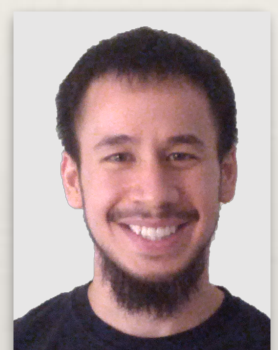
Tapir: Embedding Fork-Join Parallelism into LLVM's Intermediate Representation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6.S898 Lecture
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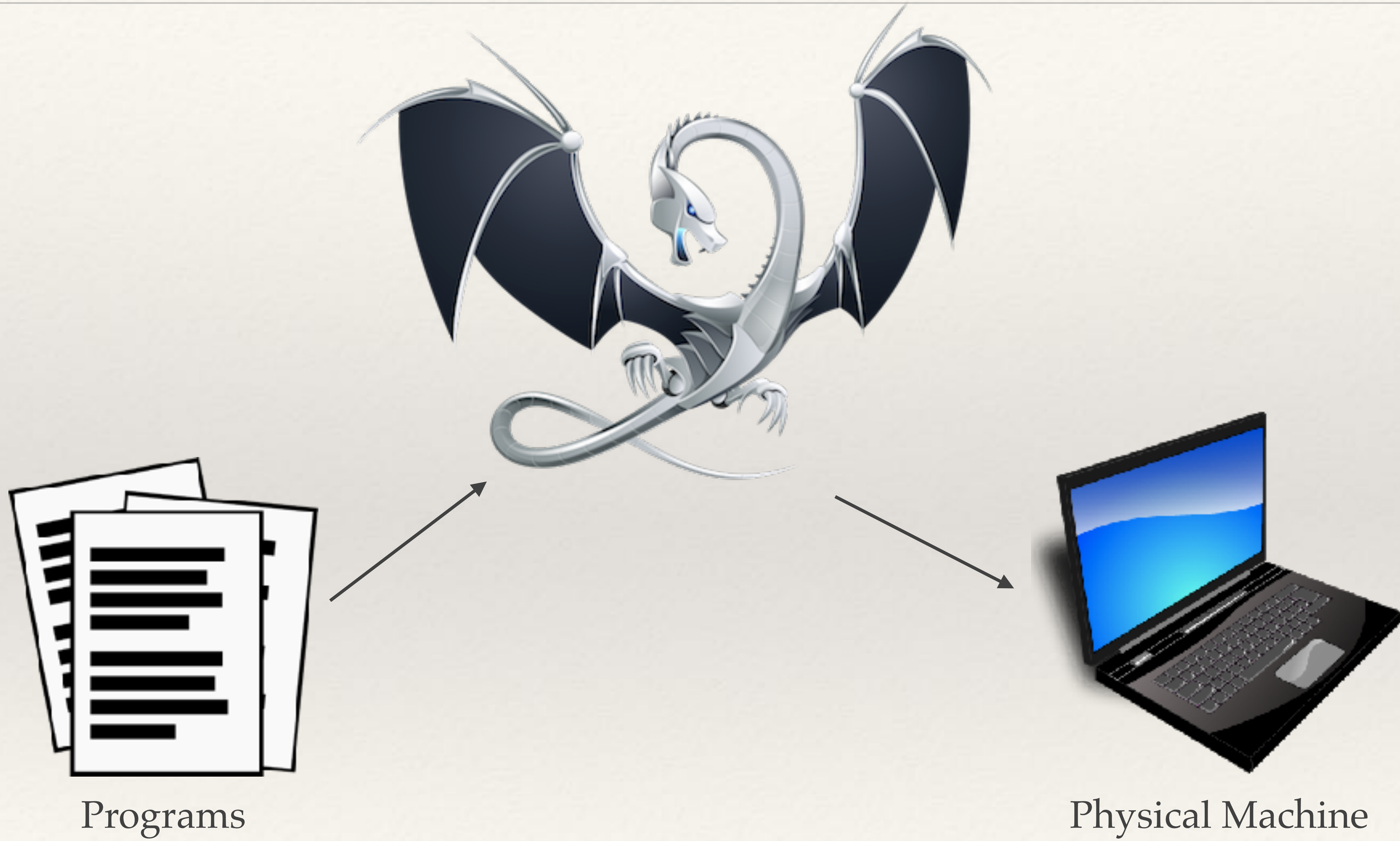
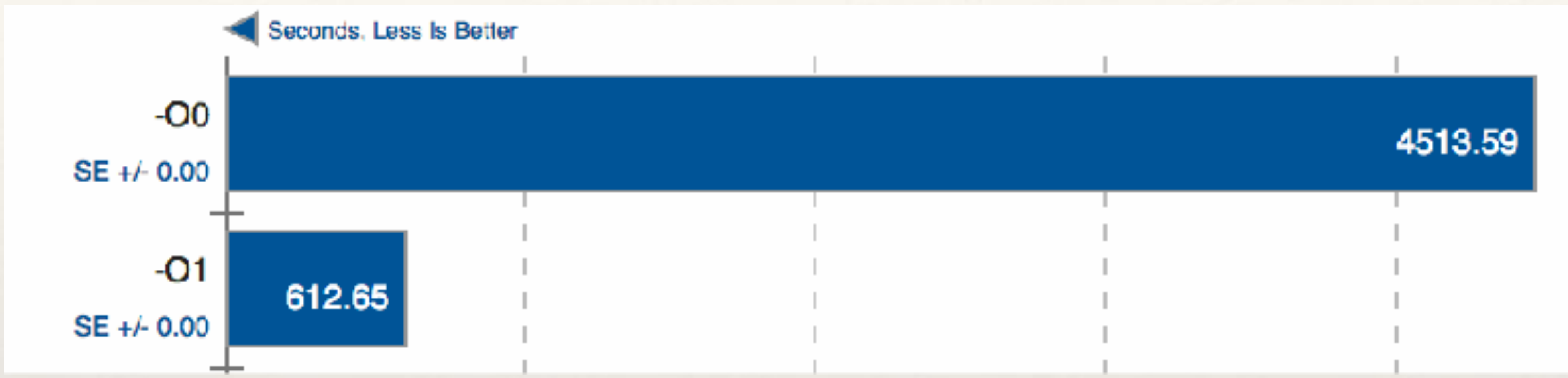
CSAIL
MIT COMPUTER SCIENCE AND ARTIFICIAL INTELLIGENCE LABORATORY

What is a compiler?

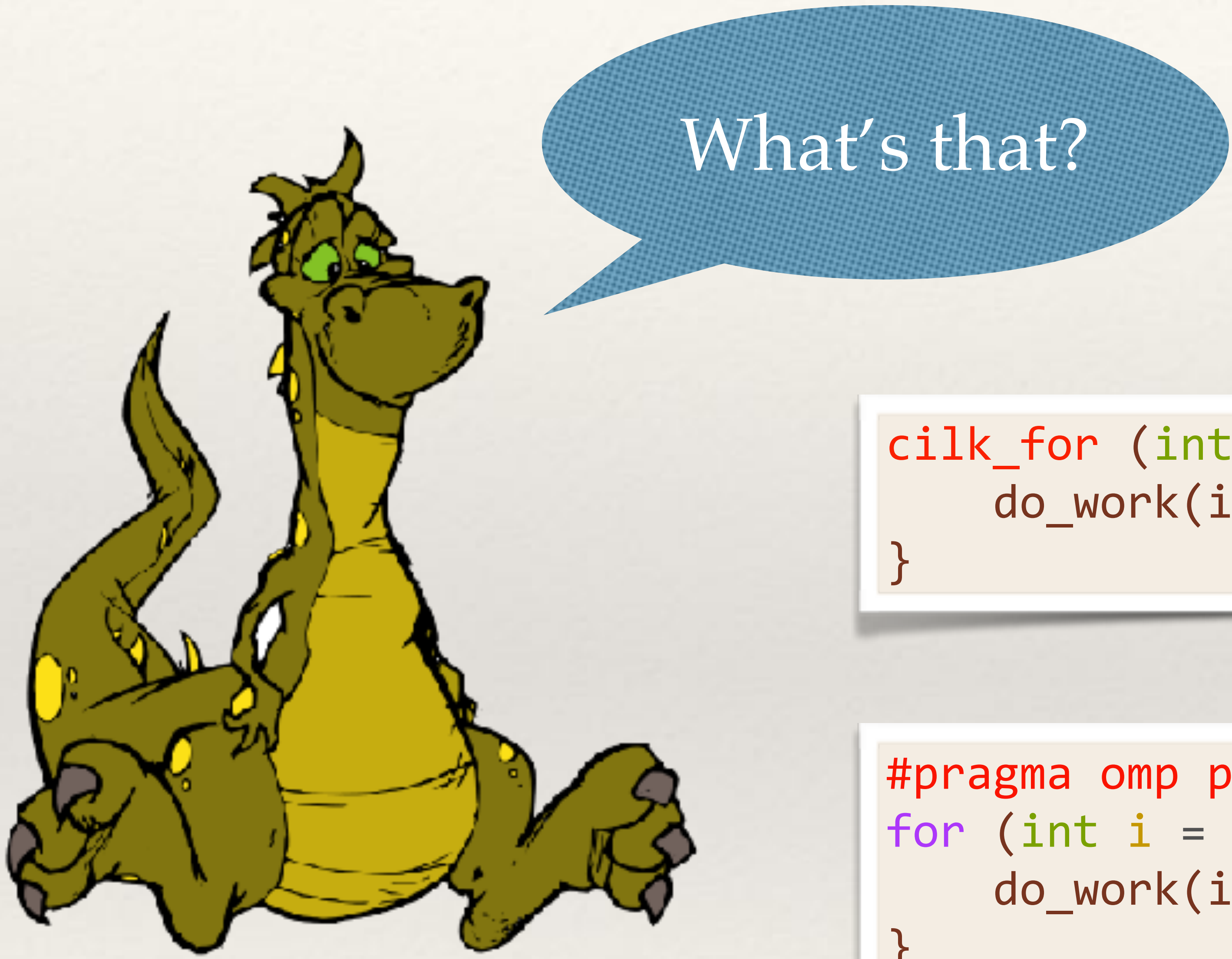


A Good Compiler Does Wonders



Minutes vs Hours!

