Tapir: Embedding Fork-Join Parallelism into LLVM IR

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CSAIL

Writing Fast Code

```
double norm(const double *A, int n);

void normalize(double *restrict out, const double *restrict in, int n) {
  for (int i = 0; i < n; ++i)
    out[i] = in[i] / norm(in, n);
}
```

Writing Fast Code

Declaring the return value to be `const` allows the compiler to move the call to `norm` out of the loop.

```
__attribute__((const))
double norm(const double *A, int n);

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}
```
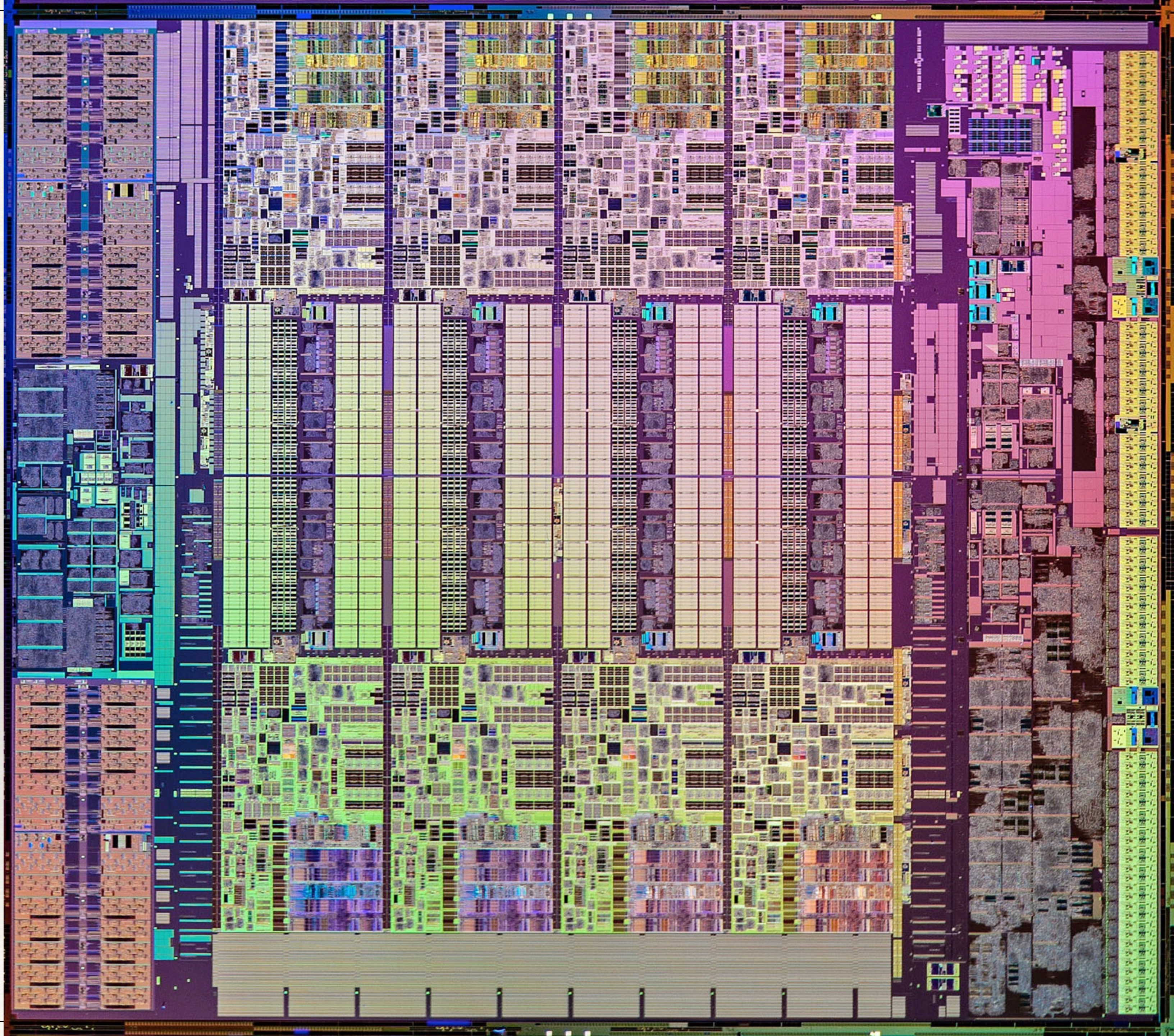

Serial running time: 0.340s

Wow! This is fun! What else can we do?

We have multiple cores! Let's make it run in parallel!



Intel Core i7-5960X

Writing Fast Code

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__attribute__((const))
double norm(const double *A, int n);

void normalize(double *restrict out, const double *restrict in, int n) {
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Writing Half-Fast Code

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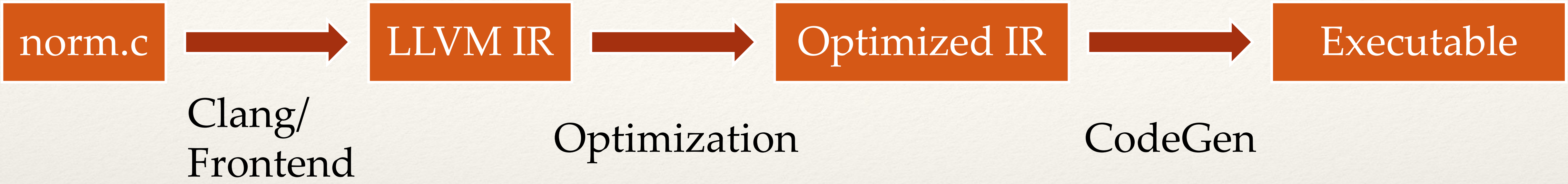
~25,000 cores needed to get parallel speedup!

What happened?

LLVM/Clang pipeline



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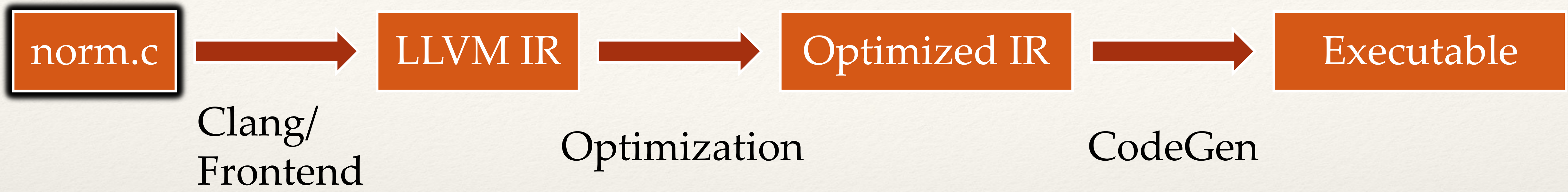


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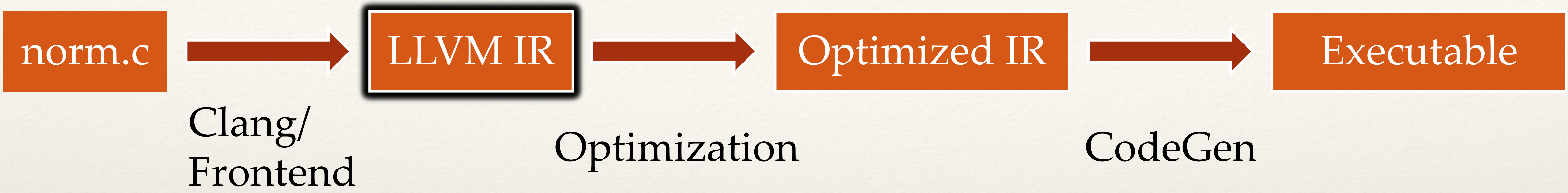


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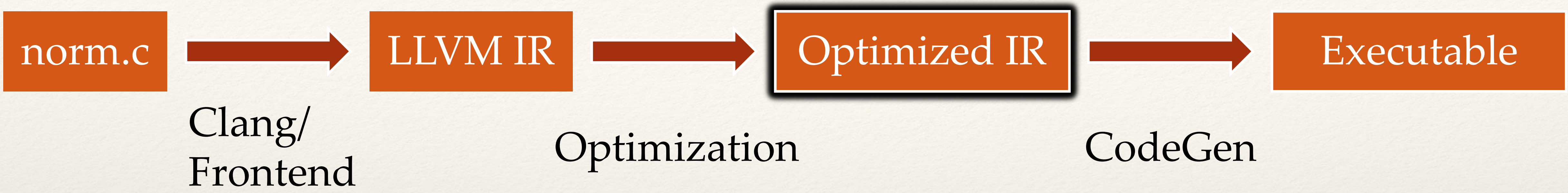


```c
__attribute__((const))
double norm(const double *A, int n);

void normalize(double *restrict out, const double *restrict in, int n)
 int tmp = norm(in, n);
 for(int i = 0; i < n; ++i)
    out[i] = in[i] / tmp;
}
```

LLVM/Clang pipeline (Cilkplus)

norm.c → LLVM IR → Optimized IR → Executable

Clang/ Frontend — Optimization — CodeGen

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double norm(const double *A, int n);

void normalize(double *restrict out, const double *restrict in, int n)
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    out[i] = in[i] / norm(in, n);
}
```

LLVM/Clang pipeline (Cilkplus)

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Clang/ Frontend

Optimization

CodeGen

```
void normalize(double *restrict out, const double *restrict in, int n)
  int* close[3] = { n, in, out };
  __cilk_rts_for(cilk_for_helper, close, 0, n);
}
void cilk_for_helper (int start, int end) {
  int n = *(int*)close;
  int* in = *(int**)(close+1);
  int* out = *(int**)(close+2);
  out[i] = in[i] / norm(in, n);
}
```

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  out[i] = in[i] / norm(in, n);
}
```

And this is a *simple* example!

Another example

```
int fib(int n) {
  if (n < 2) return n;
  int x, y;
  x = cilk_spawn fib(n-1);
  y = fib(n-2);
  cilk_sync;
  return x + y;
}
```

```
int fib(int n) {
  __cilkrts_stack_frame_t sf;
  __cilkrts_enter_frame(&sf);
  if (n < 2) return n;
  int x, y;
  if (!setjmp(sf.ctx))
    spawn_fib(&x, n-1);
  y = fib(n-2);
  if (sf.flags & CILK_FRAME_UNSYNCHED)
    if (!setjmp(sf.ctx))
      __cilkrts_sync(&sf);
  int result = x + y;
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
  return result;
}
void spawn_fib(int *x, int n) {
  __cilkrts_stack_frame sf;
  __cilkrts_enter_frame_fast(&sf);
  __cilkrts_detach();
  *x = fib(n);
  __cilkrts_pop_frame(&sf);
  if (sf.flags)
    __cilkrts_leave_frame(&sf);
}
```

How is an optimization pass supposed to figure its way around this mess of opaque system calls?

Parallelism Should Not Be "Lowered" in the Front End

- Opaque runtime calls do not allow optimization passes on the IR to do their jobs on parallel constructs.
- Unoptimized parallel performance can be much worse than optimized serial performance.
- Optimizing parallel constructs in the front end duplicates work that the IR optimization passes are already doing for serial constructs.
- Optimizing parallel constructs in the front end is error prone.

Let’s put parallelism in the IR!

But...

Comments on the idea from the llvm-dev mailing list [1]

- "[D]efining a parallel IR (with first class parallelism) is a research topic…."
- "[It] is not an easy problem."
- "[P]arallelism is a very invasive concept and introducing it into a so far `sequential' IR will cause severe breakage and headaches."
- "[P]arallelism is invasive by nature and would have to influence most optimizations."

[1] http://lists.llvm.org/pipermail/llvm-dev/2016-March/096581.html

Prior Work

SPIRE [2, 3], INSPIRE [4], HPIR [5].

[2] Khaldi, Dounia, Pierre Jouvelot, François Irigoin, and Corinne Ancourt. “SPIRE: A methodology for sequential to parallel intermediate representation extension.” In *17th Workshop on Compilers for Parallel Computing (CPC)*, 2012.

[3] Dounia Khaldi, Pierre Jouvelot, François Irigoin, Corinne Ancourt, and Barbara Chapman. “LLVM parallel intermediate representation: design and evaluation using OpenSHMEM communications.” In *2nd Workshop on the LLVM Compiler Infrastructure in HPC* (LLVM '15), 2015.

[4] Herbert Jordan, Simone Pellegrini, Peter Thoman, Klaus Kofler and Thomas Fahringer, "INSPIRE: The Insieme parallel intermediate representation.” In *22nd International Conference on Parallel Architectures and Compilation Techniques (PACT)*, 2013.

[5] Rajkishore Barik, Jisheng Zhao, and Vivek Sarkar. “Interprocedural strength reduction of critical sections in explicitly-parallel programs.” In *22nd International Conference on Parallel Architectures and Compilation Techniques (PACT)*, 2013.

