not-So-Good News



PARSEC blackscholes for OpenMP

By the way ...

In testing, DOMP uncovered a hitherto unnoticed data race in the blackscholes (OpenMP version) code. ☺

- Bug-finding is not DOMP's primary goal
- But nice that its model shakes out concurrency bugs automatically

Conclusion

- DOMP: proposed race-free, deterministic parallel programming framework
- API based on OpenMP—new semantics & extensions
- Applies working-copies approach to enforce determinism
- Combines expressiveness, reliability, and (we hope) efficiency

Thank you