Compilers Don't Understand Parallel Code




```
cilk_for (int i = 0; i < n; ++i) {
    do_work(i);
}
```

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    do_work(i);
}
```

Example: Normalizing a Vector

```
__attribute__((const)) 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);
}
```

Test: random vector, n = 64M.

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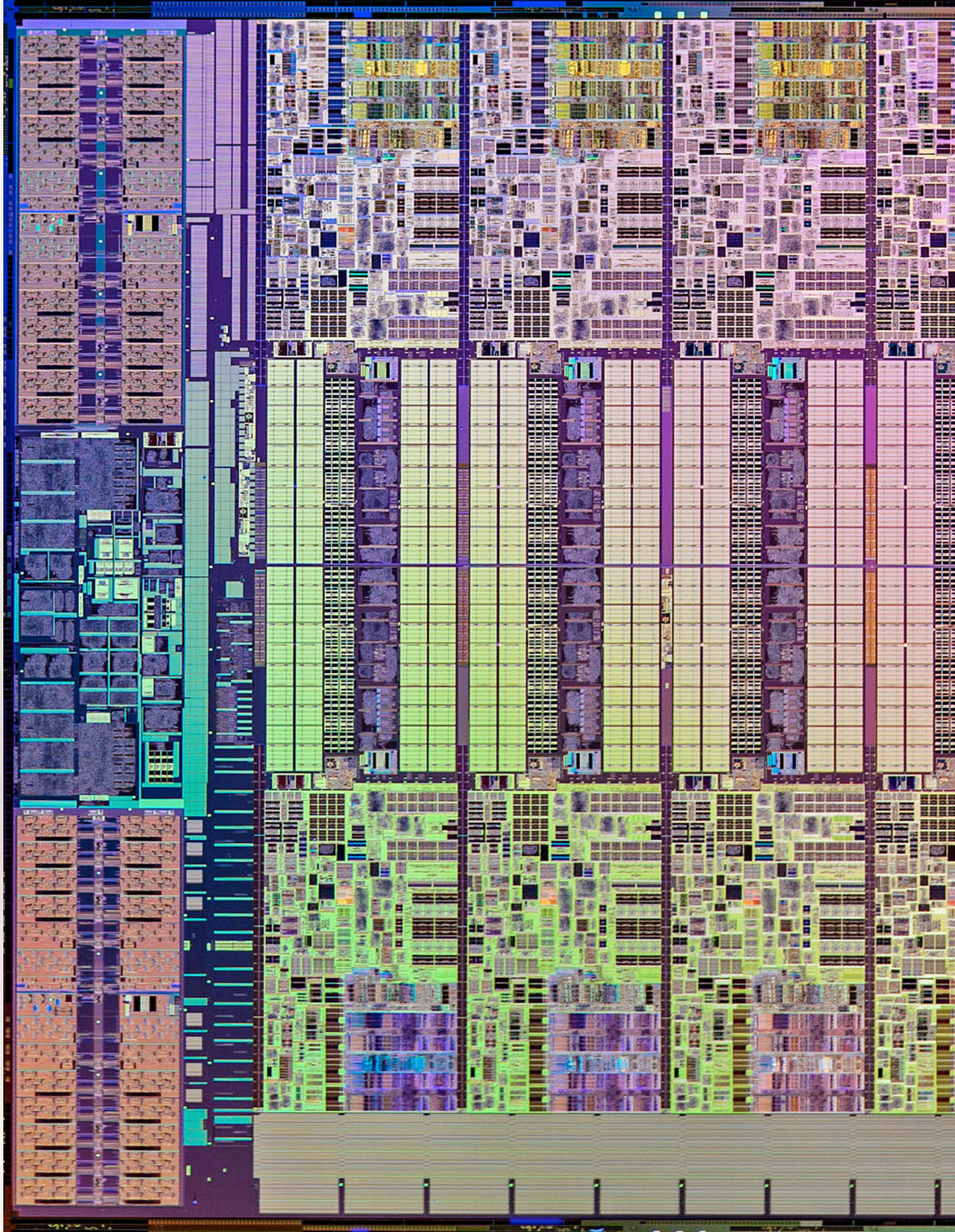
}
```

Test: random vector, n = 64M.

Running time: 0.312 s

Idea: Run in Parallel!



Example: Normalizing a Vector in Parallel

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

void normalize(double *restrict out, const double *restrict in, int n) {
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```

A parallel loop replaces the original serial loop.

Test: random vector, n = 64M.

Original serial running time: $T_S = 0.312$ s

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Test: random vector, n = 64M.

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18-core running time: 180.657s

Example: Normalizing a Vector in Parallel

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A parallel loop replaces the original serial loop.

Test: random vector, n = 64M.

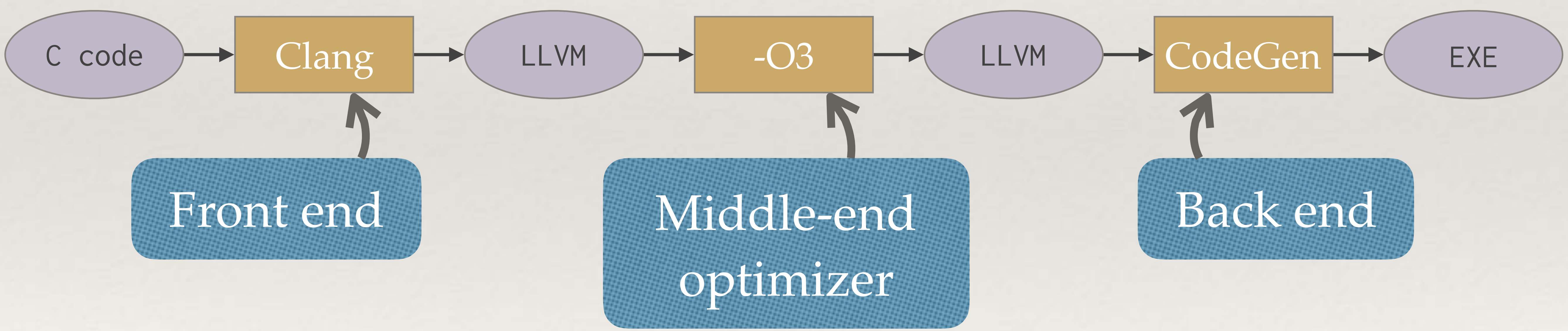
Original serial running time: $T_S = 0.312$ s

18-core running time: 180.657s

1-core running time: 2600.287s

What happend?

The LLVM Compilation Pipeline



Effect of Compiling Serial Code

```c
__attribute__((const)) 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);
}
```

-O3

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

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

Compiling Parallel Code Today

LLVM pipeline

Cilk Plus/LLVM pipeline

The front end translates all parallel language constructs.

Effect of Compiling Parallel Code

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

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);
}
```

PClang

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

void normalize(double *restrict out, const double *restrict in, int n) {
  struct args_t args = { out, in, n };
  __cilkrts_cilk_for(normalize_helper, args, 0, n);
}

void normalize_helper(struct args_t args, int i) {
  double *out = args.out;
  double *in = args.in;
  int n = args.n;
  out[i] = in[i] / norm(in, n);
}
```

Call into runtime to execute parallel loop.

Helper function encodes the loop body.

Existing optimizations cannot move call to norm out of the loop.

A More Complex Example

Cilk Fibonacci code

```
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;
}
```

PClang

```
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);
}
```

Optimization passes struggle to optimize around these opaque runtime calls.

Old Idea: A Parallel IR

💡 Let's embed parallelism directly into the compiler's intermediate representation (IR)!

LLVM pipeline

Cilk Plus/LLVM pipeline

A better Cilk compilation pipeline

New IR that encodes parallelism for optimization.

Previous Attempts at Parallel IR's

- Parallel precedence graphs [SW91, SHW93]
- Parallel flow graphs [SG91, GS93]
- Concurrent SSA [LMP97, NUS98]
- Parallel program graphs [SS94, S98]
- HPIR [ZS11, BZS13]
- SPIRE [KJAI12]
- INSPIRE [JPTKF13]
- LLVM's parallel loop metadata
- "[LLVMdev] [RFC] Parallelization metadata and intrinsics in LLVM (for OpenMP, etc.)" http://lists.llvm.org/pipermail/llvm-dev/2012-August/052477.html
- "[LLVMdev] [RFC] Progress towards OpenMP support" http://lists.llvm.org/pipermail/llvm-dev/2012-September/053326.html
- LLVM Parallel Intermediate Representation: Design and Evaluation Using OpenSHMEM Communications [KJIAC15]
- LLVM Framework and IR Extensions for Parallelization, SIMD Vectorization and Offloading [TSSGMGZ16]

Parallel IR: A Bad Idea?

From "[LLVMdev] LLVM Parallel IR," 2015:

- "[I]ntroducing [parallelism] 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**."
- "[It] is not an easy problem."
- "[D]efining a parallel IR (with first class parallelism) is a research topic…"

Other communications, 2016–2017:

- "There are **a lot of information needs** to be represented in IR for [back end] transformations for OpenMP." [Private communication]
- "If you support all [parallel programming features] in the IR, a *lot* [of LOC]… would probably have to be modified in LLVM." [[RFC] IR-level Region Annotations]

Tapir: Task-based Asymmetric Parallel IR

Cilk Plus/LLVM pipeline

Cilk → PClang → LLVM → -O3 → LLVM → CodeGen → EXE

Tapir/LLVM pipeline

Cilk → PClang → Tapir → -O3 → Tapir → CodeGen → EXE

Tapir adds **three instructions** to LLVM IR that encode **fork-join parallelism**.

With **few changes**, LLVM's **existing optimizations and analyses** work on **parallel code**.