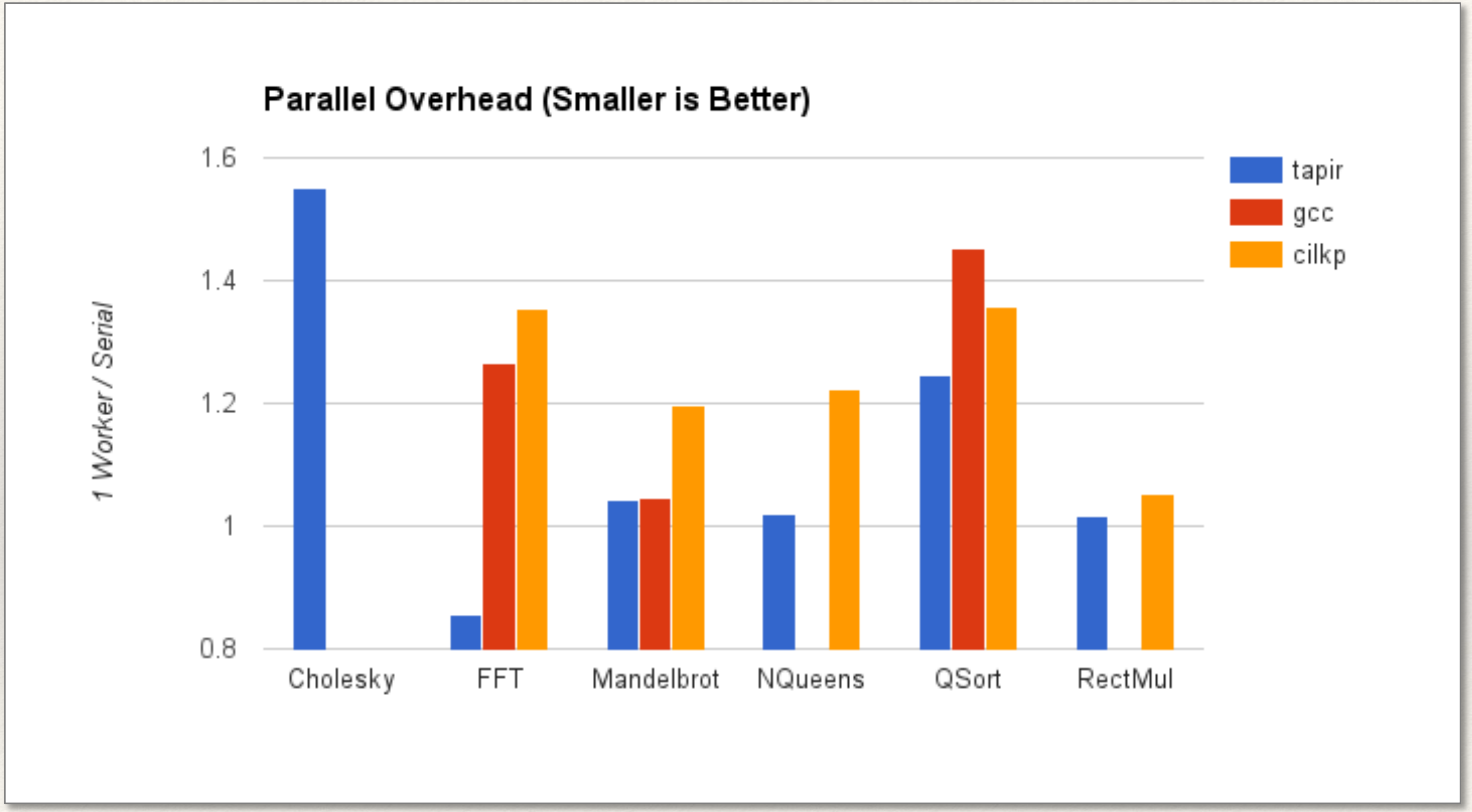
Typical Issues

- Parallel IR is language specific.
- Parallel IR offers minimal benefits to optimization.
- Parallel IR is incompatible with existing serial optimizations.
- Parallel IR requires many changes to the compiler.

Tapir: **T**ask-based **A**symmetric **P**arallel **IR**

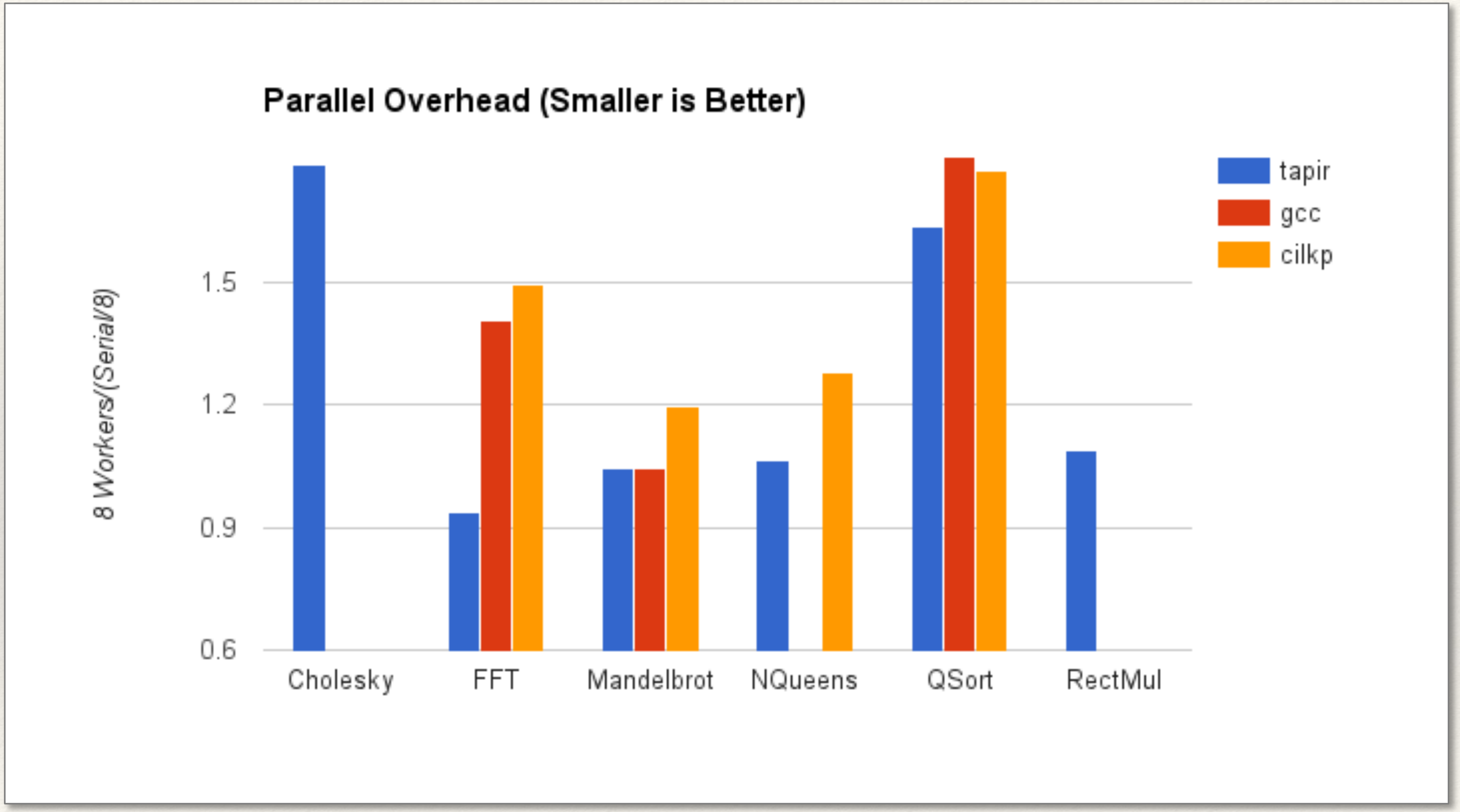
- Tapir is an IR that exposes logical parallelism.
- Tapir enables existing serial optimization passes to operate across parallel control with few or no changes.
- Each of Tapir's "asymmetric" parallelism constructs can also be viewed as a serial construct having ordinary serial semantics.
- Only 5123 LOC were needed to implement Tapir/LLVM.
- Tapir/LLVM includes a provably good determinacy race detector both to verify code transformations and to debug buggy source code.

Overhead Comparison on 1 Worker



Cilk and Intel Sample Benchmarks
Minimum of 5 runs on AWS c4.8xlarge

Overhead Comparison on 8 Workers



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Outline

- LLVM Overview
- Naive Parallel IR
- Tapir Syntax and Semantics
- Optimization Passes
- Evaluation
- Conclusion

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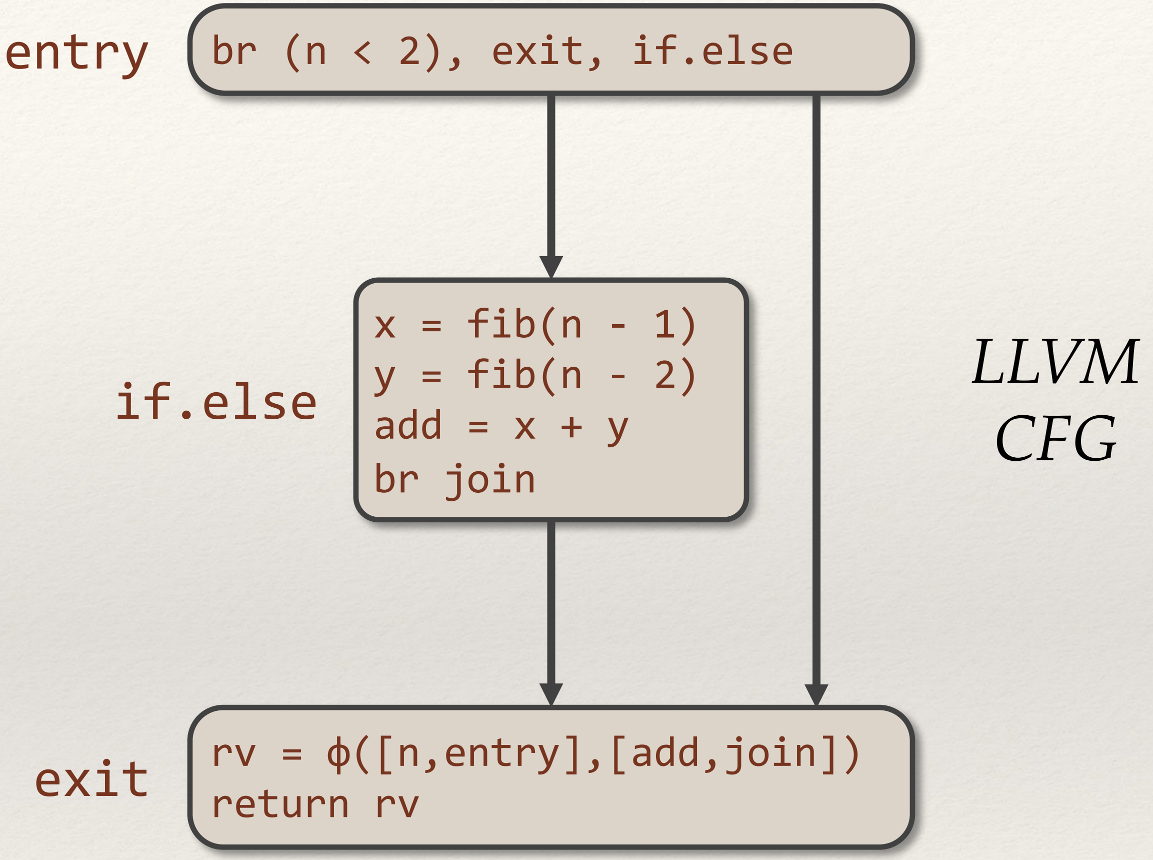
LLVM Overview

```
int fib(int n) {
  if (n < 2) return n;
  int x = fib(n-1);
  int y = fib(n-2);
  return x + y;
}
```

Control flow graph (CFG)

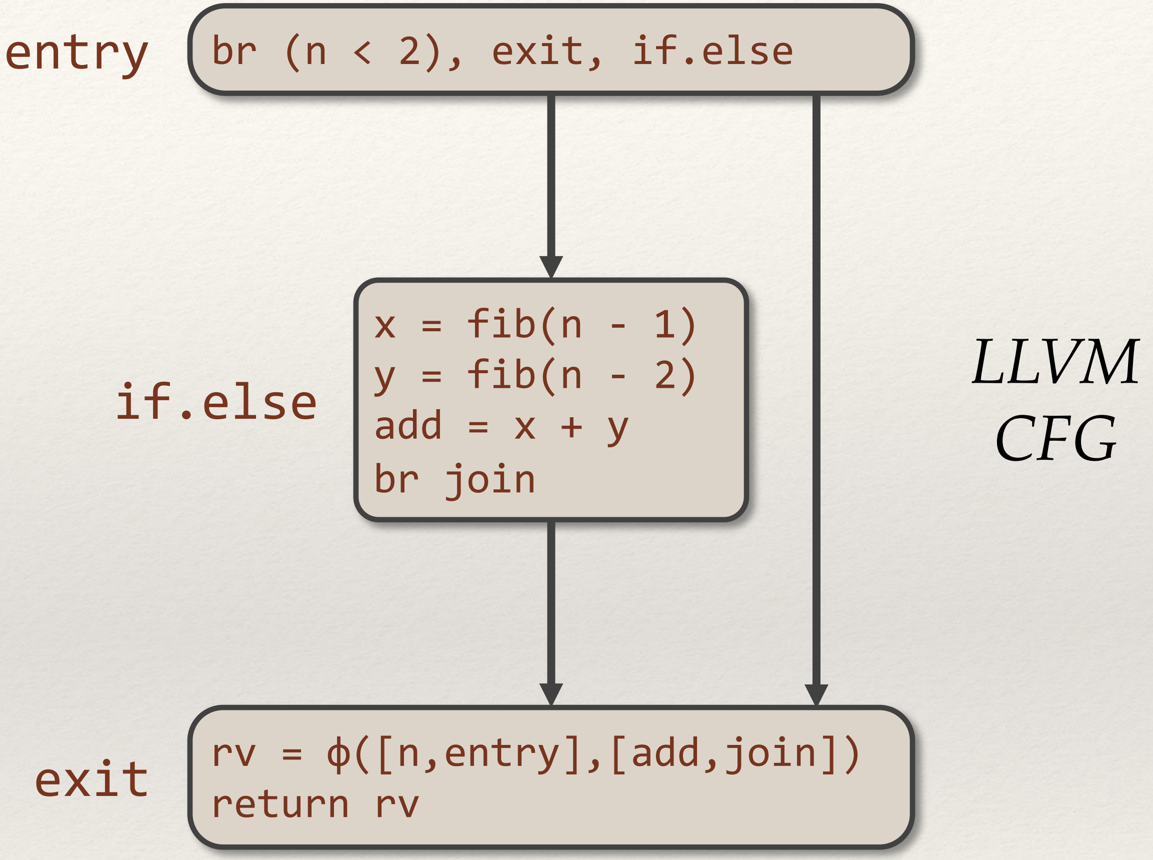
- Basic blocks contain instructions.
- Values are stored in registers.
- Edges create control flow.