Normalizing a Vector in Parallel with Tapir

Cilk code for `normalize()`

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

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);
}
```

Test: random vector, n = 64M. Machine: Amazon AWS c4.8xlarge, 18 cores.

Running time of original serial code: $T_S = 0.312$ s

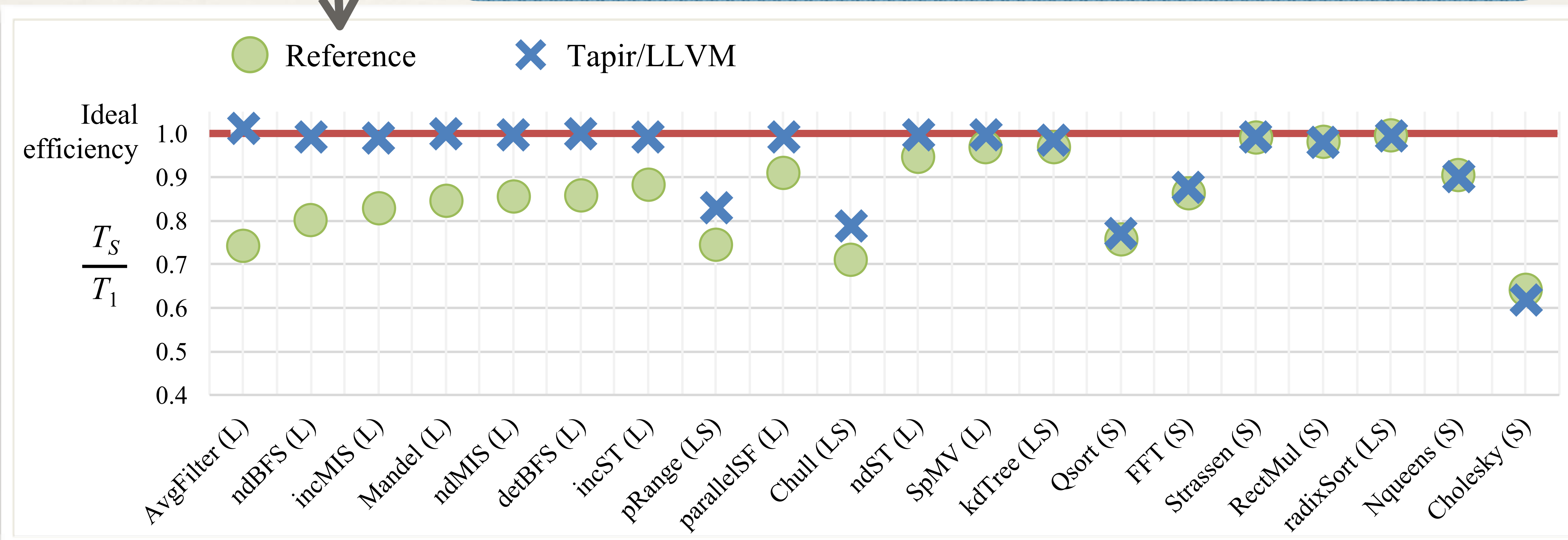
Compiled with Tapir/LLVM, running time on 1 core: $T_1 = 0.321$ s

Compiled with Tapir/LLVM, running time on 18 cores: $T_{18} = 0.081$ s

Great work efficiency:
$T_S / T_1 = 97\%$

Work-Efficiency Improvement

Same as Tapir/LLVM, but the front end handles parallel language constructs the traditional way.



Decreasing difference between Tapir/LLVM and Reference

Test machine: Amazon AWS c4.8xlarge, with 18 cores clocked at 2.9 GHz, 60 GiB DRAM

Implementing Tapir/LLVM

Compiler component	*LLVM 4.0svn (lines)*	*Tapir/LLVM (lines)*	
Instructions	105,995	943	
Memory behavior	21,788	445	1,768
Optimizations	152,229	380	
Parallelism lowering	0	3,782	
Other	3,803,831	460	
Total	4,083,843	6,010	

Compiler Analyses and Optimizations

What did we do to **adapt existing analyses and optimizations**?

- Dominator analysis: no change
- Common-subexpression elimination: no change
- Loop-invariant-code motion: 25-line change
- Tail-recursion elimination: 68-line change

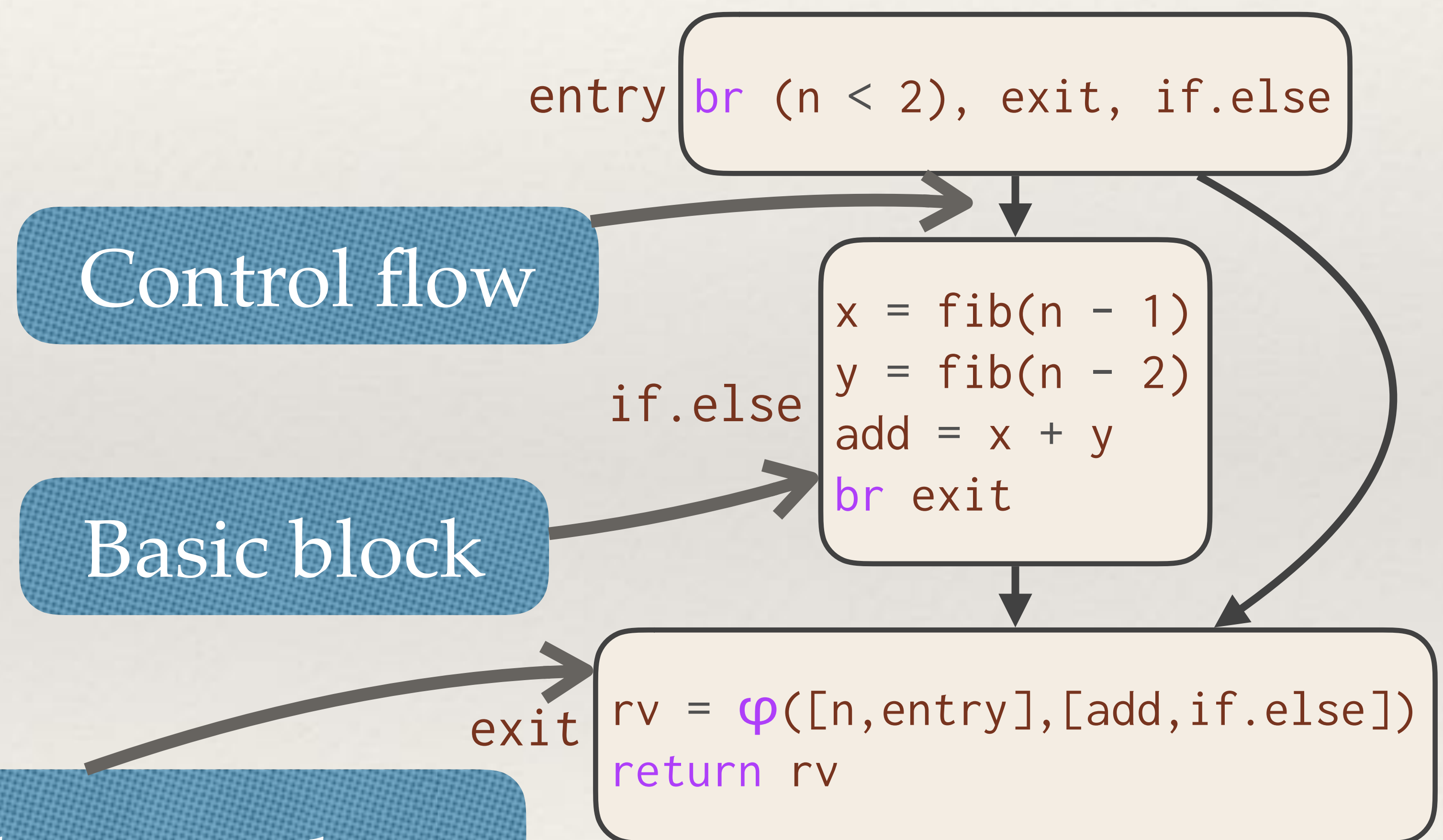
Tapir also enables **new parallel optimizations**, such as **unnecessary-synchronization elimination** and **puny-task elimination**, which were implemented in 52 lines total.

Why does it work?

LLVM IR

LLVM represents each function as a **control-flow graph (CFG)**.

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

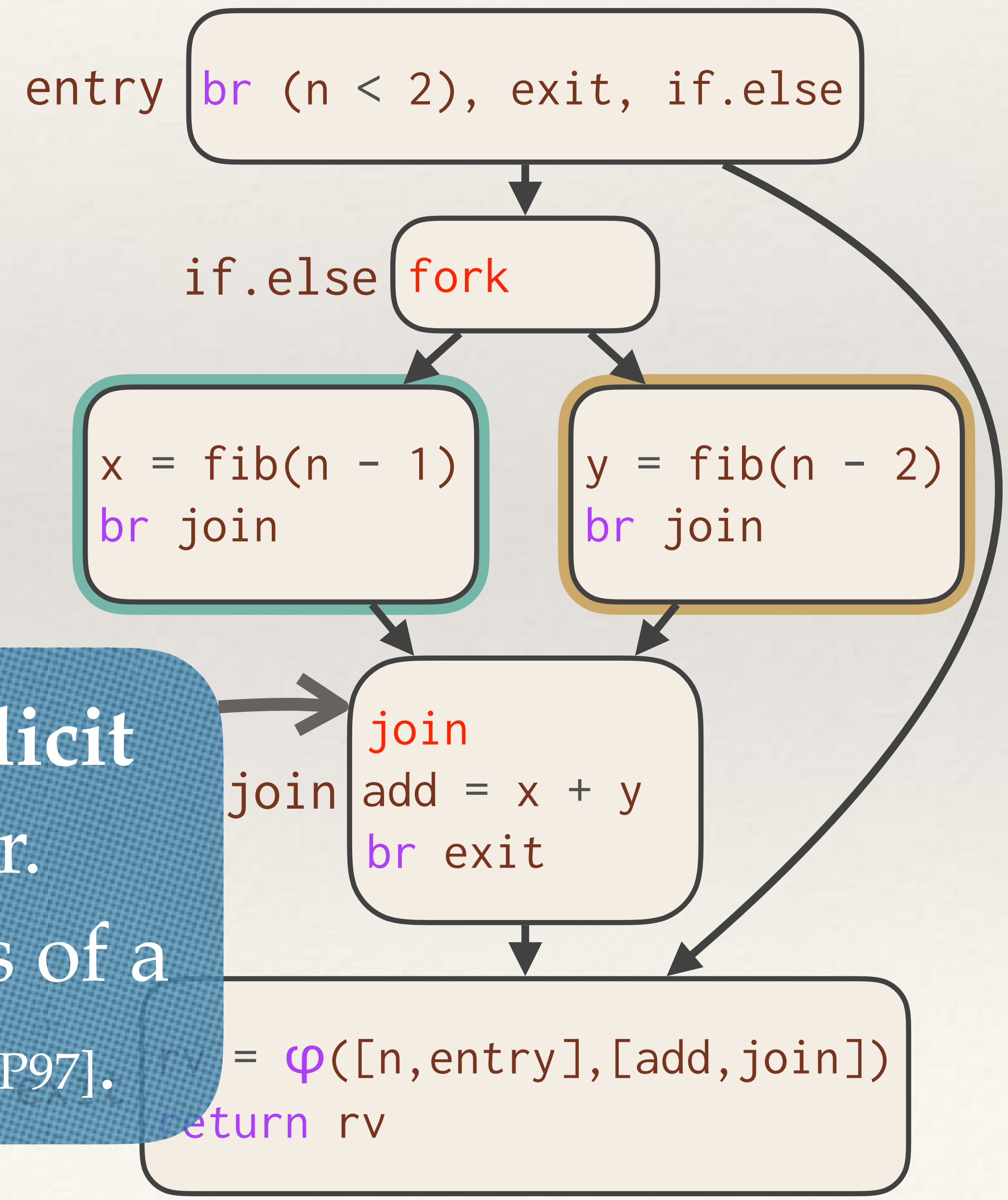


For serial code a basic block sees values from **just one predecessor** at runtime.

Example Previous Parallel IR

Previous parallel IR's based on CFG's model parallel tasks **symmetrically**.

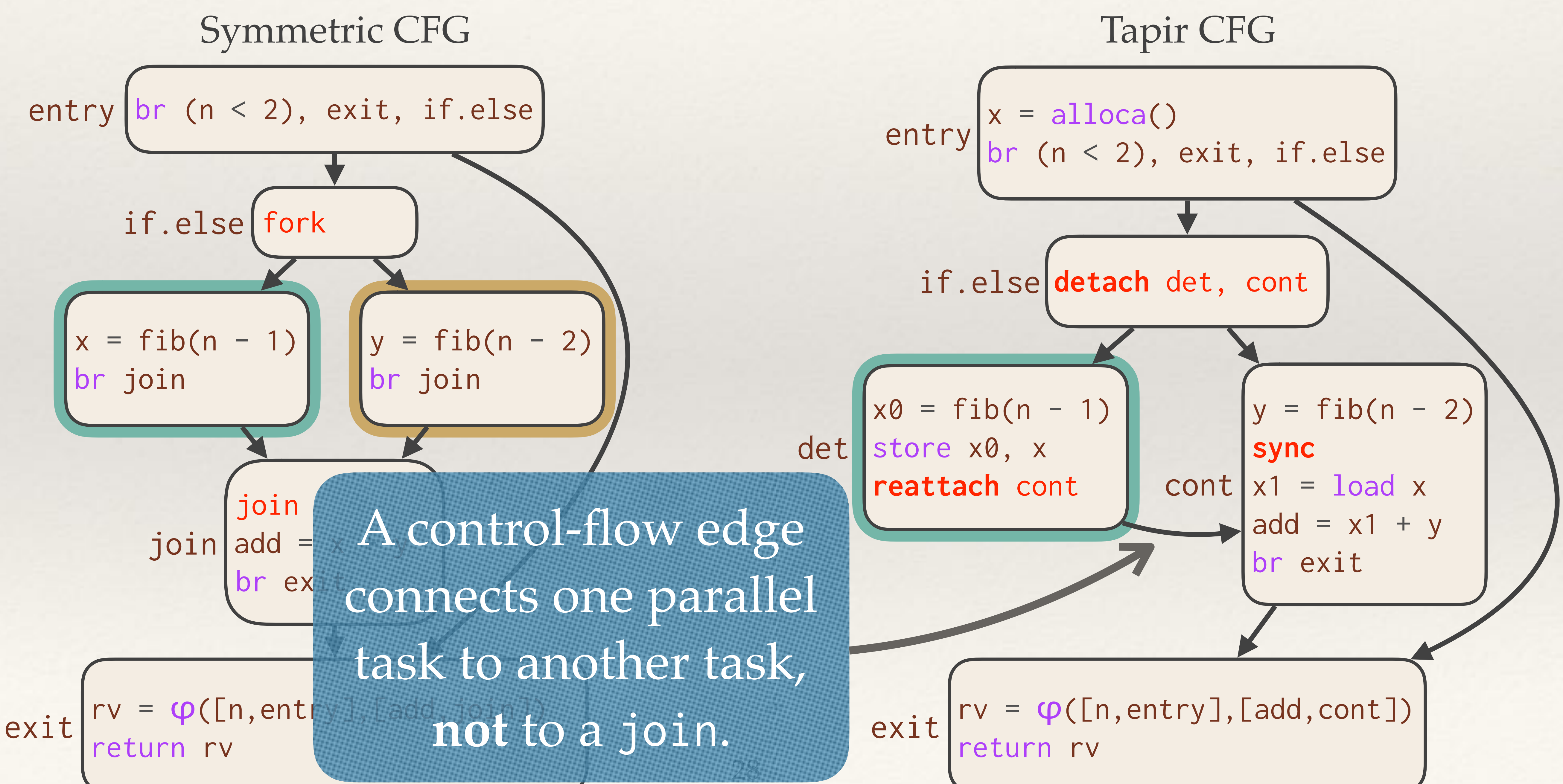
```
int fib(int n) {
  if (n < 2) return n;
  int x, y;
  x = cilk_spawn fib(n - 1);
  y = fib(n - 2);
  cilk_sync;
  return x + y;
}
```



Problem: The join block **breaks implicit assumptions** made by the compiler.