LLVM Invariants

Invariants

- ***Lineage assumption***: Only one predecessor of a basic block actually executes.
- A basic block can only access a register if the register ***dominates*** the basic block.



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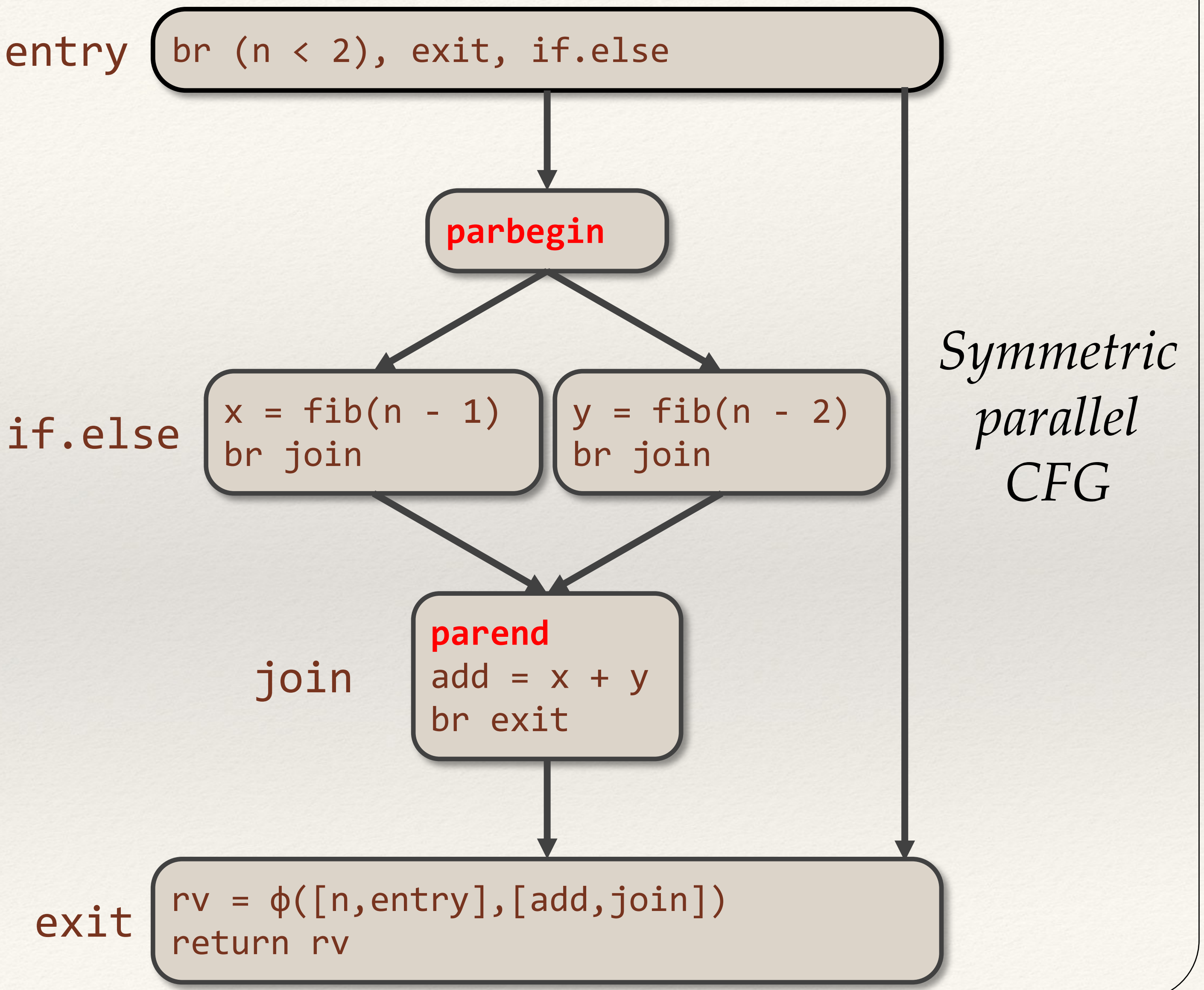
Naive Parallel IR

```
int fib(int n) {
  if (n < 2) return n;
  int x = cilk_spawn fib(n-1);
  int y = fib(n-2);
  cilk_sync;
  return x + y;
}
```

Idea

Modify the program's control-flow graph to represent logically parallel tasks symmetrically.



Initial Attempt: Naive Representation

```
int fib(int n) {
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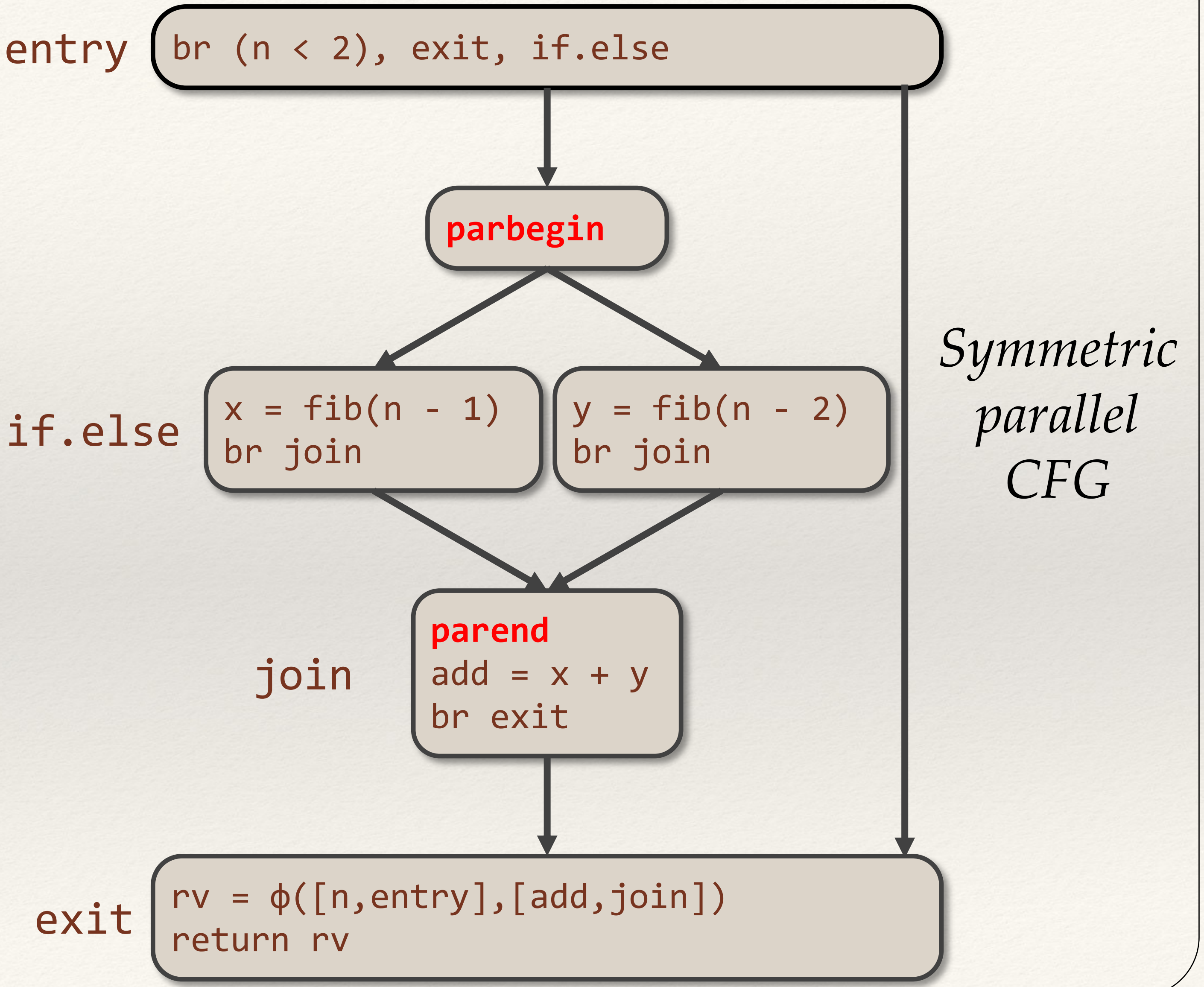
```



Major issue

- LLVM's lineage assumption breaks.
- Values from *all* predecessors must be available at the join.

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Tapir: Asymmetric Representation