Example: Values from **all** predecessors of a join must be available at runtime [LMP97].

Tapir vs. Previous Approaches

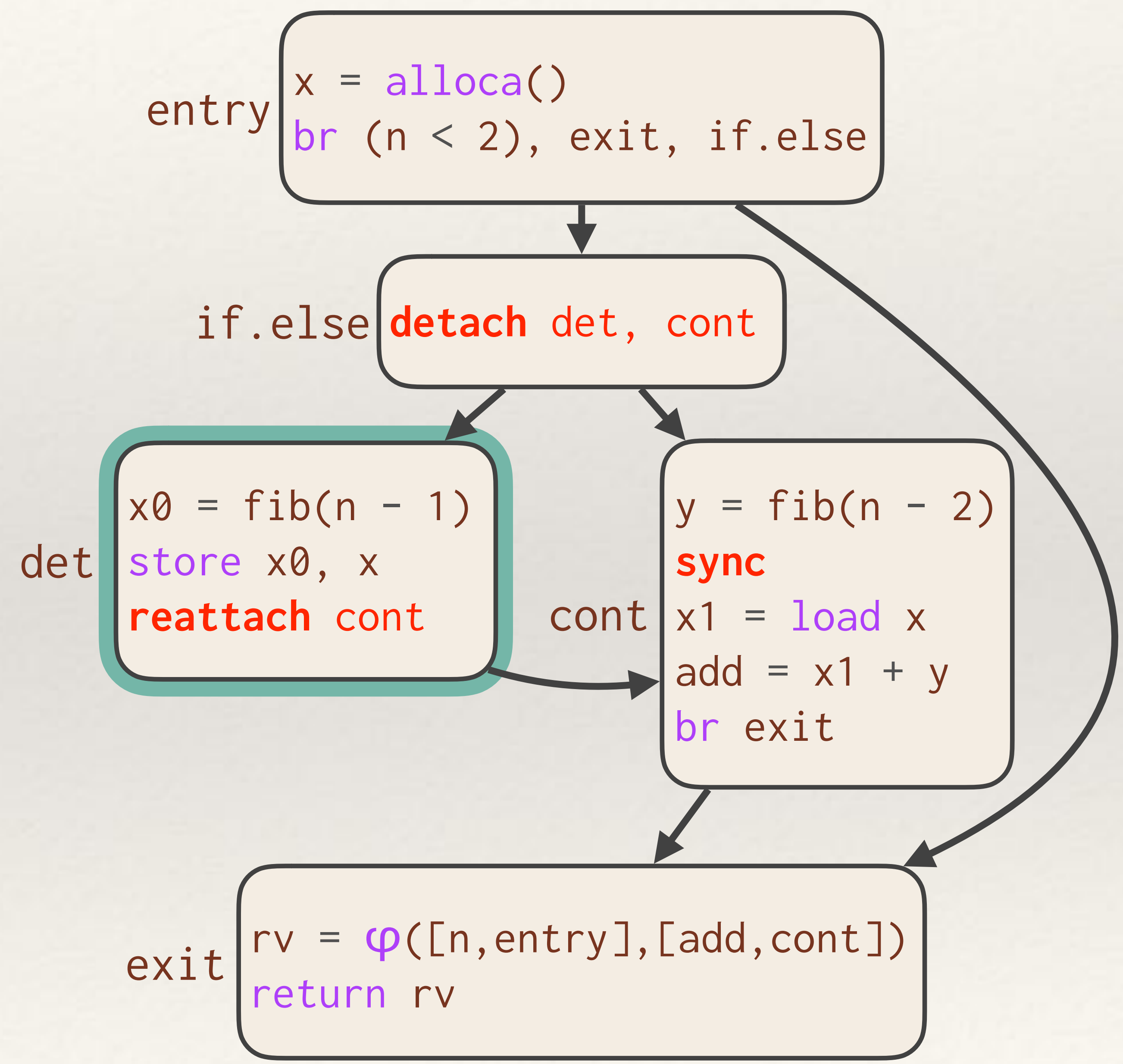
Tapir's instructions model parallel tasks **asymmetrically**.



Tapir Semantics

- Tapir introduces three new opcodes into LLVM's IR: detach, reattach, and sync
- The successors of a detach terminator are the detached block and continuation and may run in parallel
- Execution after a sync ensures that all detached CFG's in scope have completed execution

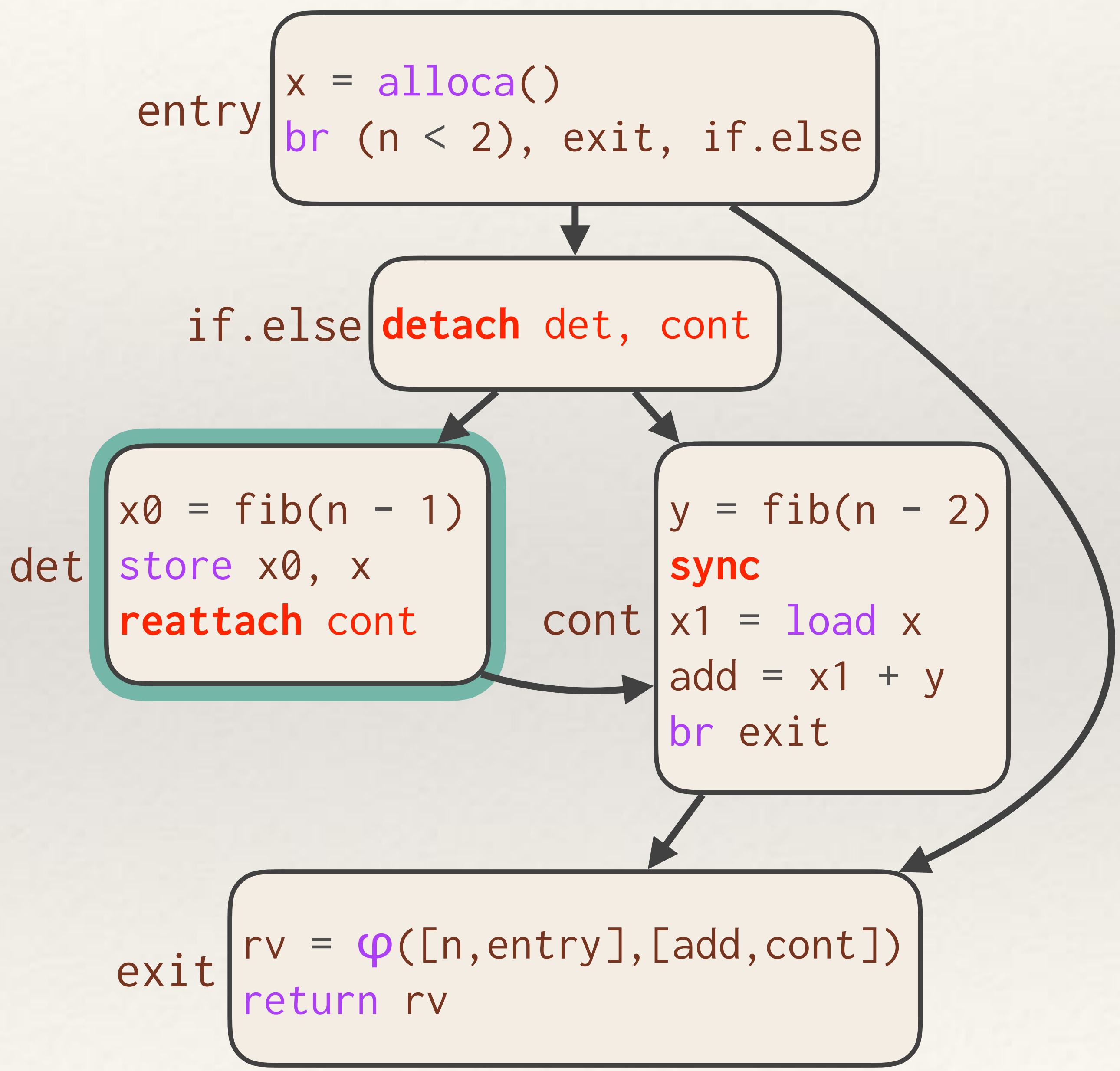
Tapir CFG



Tapir Semantics

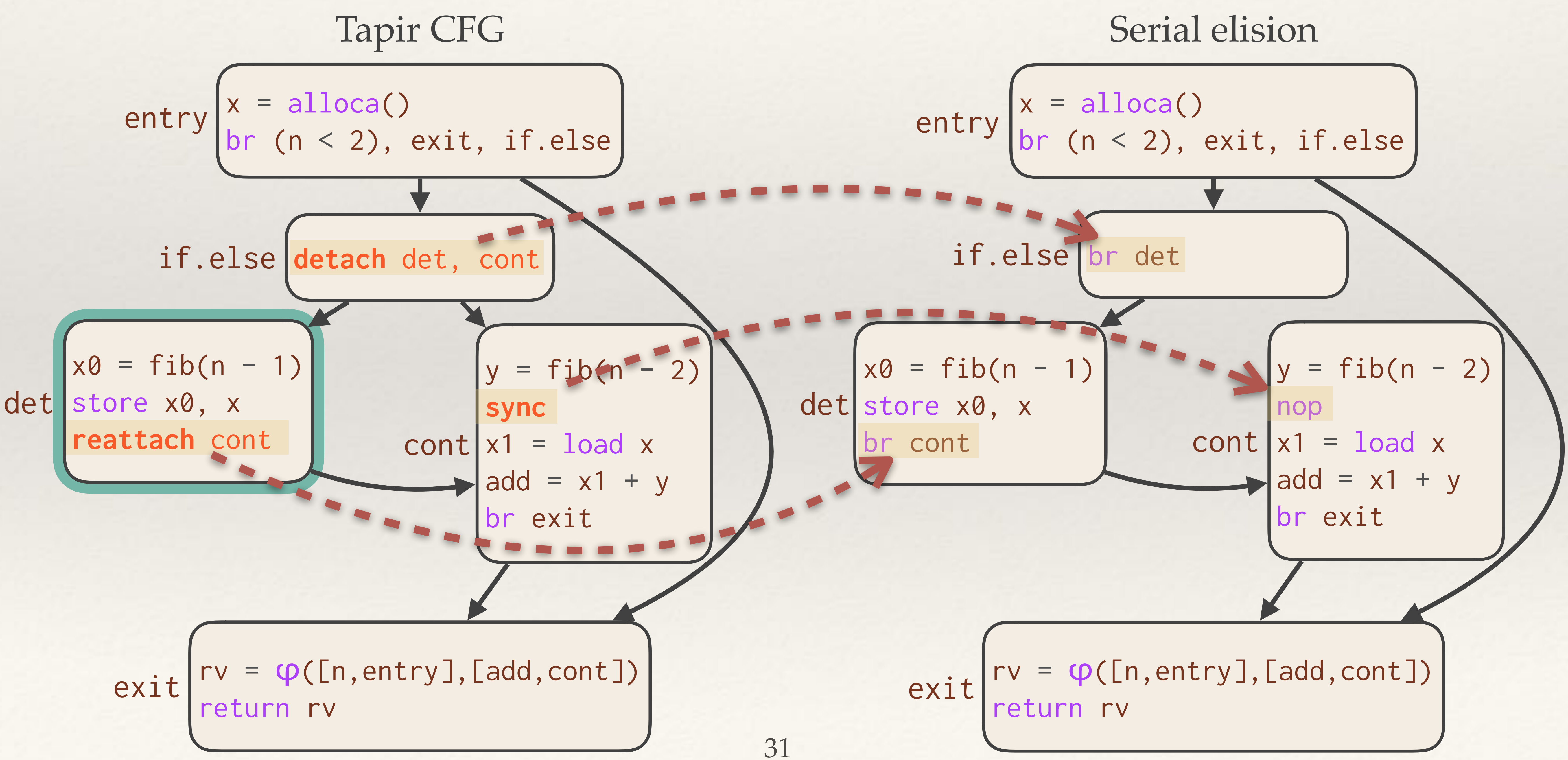
- When run serially, programs first execute the detached CFG and then the continuation
- Registers computed in the detached CFG are not available in the continuation
- Tapir simultaneously represents the serial and parallel semantics of the program

Tapir CFG



Serial Elision of a Tapir Program

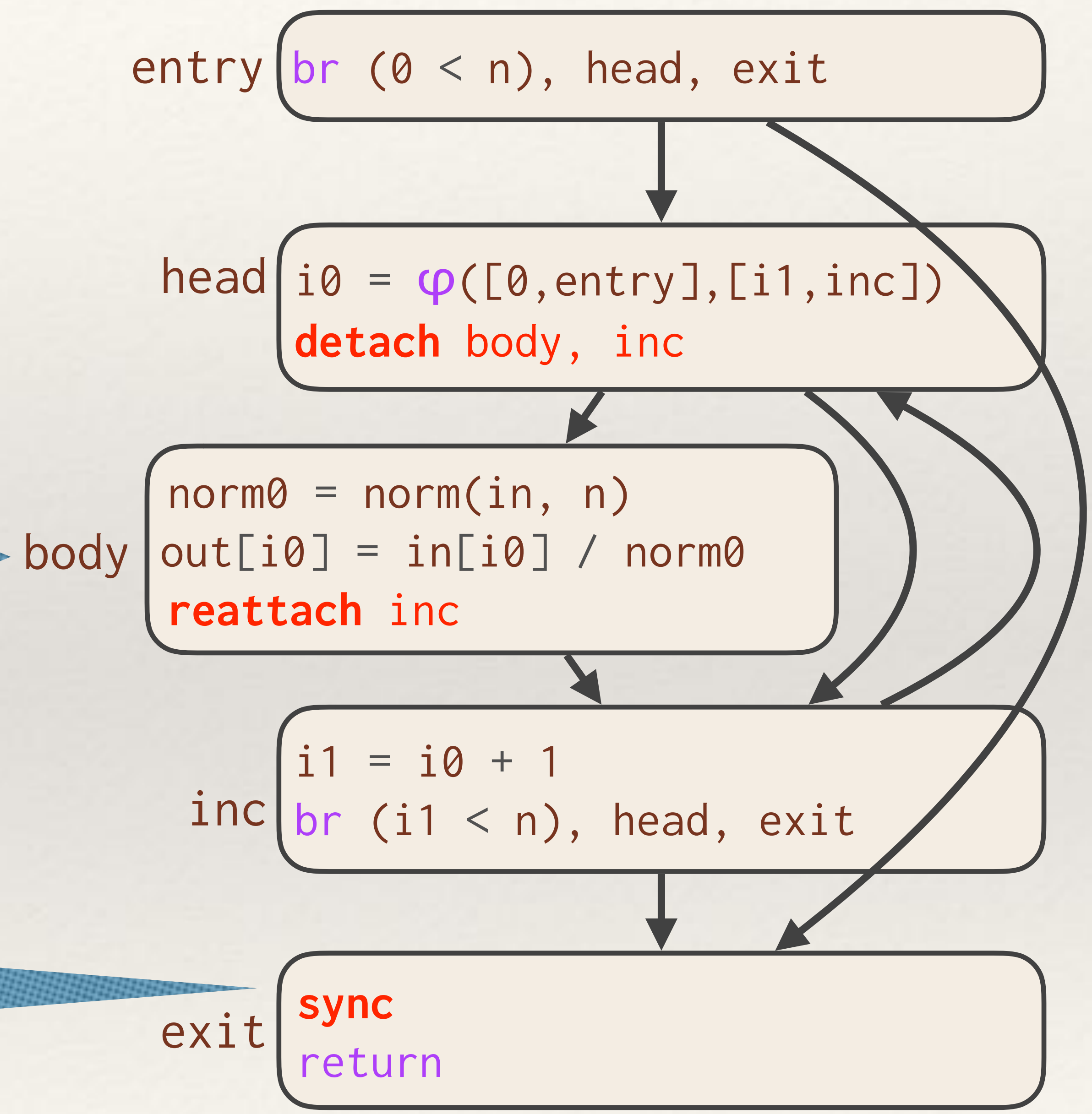
Tapir models the **serial elision** of the parallel program.



Parallel Loops in Tapir

```
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);
}
```

Parallel loop resembles a serial loop with a detached body.

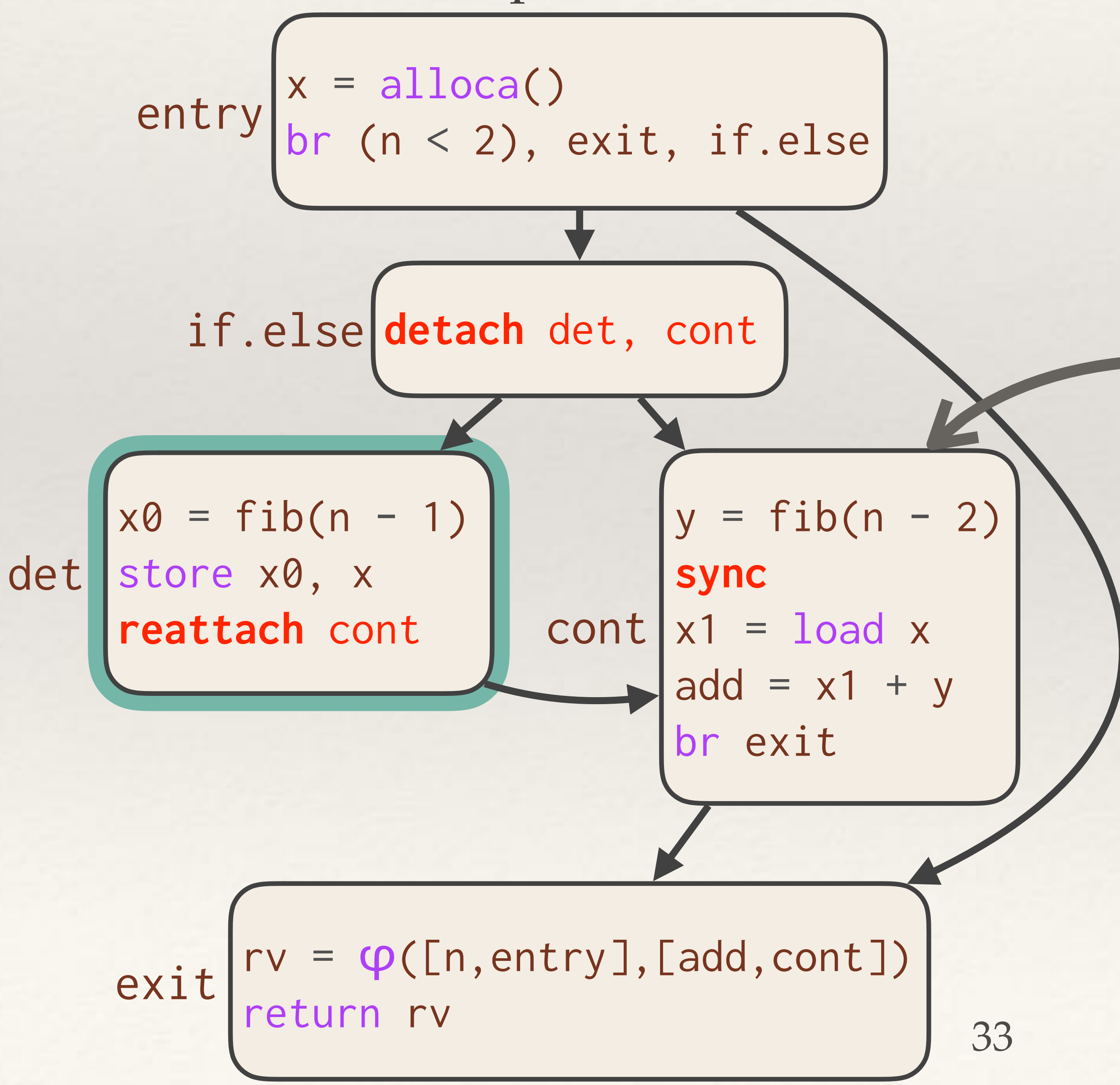


The sync waits on a dynamic set of detached sub-CFG's.

Reasoning About a Tapir CFG

Intuitively, much of the compiler can reason about a Tapir CFG as a **minor change** to that CFG's serial elision.

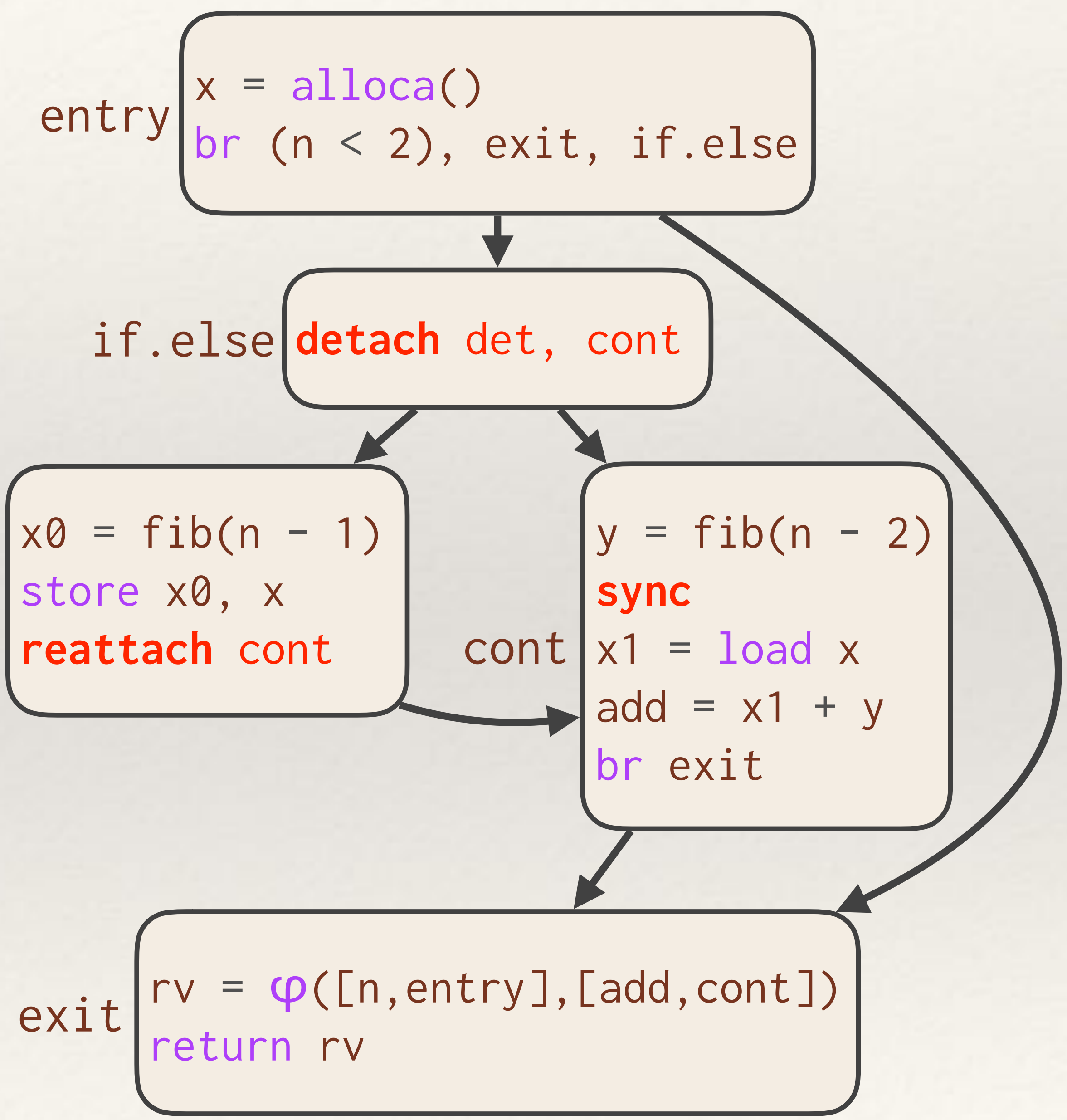
Tapir CFG



Many parts of the compiler can apply **standard implicit assumptions** of the CFG to this block.

Maintaining Correctness

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



Maintaining Correctness

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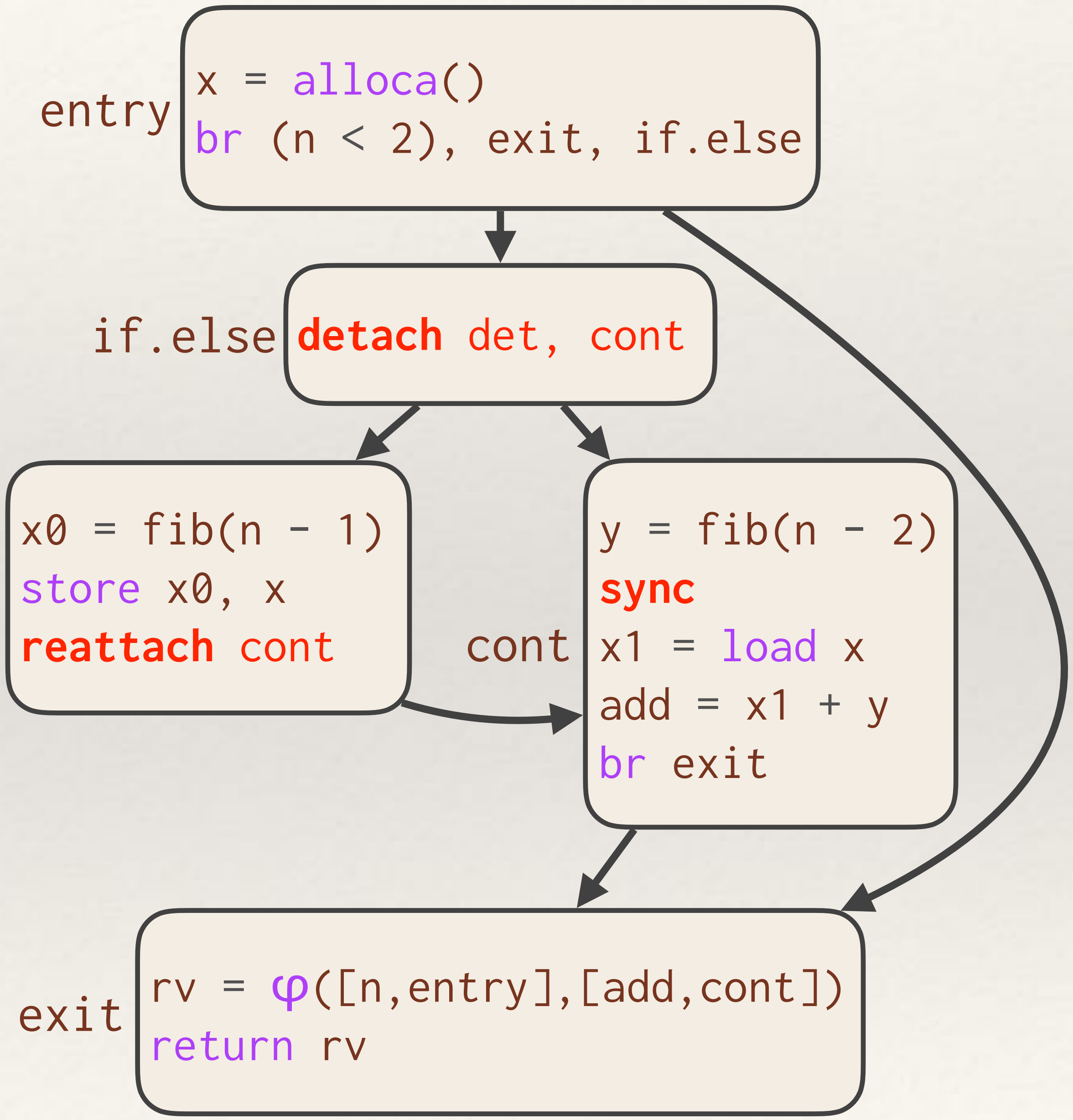
- It suffices to consider moving memory operations around each new instruction.