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  if (n < 2) return n;
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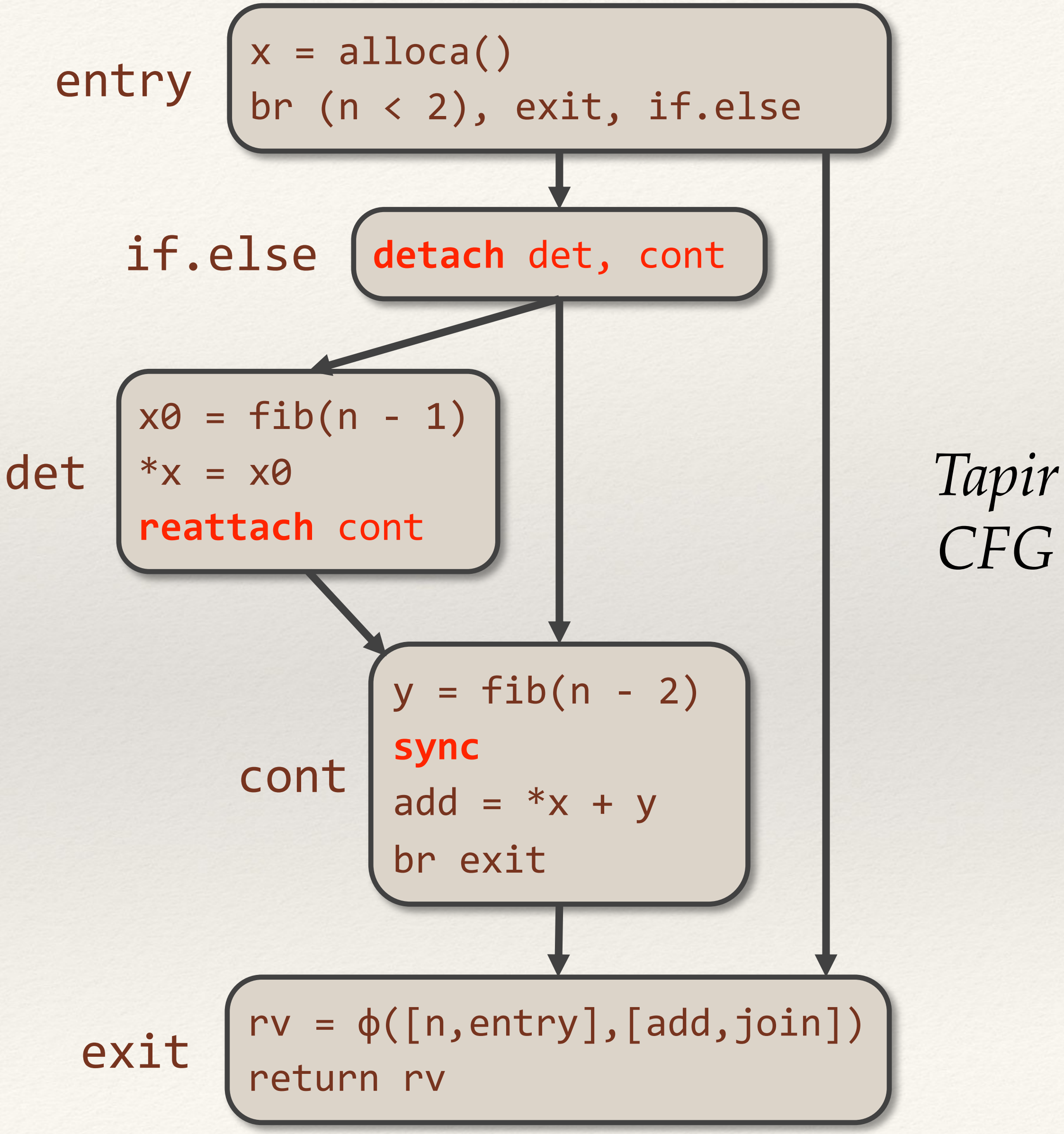
  cilk_sync;
  return x + y;
}
```

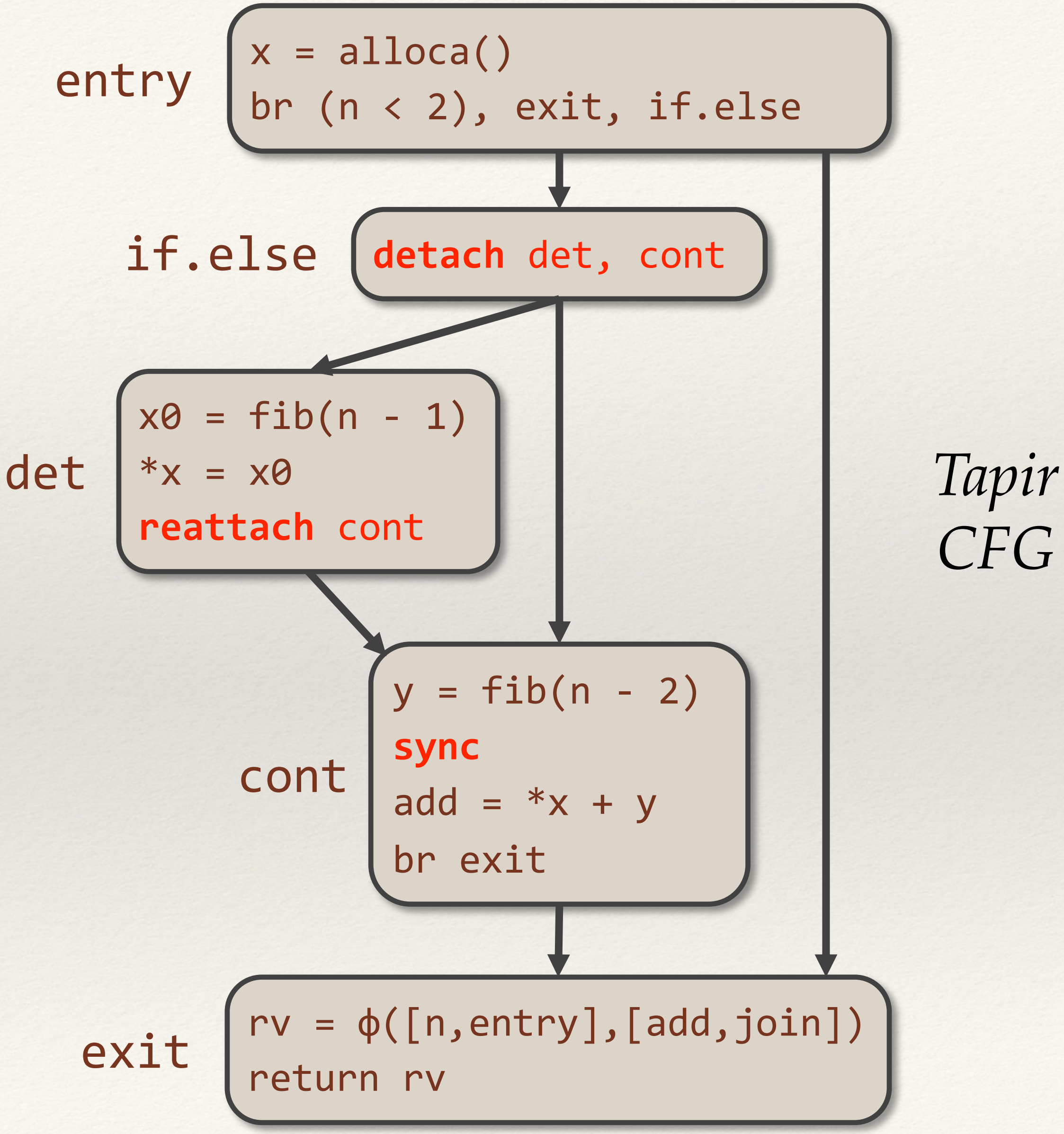


Tapir: Asymmetric Representation

```
int fib(int n) {
  if (n < 2) return n;
  int x = cilk_spawn fib(n-1);
  int y = fib(n-2);
  cilk_sync;
  return x + y;
}
```

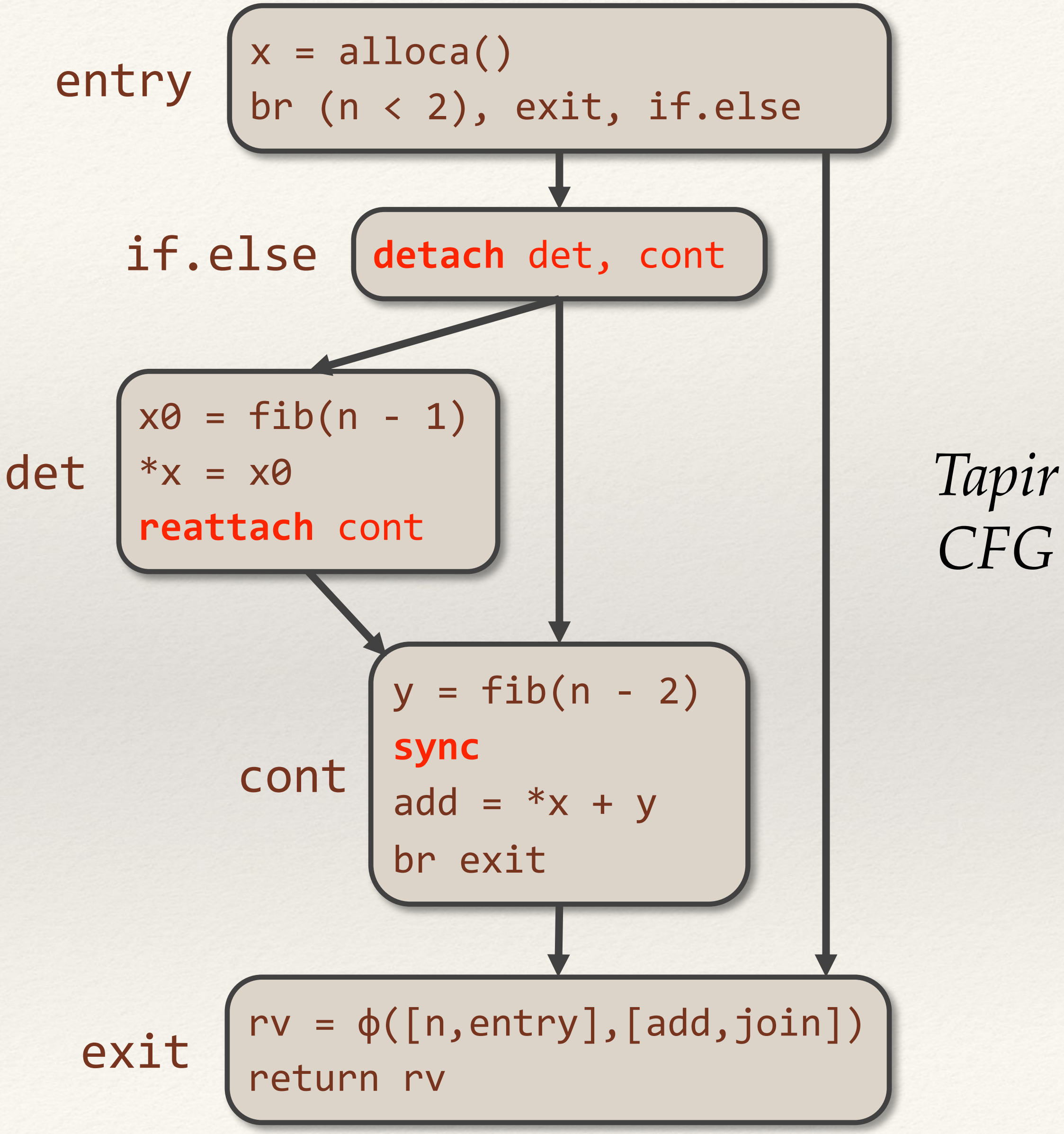
Preservation of LLVM's lineage assumption

- The continuation has no access to parallel registers (as at the low level).
- LLVM's invariants are maintained.



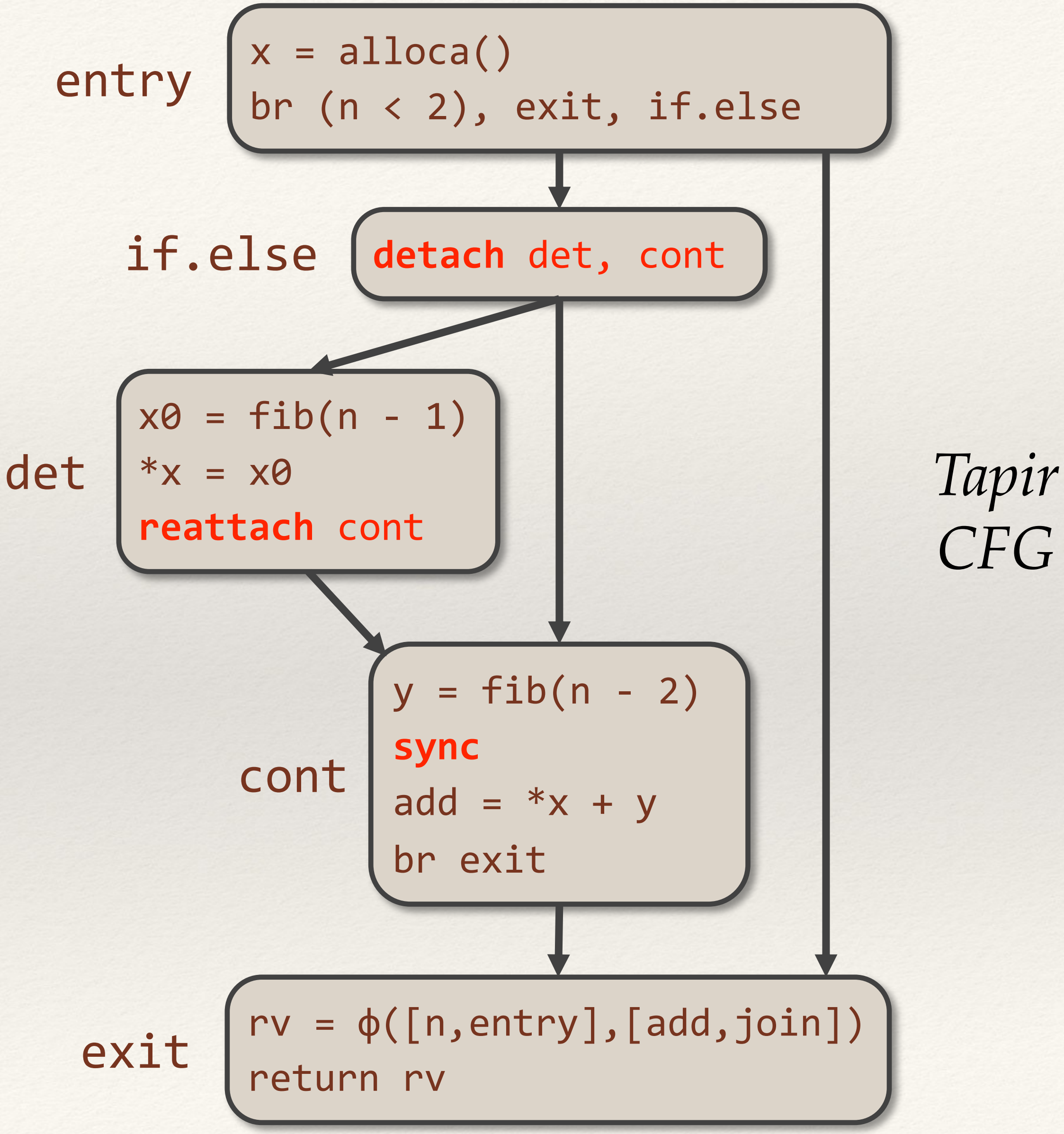
Syntax of Tapir

- Tapir introduces three new opcodes into LLVM's IR: `detach`, `reattach`, and `sync`.