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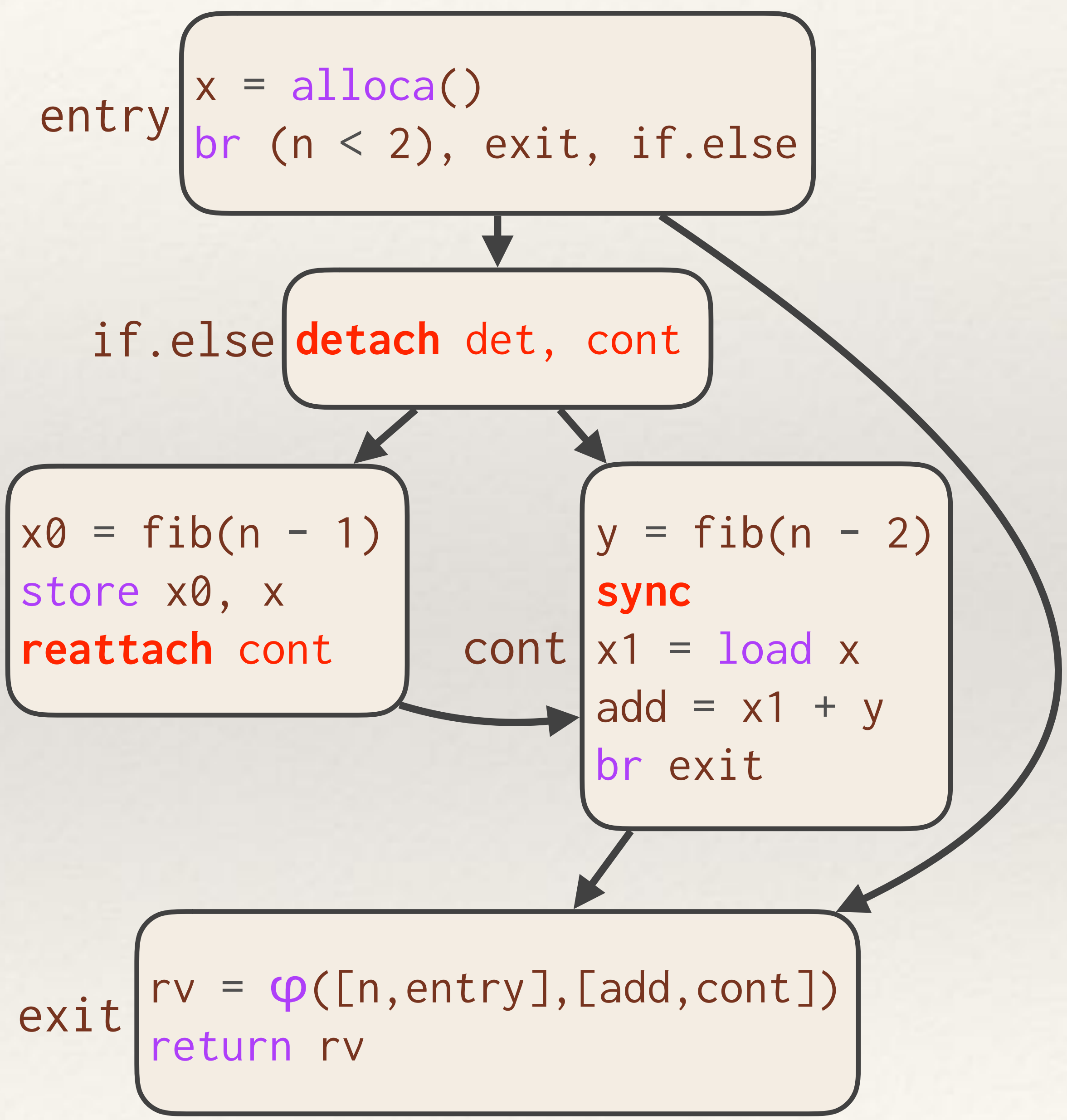
Problem: How does the compiler ensure that code motion does not introduce a determinacy race into otherwise race-free code?

- 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.



Maintaining Correctness

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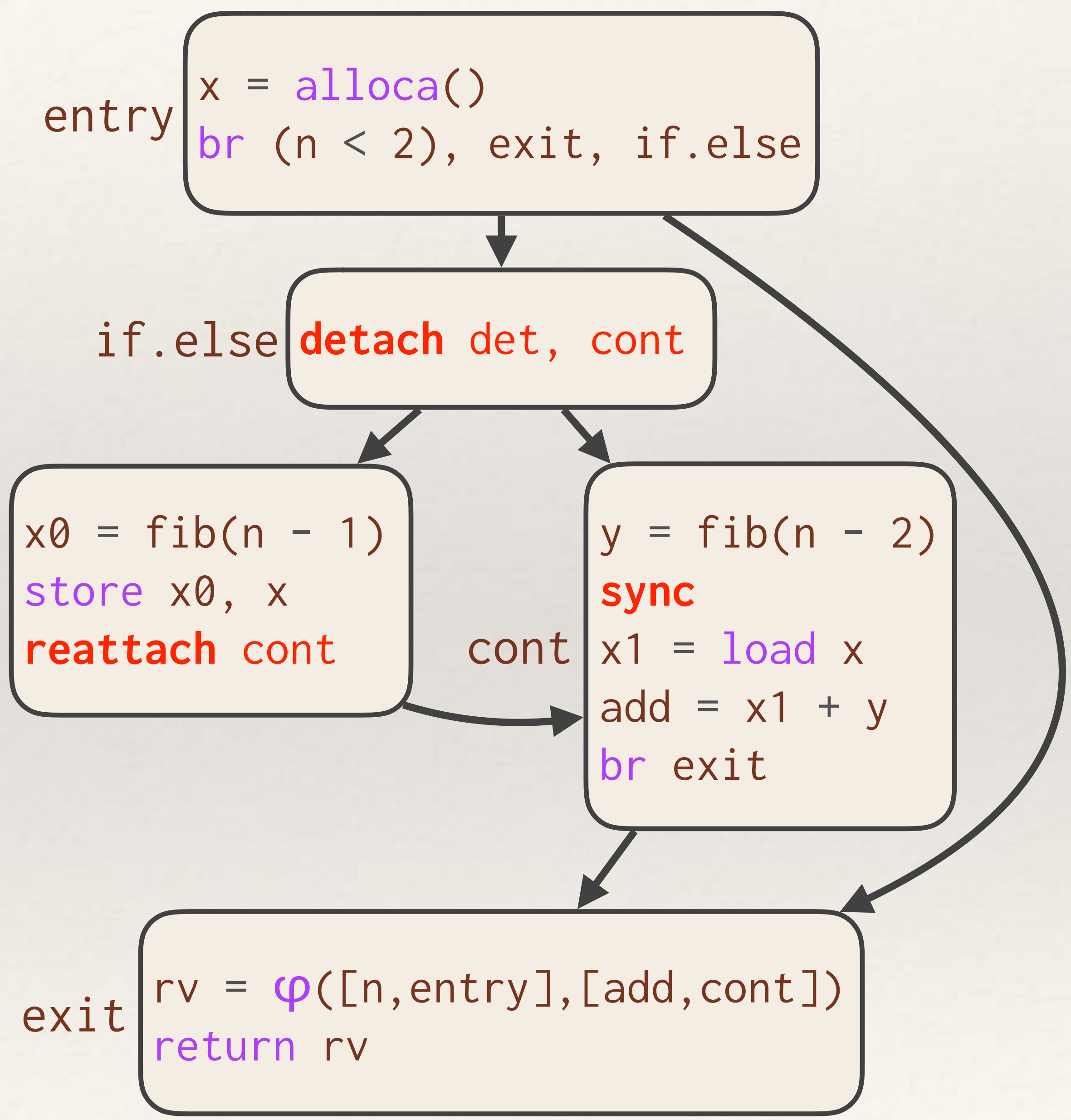
- It suffices to consider moving memory operations around each new instruction.
- Moving code above a `detach` or below a `sync` serializes it and is always valid.
- Other potential races are handled by giving `detach`, `reattach`, and `sync` appropriate attributes and by slight modifications to `mem2reg`.



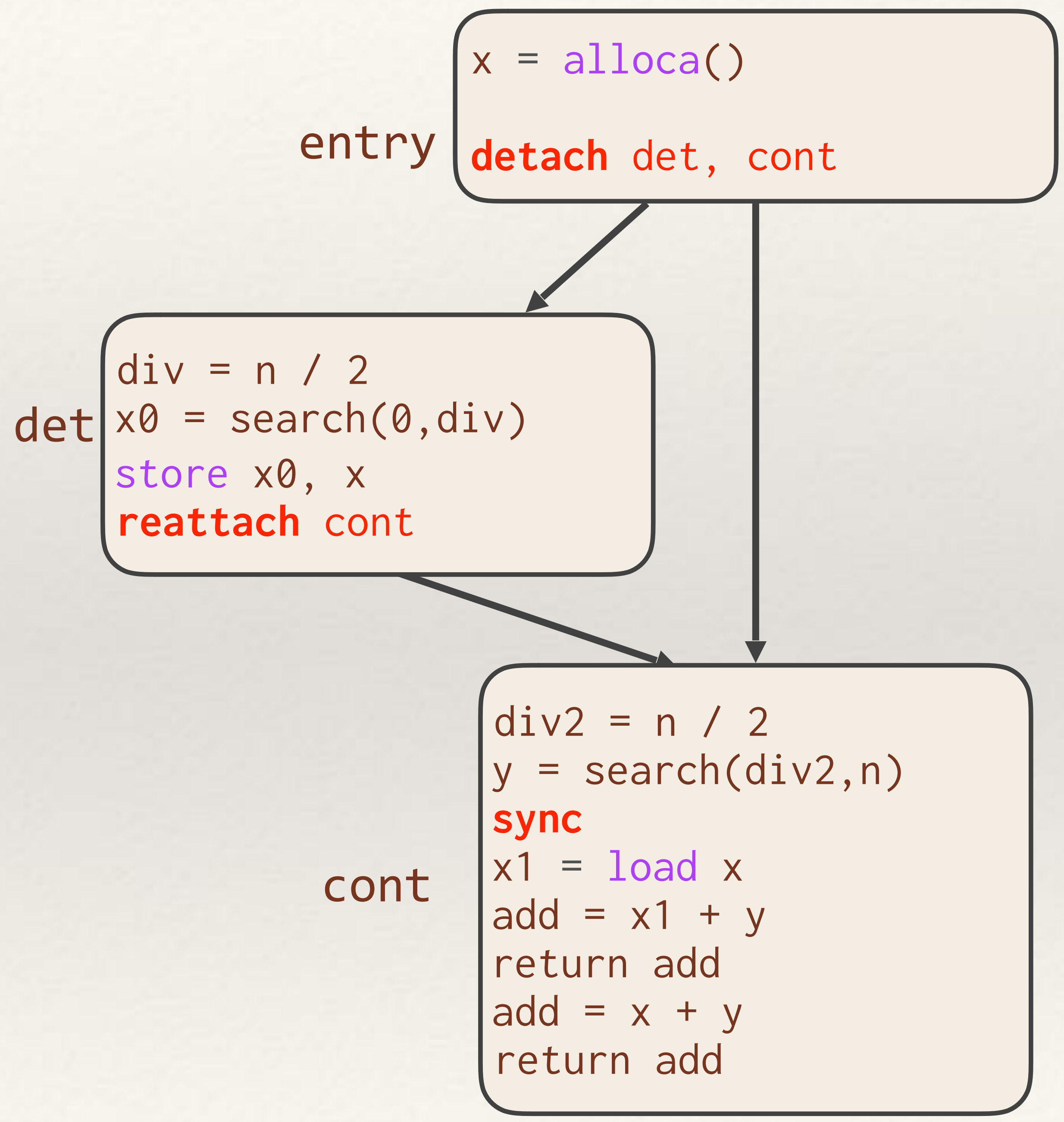
Valid serial passes cannot create race bugs.

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;
}
```