- Tapir simultaneously represents the serial and parallel semantics of the program.



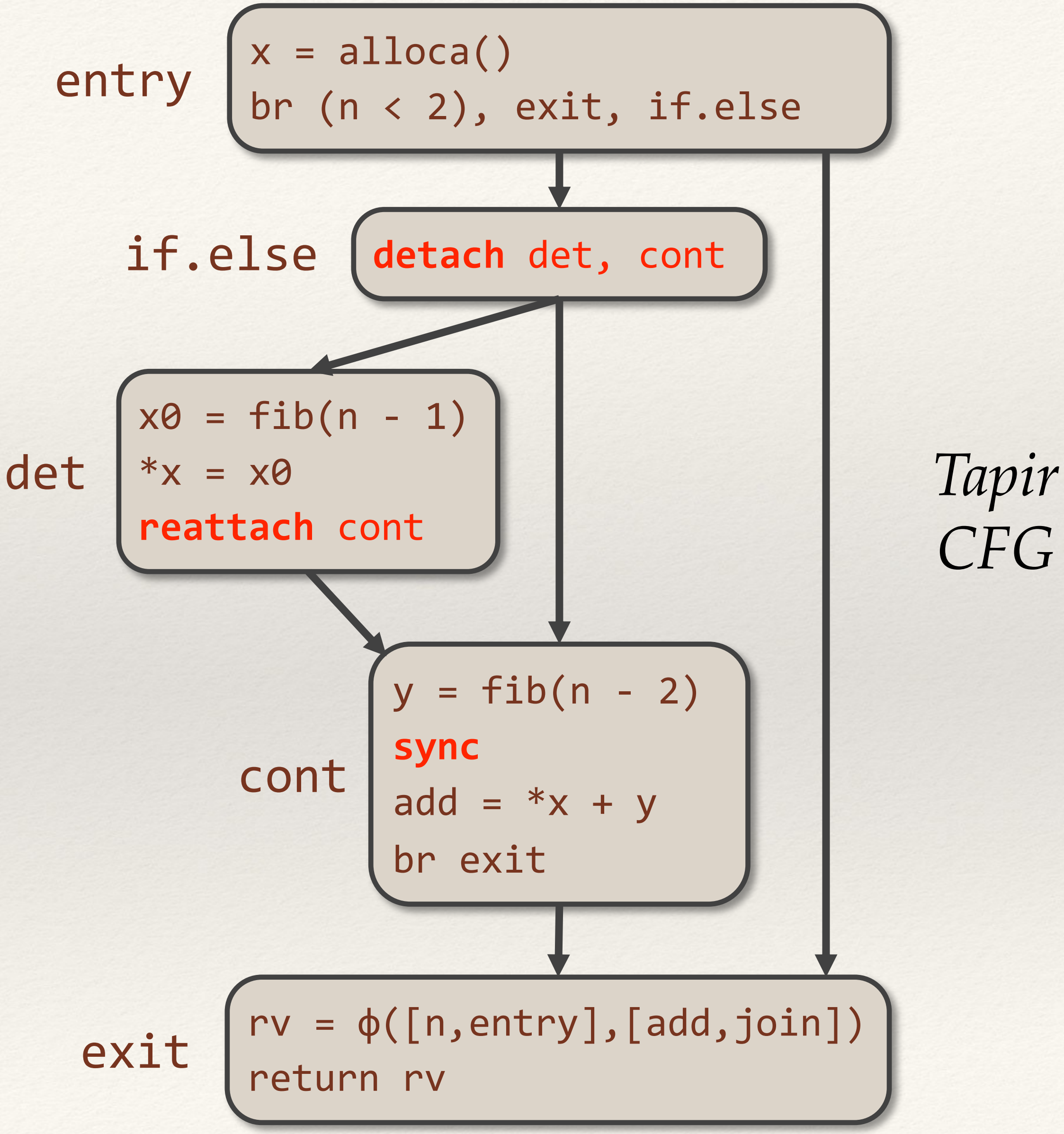
Semantics of Tapir

- The successors of a detach terminator are the ***detached block*** and ***continuation*** and *may* run in parallel.
- A ***detached CFG*** contains all blocks between a detached block and its corresponding reattach.



Semantics of Tapir (continued)

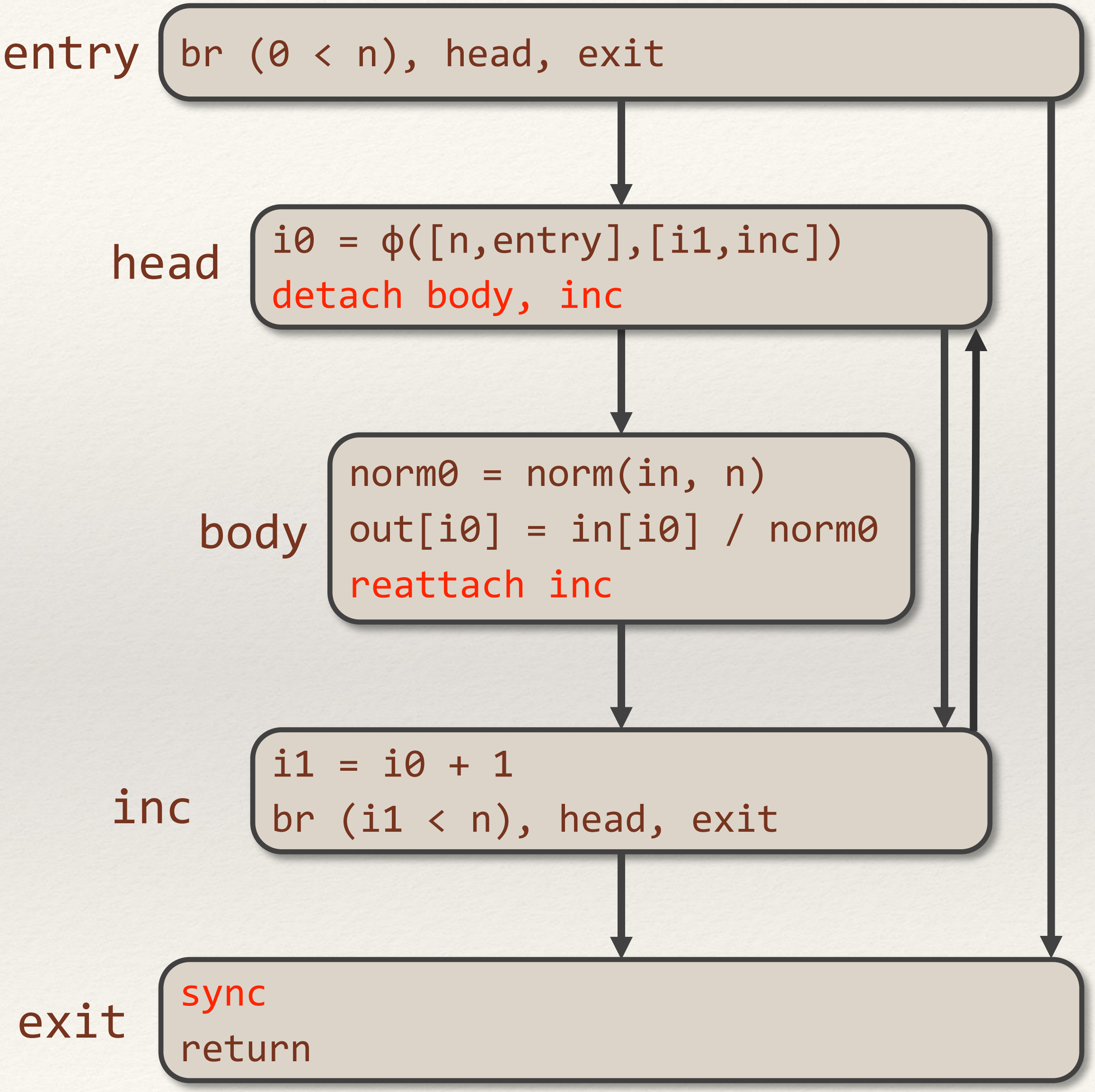
- When run serially, programs first execute the detached CFG and then the continuation.
- Registers computed in the detached CFG are not available in the continuation.
- Execution after a `sync` ensures that all detached CFG's in scope have completed execution.



Parallel Loops in Tapir

- Identical to serial loops, except with the body detached.

```
void normalize(
    double *restrict out,
    const double *restrict in,
    int n)
{
  cilk_for(int i = 0; i < n; ++i)
    out[i] = in[i] / norm(in, n);
}
```



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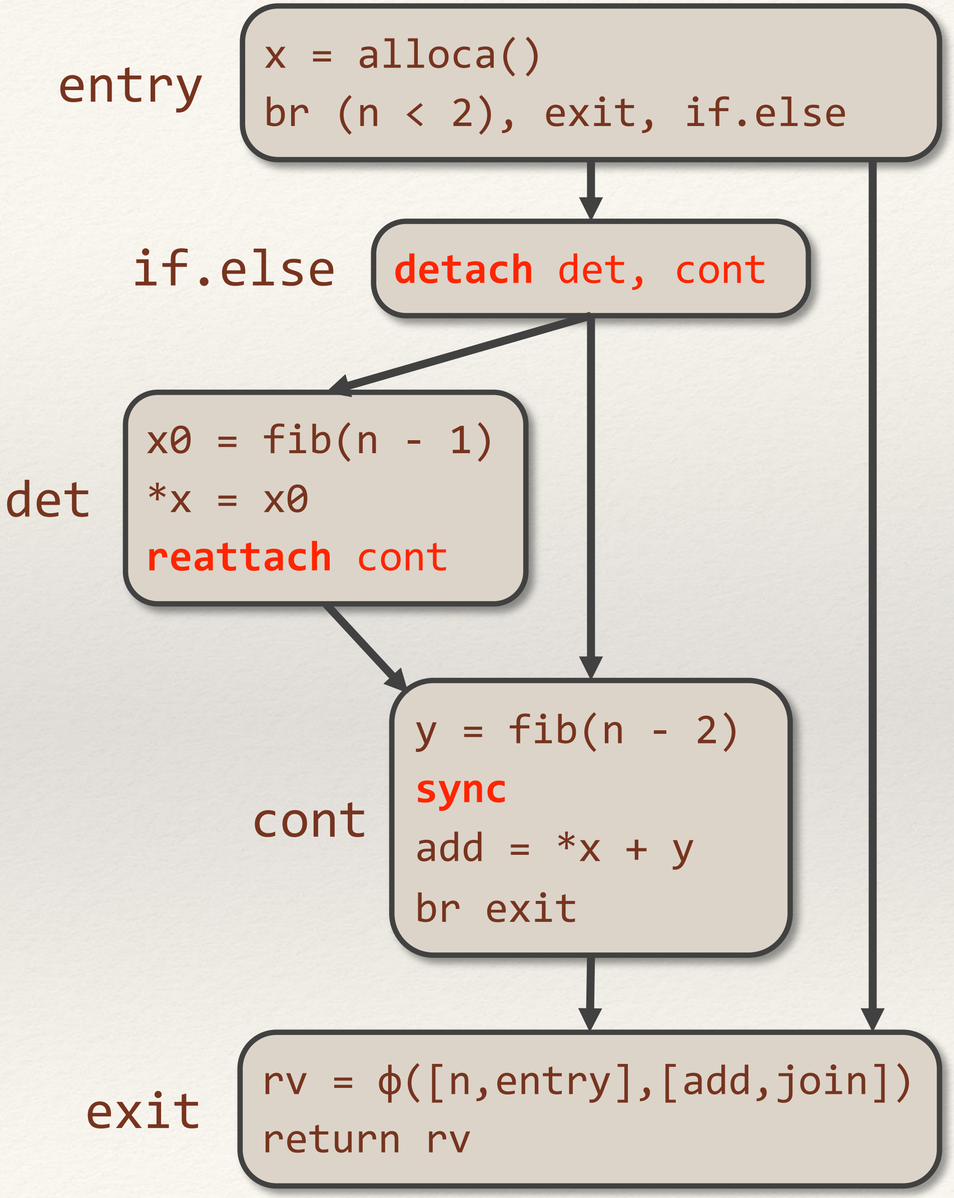
Maintaining Correctness

Problem: How does the compiler ensure that code motion does not introduce a determinacy race into otherwise race-free code?



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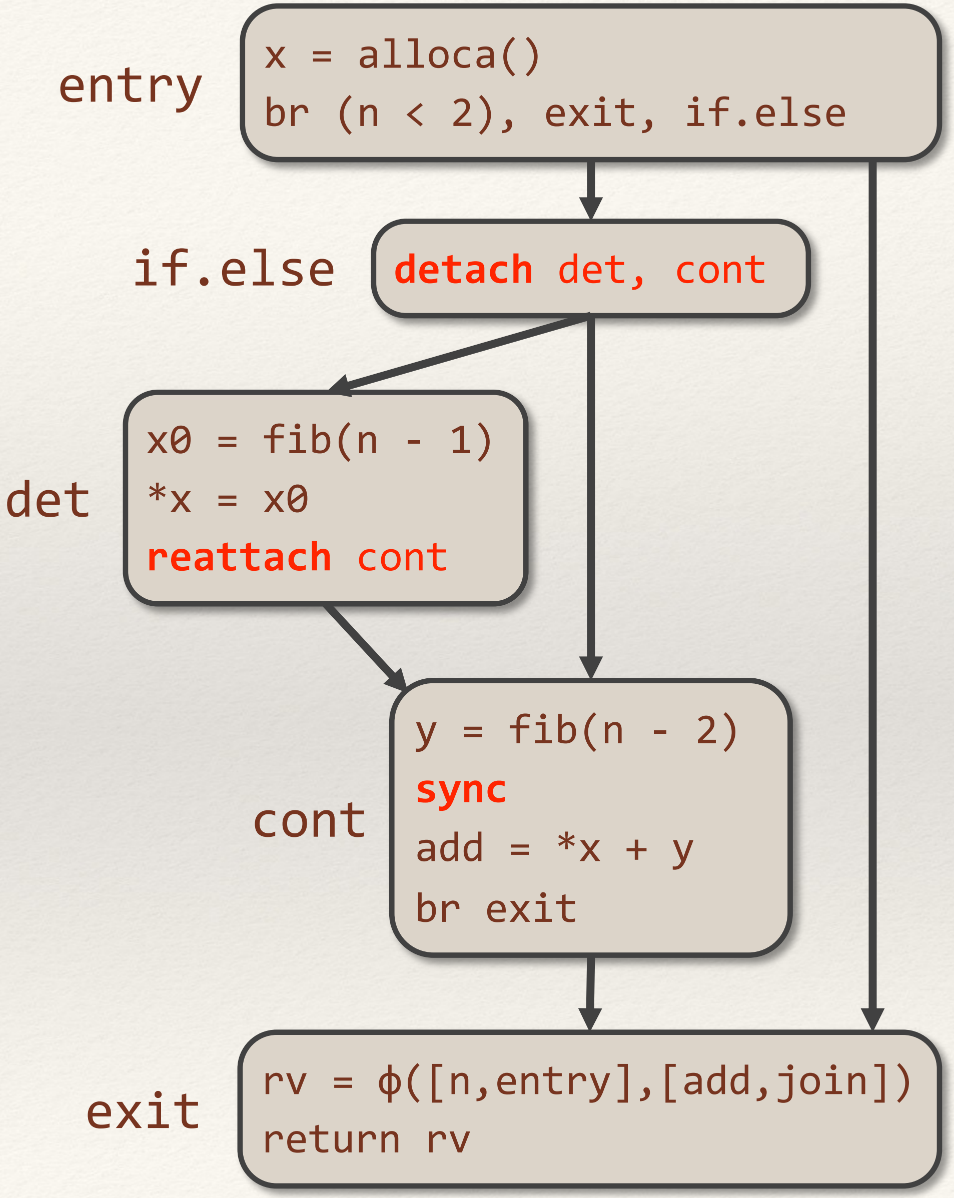

Maintaining Correctness

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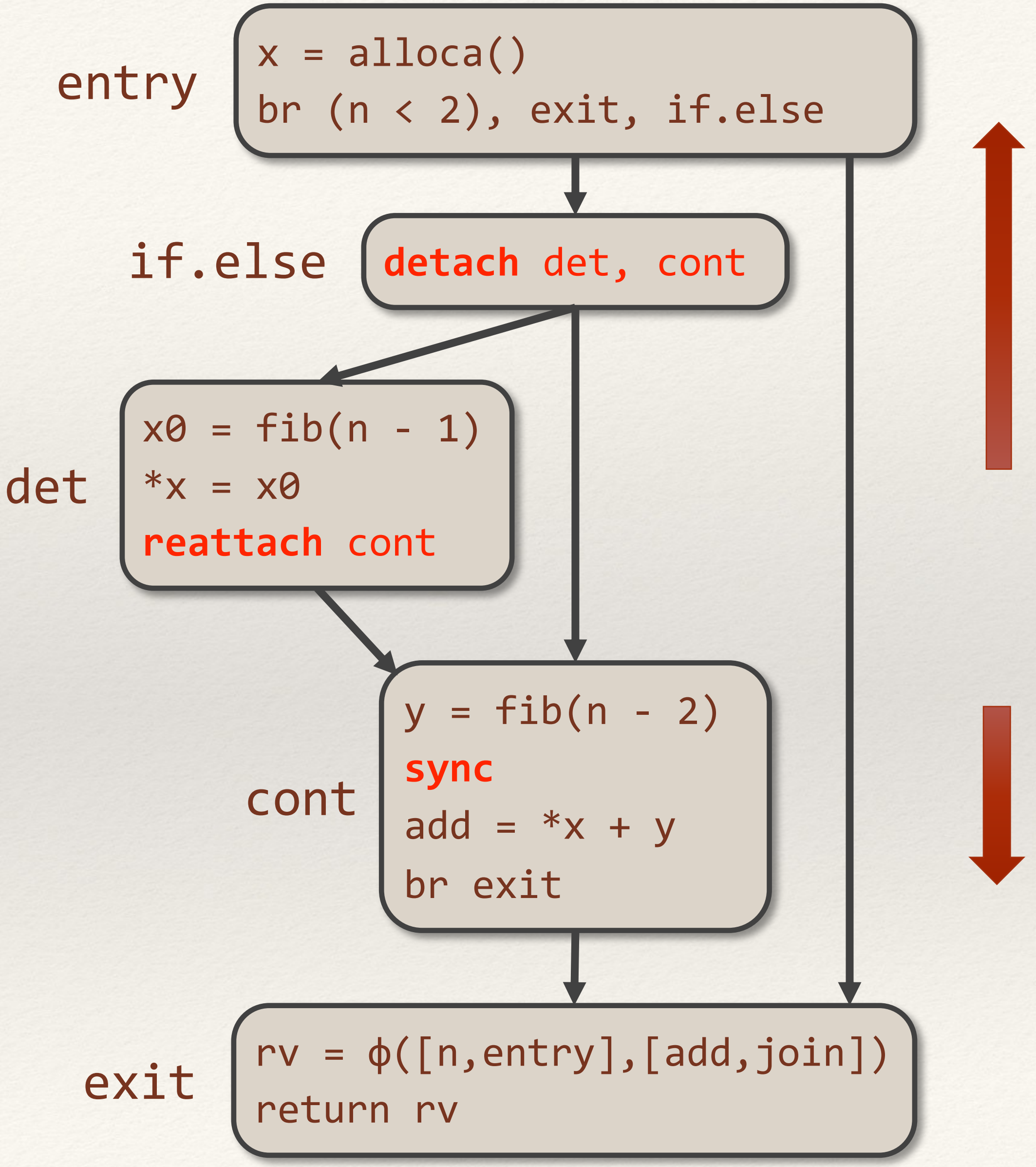
- It suffices to consider moving memory operations around each new instruction.
- Moving code above a `detach` or below a `sync` serializes it and is always valid.



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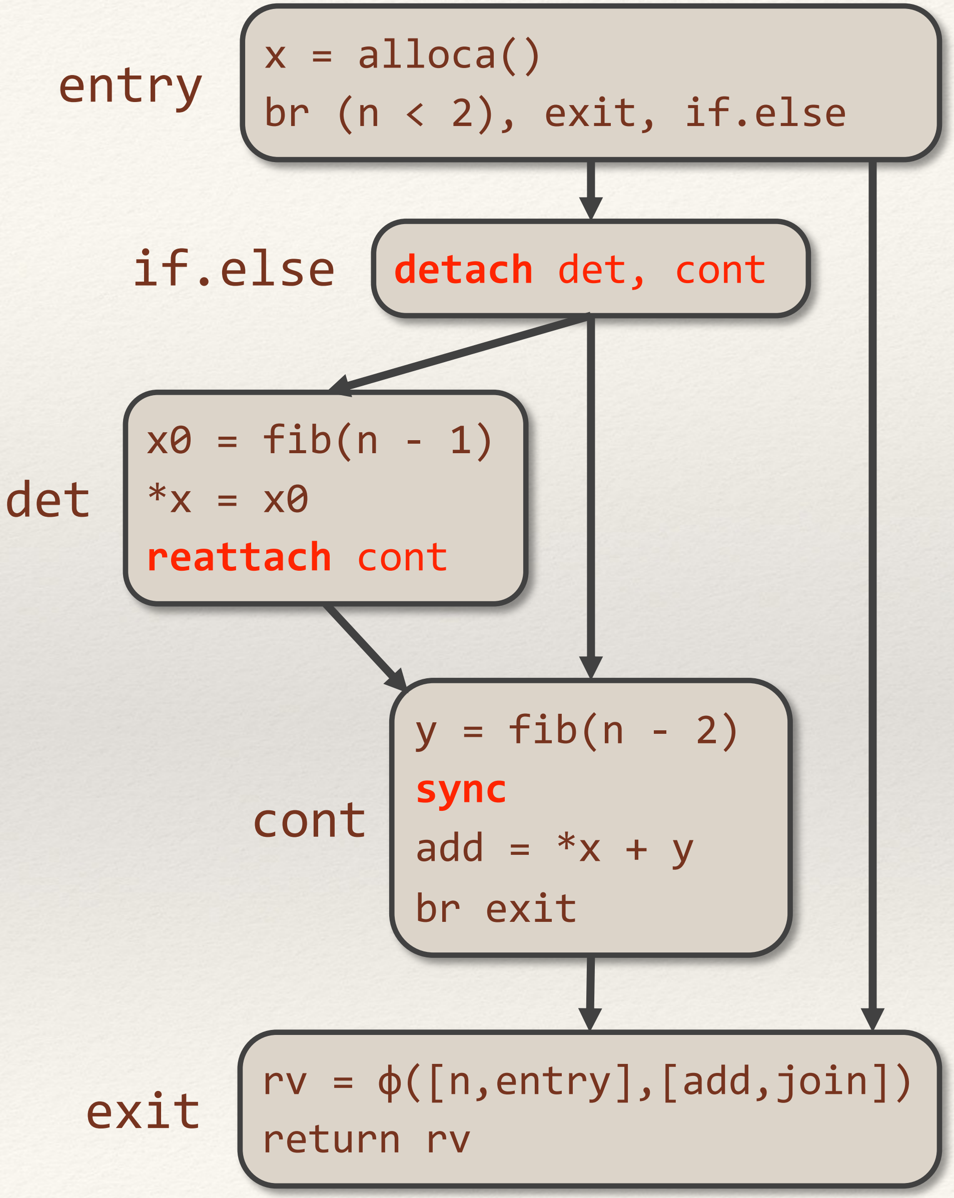
- It suffices to consider moving memory operations around each new instruction.
- Moving code above a `detach` or below a `sync` serializes it and is always valid.
- Other potential races are handled by giving `detach`, `reattach`, and `sync` appropriate attributes and by slight modifications to `mem2reg`.

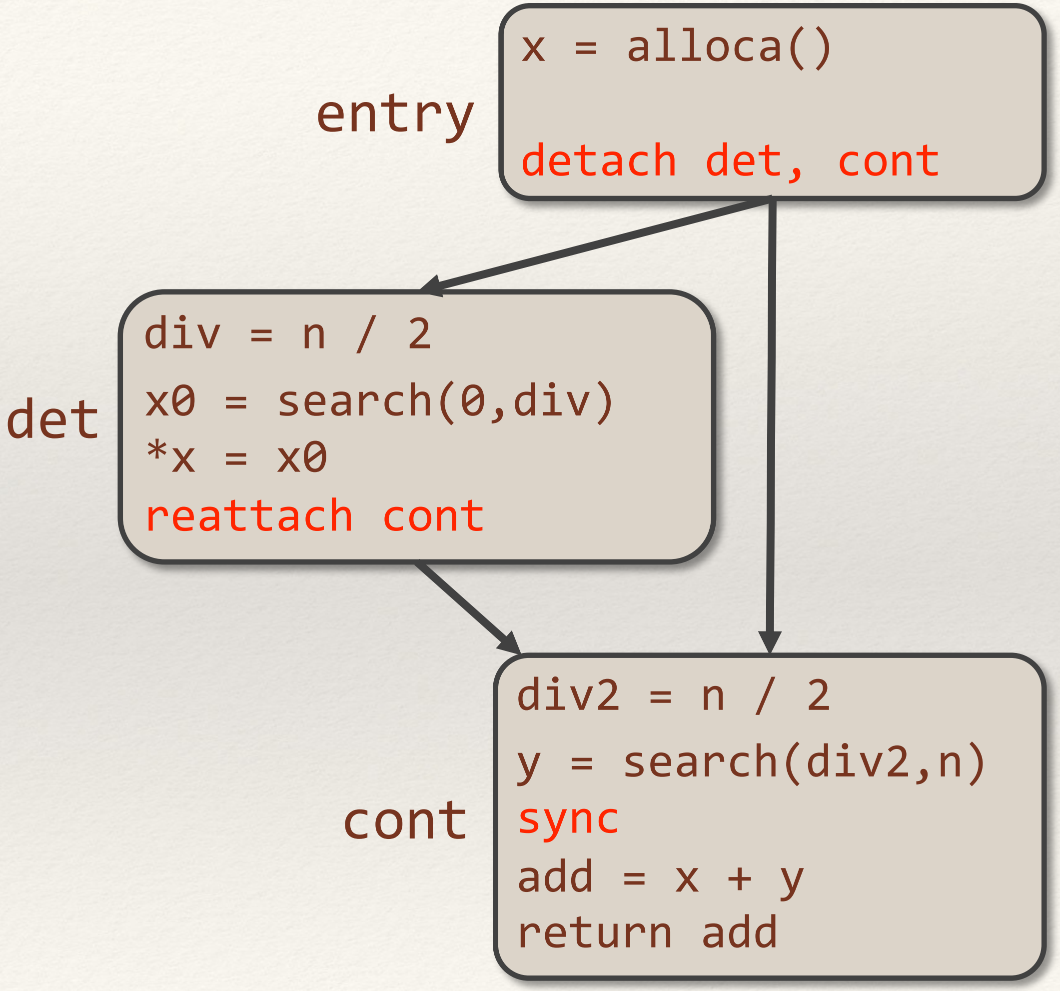


Valid serial passes cannot create race bugs.

Most of LLVM's existing serial passes "just work" on parallel code.

Case Study: Common Subexpression Elimination

- CSE "just works."
- Finding duplicate expressions and condensing them at their lowest common ancestor works fine for `detach`/`reattach`.




```
void query(int n) {
  int x = cilk_spawn { search(0,n/2); }
  int y = search(n/2,n);
  cilk_sync;
  return x+y;
}
```

Case Study: Common Subexpression Elimination

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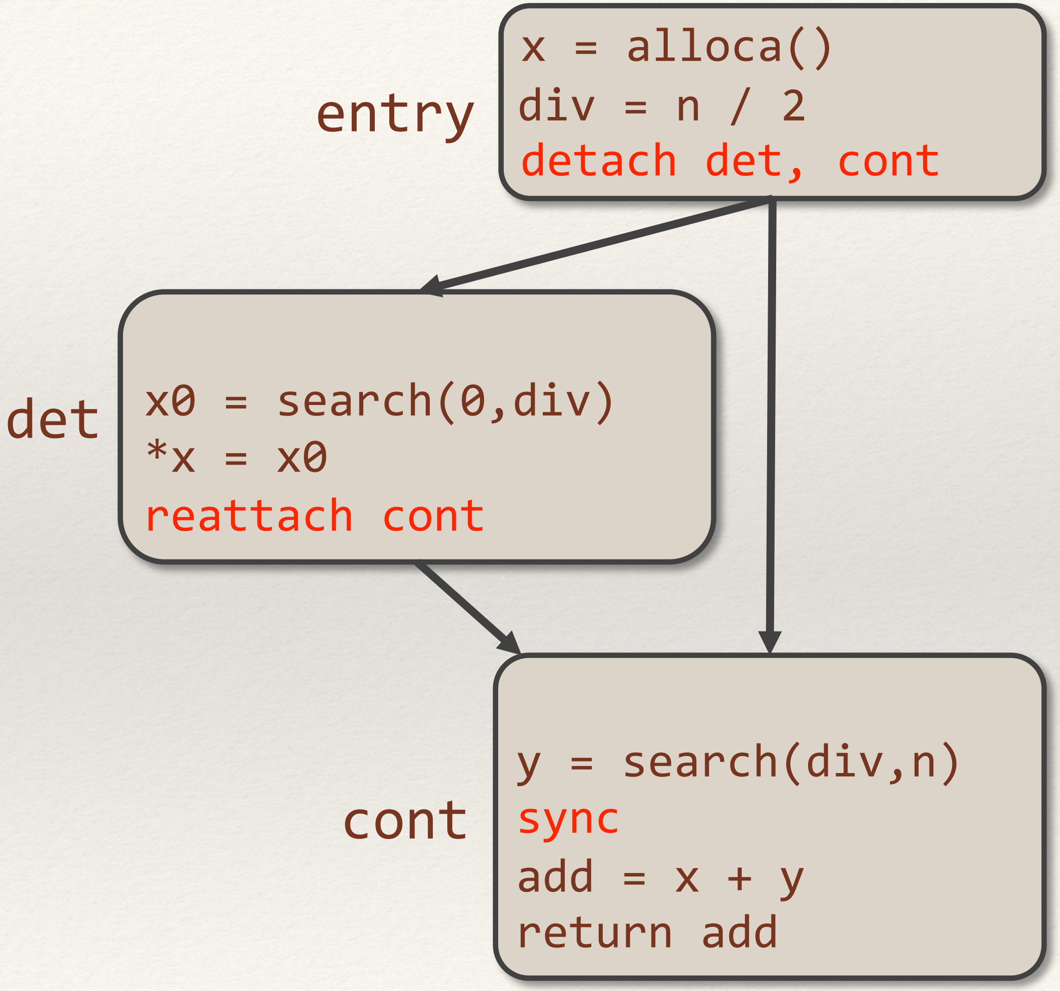
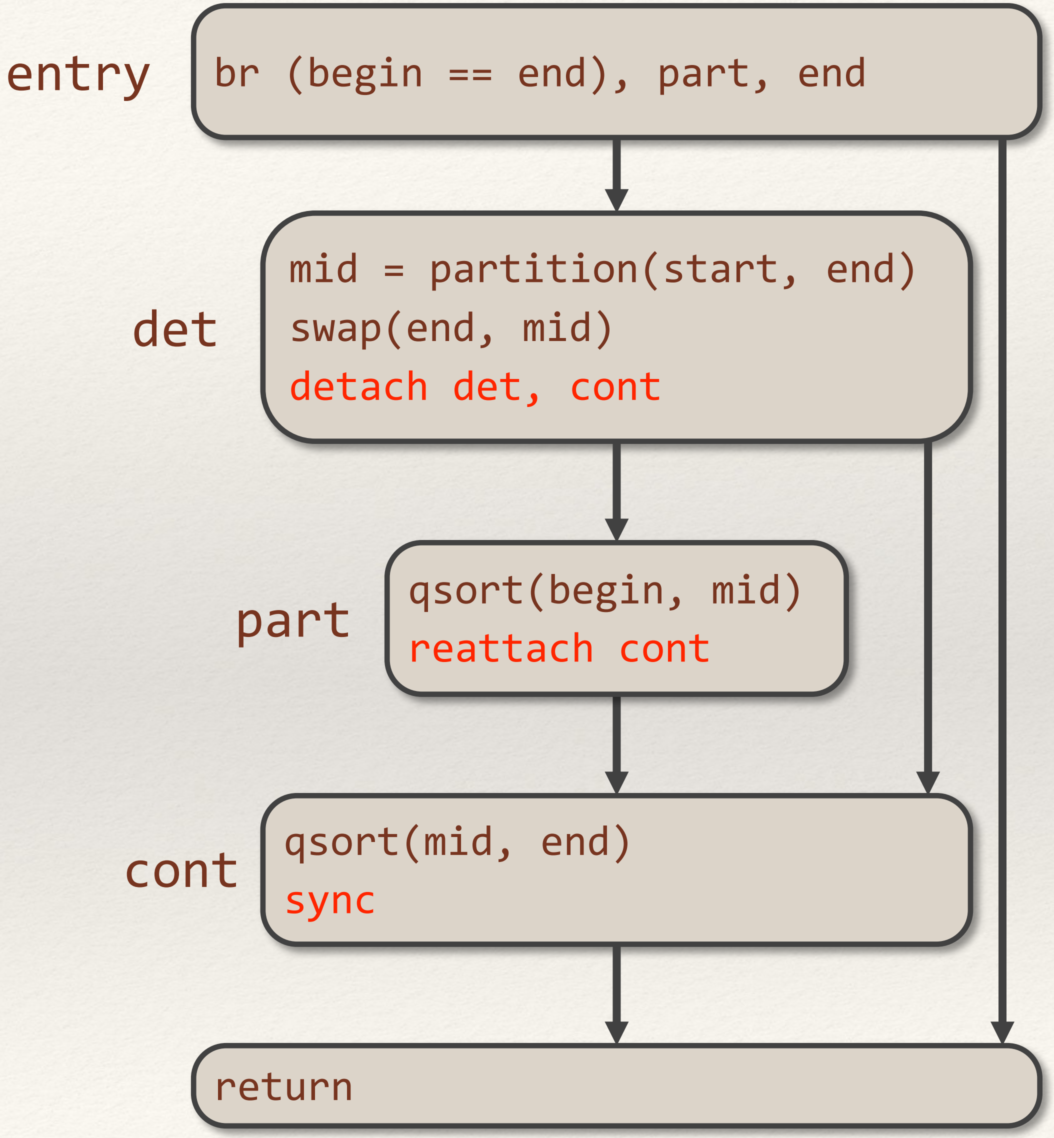


Case Study: Parallel Tail-Recursion Elimination

- A minor modification allows TRE to run on parallel code.
- Ignore `sync`'s before a recursive call and add `sync`'s before intermediate returns.

```
void qsort(int* start, int* end) {
  if (begin == end) return;
  int* mid = partition(start, end);
  swap(end, mid);
  cilk_spawn qsort(begin, mid);
  qsort(mid, end);
  cilk_sync;
}
```



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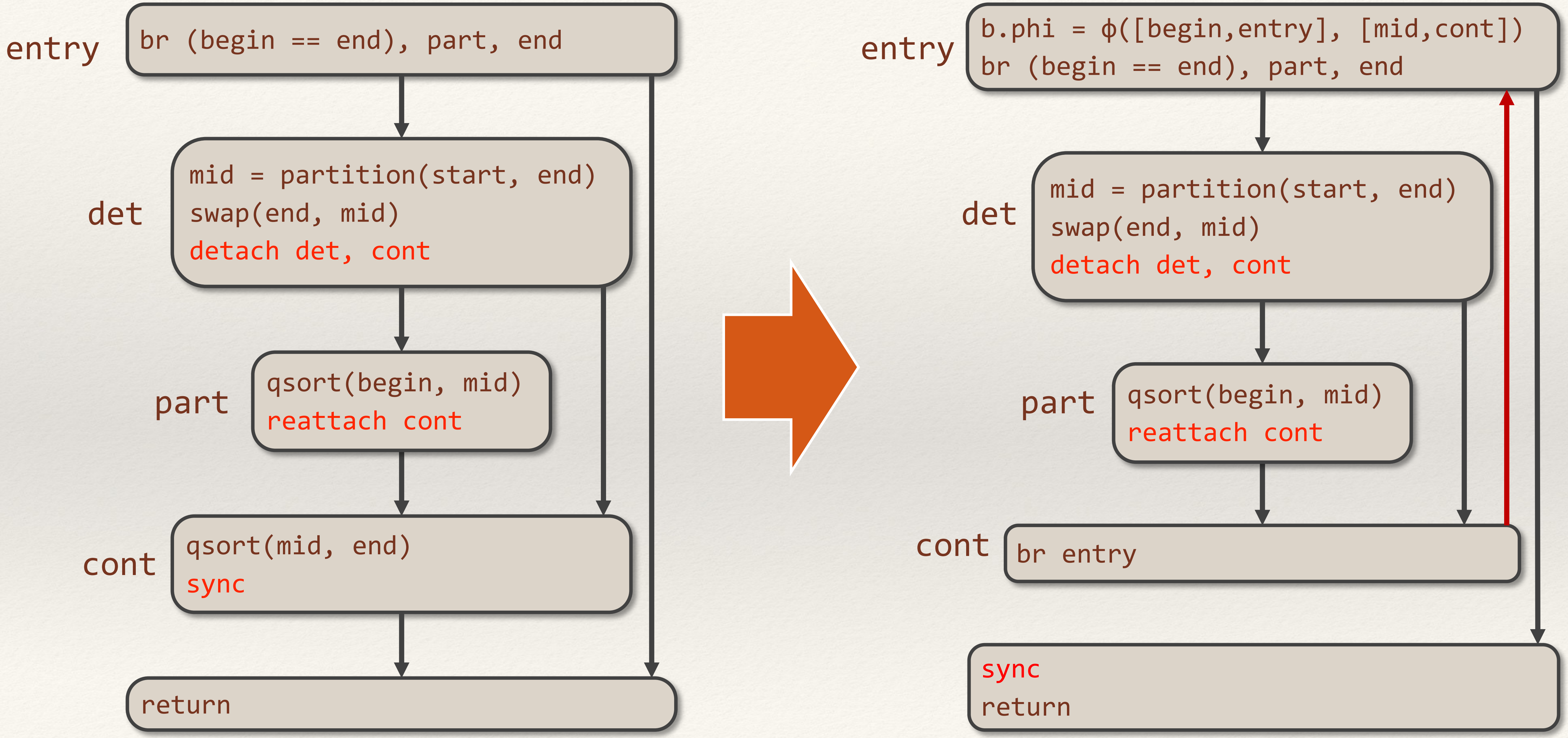

Lines of Code for LLVM-3.8

Compiler component	*LLVM-3.8*
Instructions	148,558
Memory	10,549
Optimizations	140,843
CodeGen	205,378
Cilk ABI Lowering	0
Total	3,359,893

Lines of Code for LLVM-3.8 versus Tapir

Compiler component	*LLVM-3.8*	*Tapir*
Instructions	148,558	900
Memory	10,549	588
Optimizations	140,843	306
CodeGen	205,378	145
Cilk ABI Lowering	0	3,184
Total	3,359,893	5,123

Lines of Code for LLVM-3.8 versus Tapir

Compiler component	*LLVM-3.8*	*Tapir*
Instructions	148,558	900
Memory	10,549	588
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1,939

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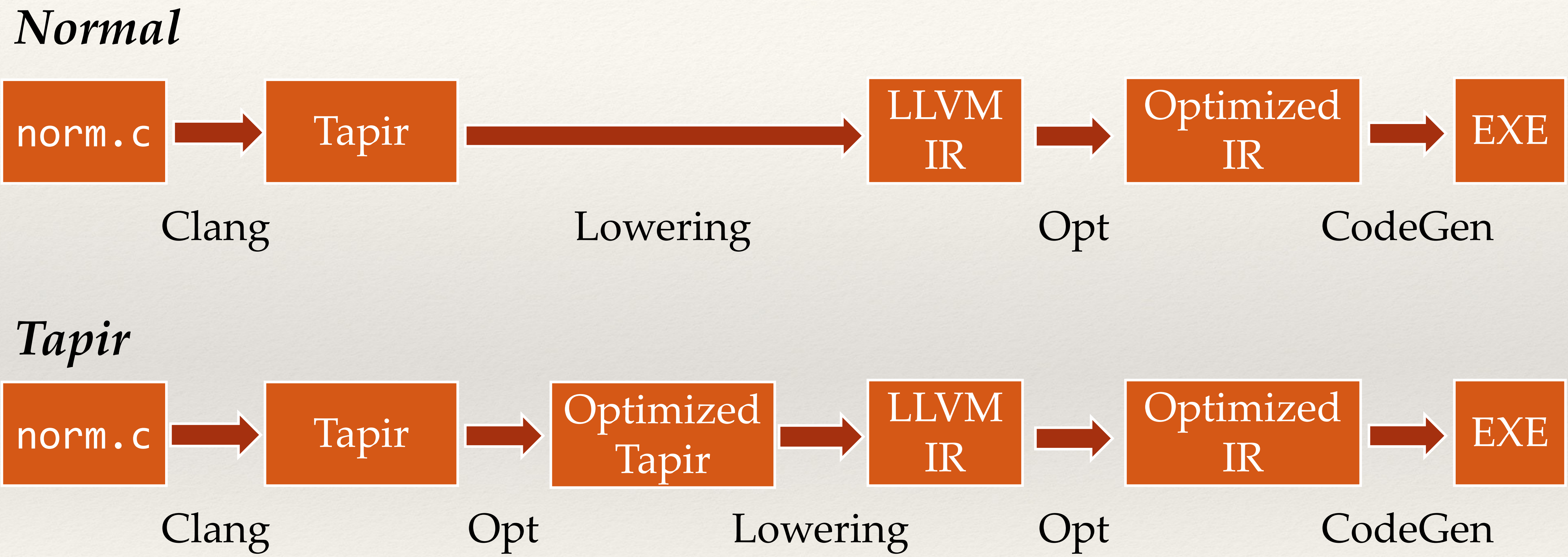
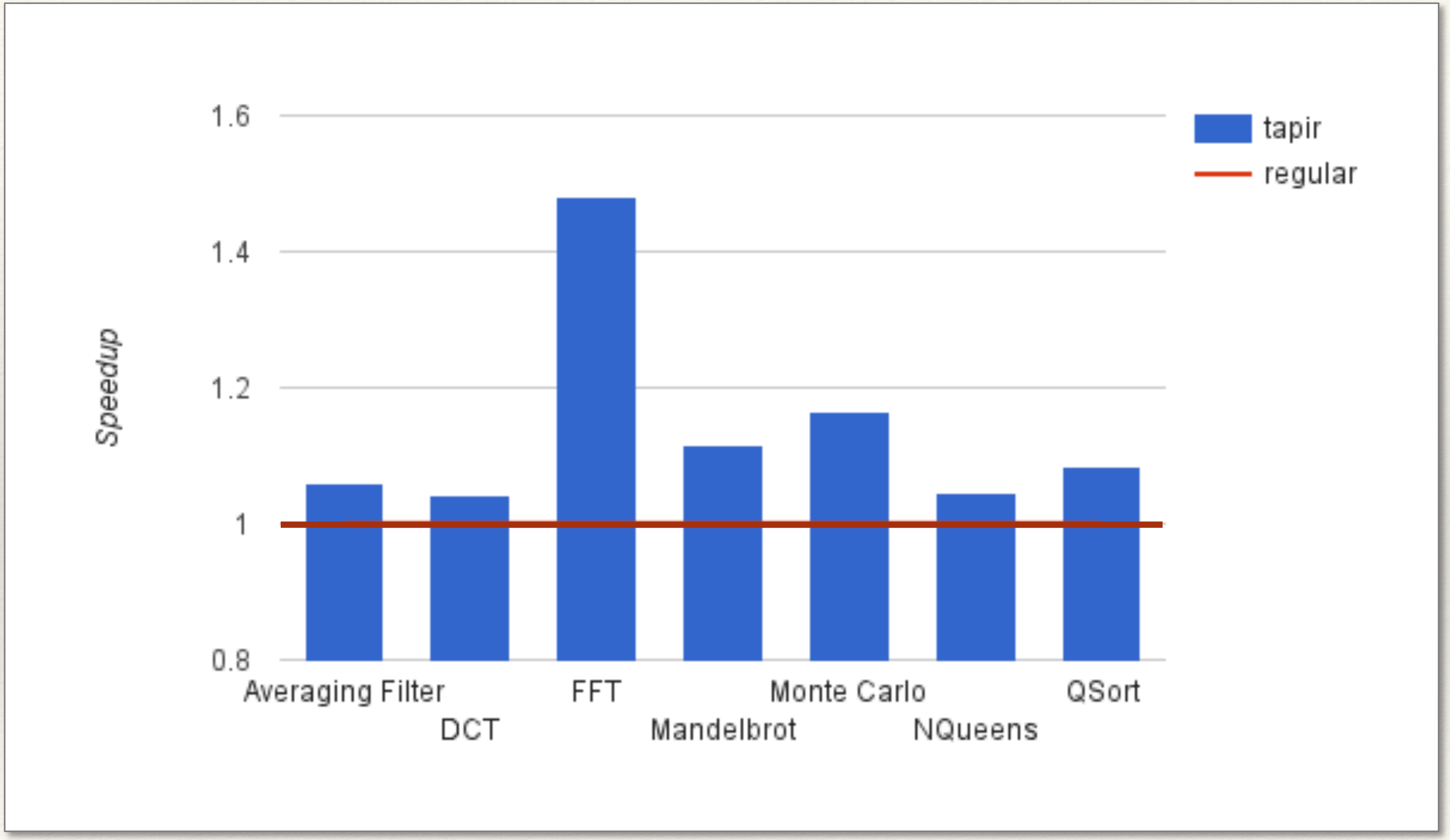
Tapir/LLVM Pipeline

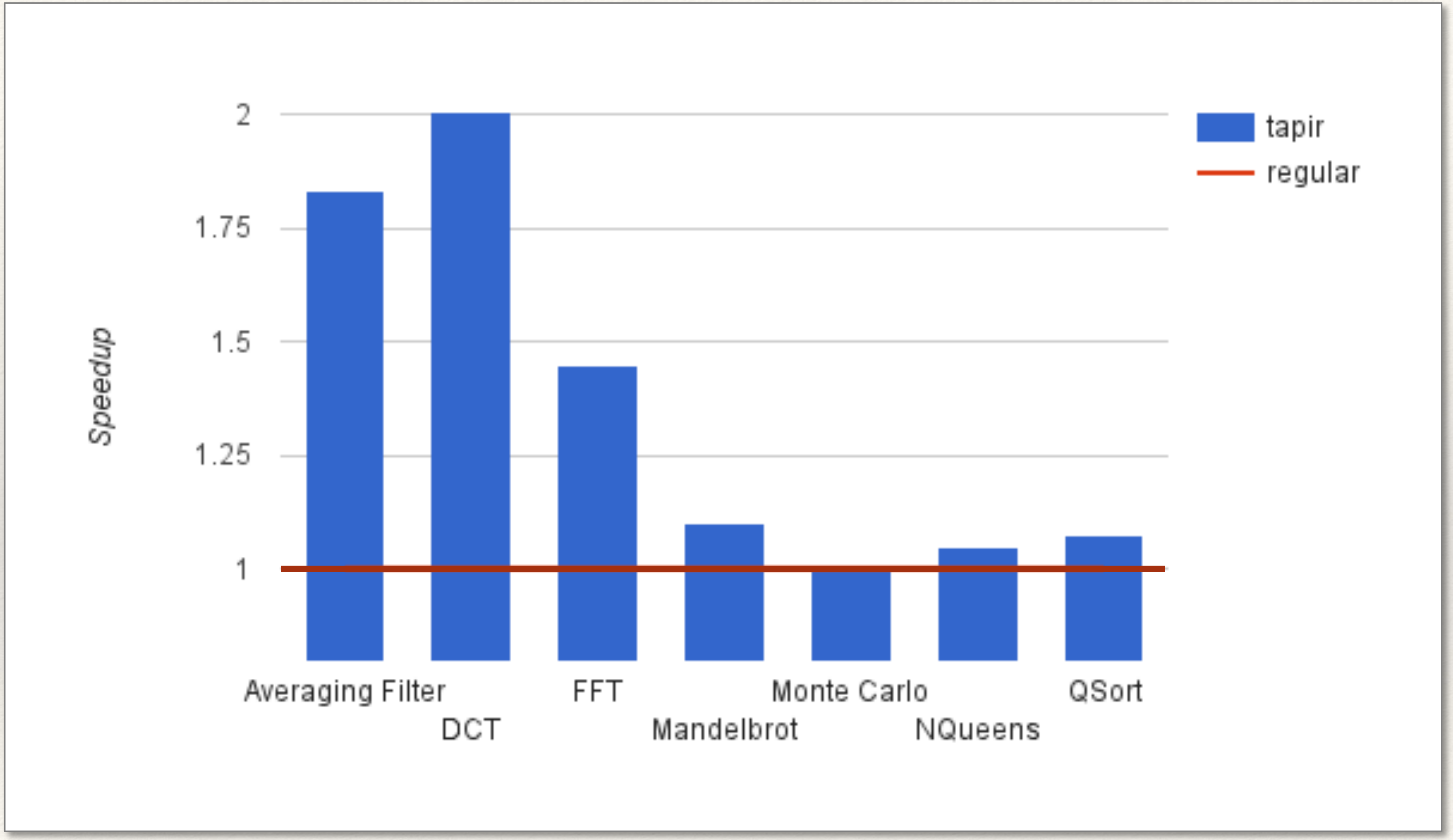


Tapir Speedups — 1 Worker (higher is better)



Cilk and Intel Sample Benchmarks
Min of 5 runs on AWS c4.8xlarge

Tapir Speedups — 8 Workers (higher is better)



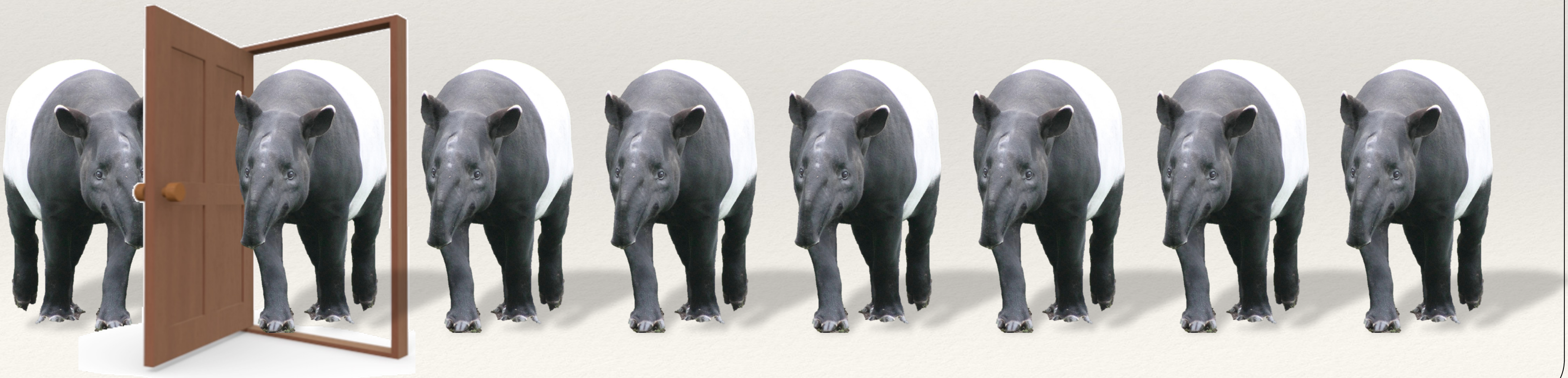
Cilk and Intel Sample Benchmarks
Min of 5 runs on AWS c4.8xlarge

Outline

- LLVM Overview
- Naive Parallel IR
- Tapir Syntax and Semantics
- Optimization Passes
- Evaluation
- Conclusion

Conclusion

- Tapir enables existing serial optimizations to operate on fork-join parallel code.
- Tapir requires minimal compiler modifications.
- Tapir opens the door for parallel optimizations.



Thank You!

Questions?