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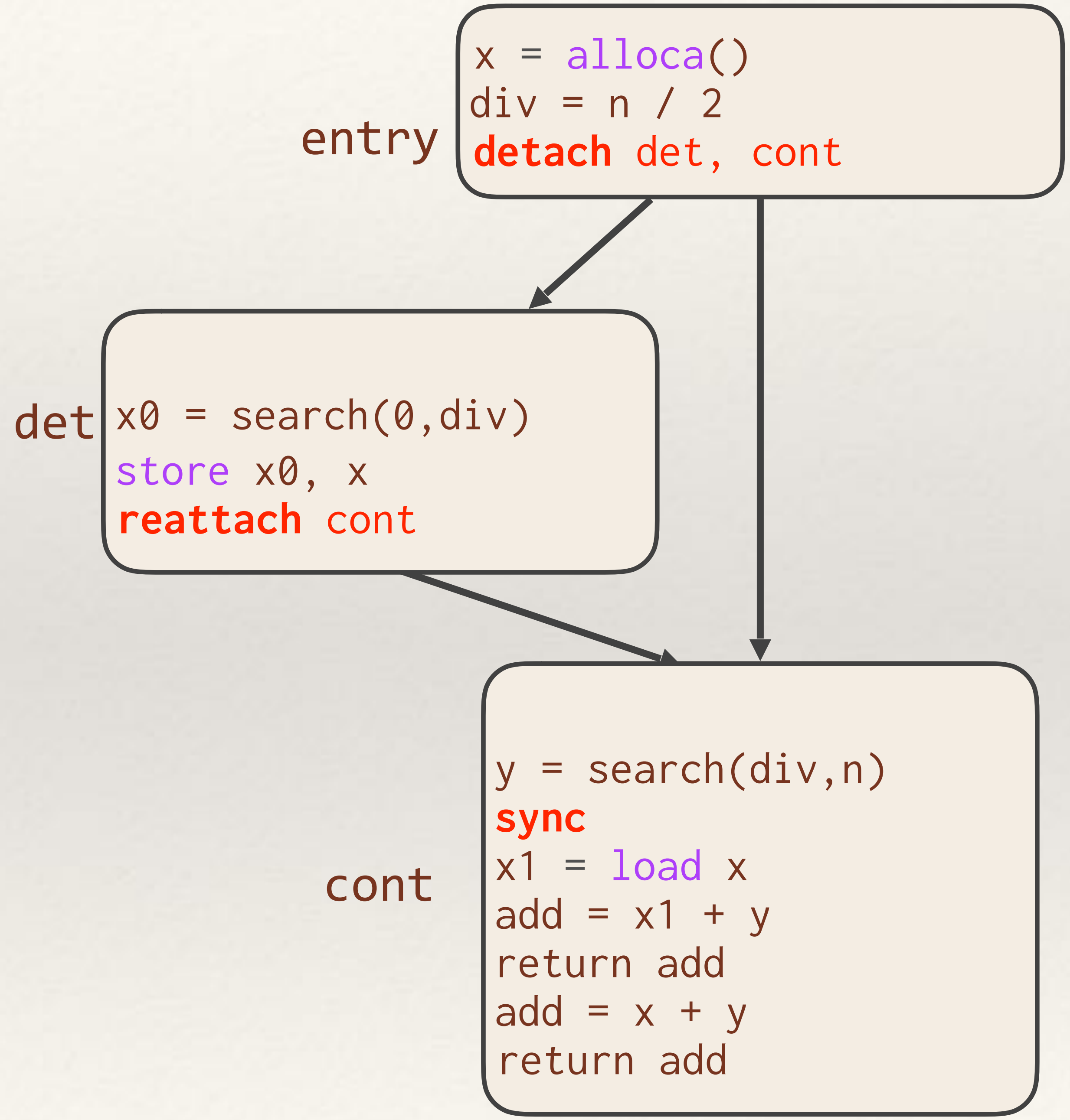
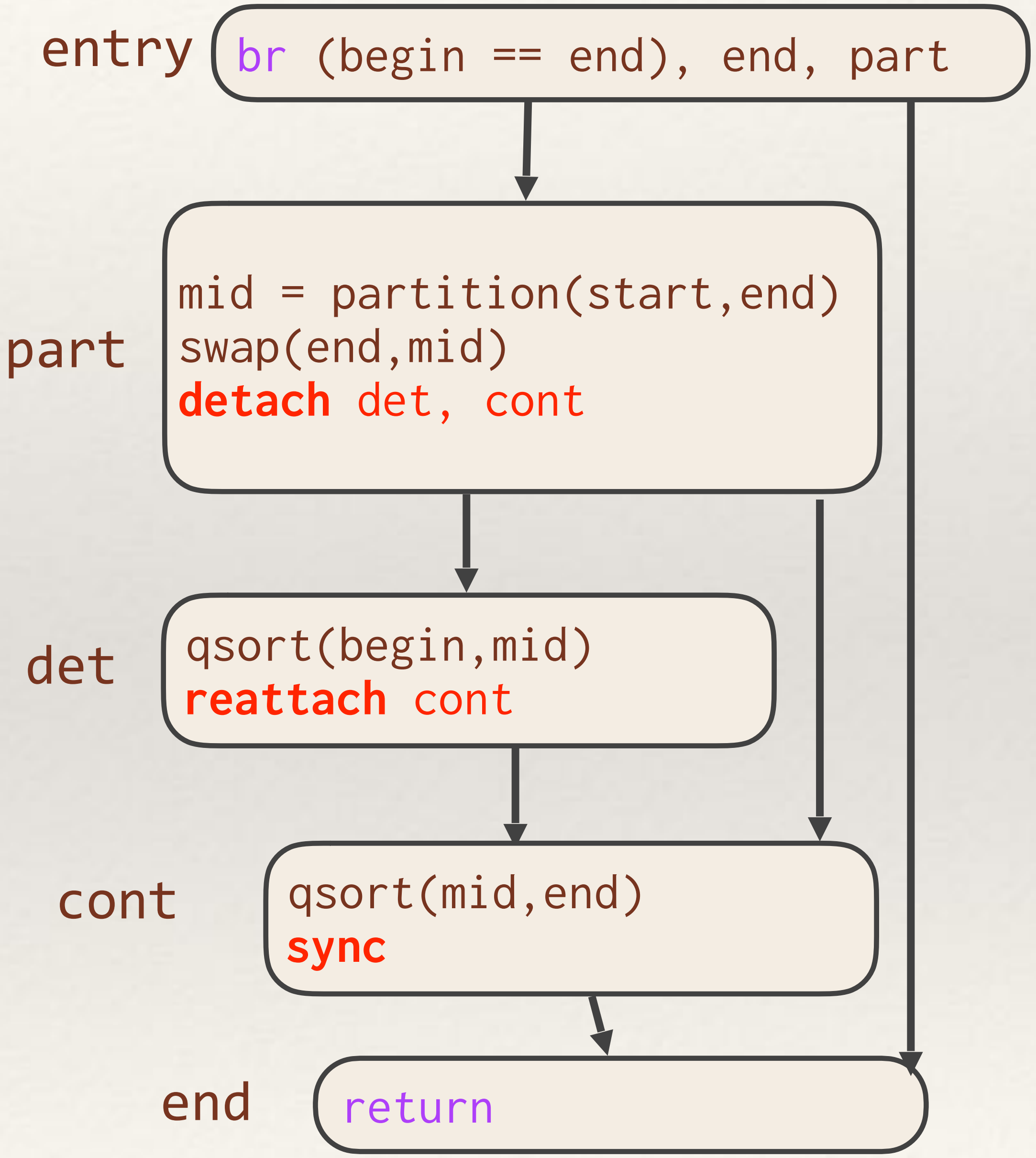


Case Study: Parallel Tail-Recursion Elimination

- 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* begin, 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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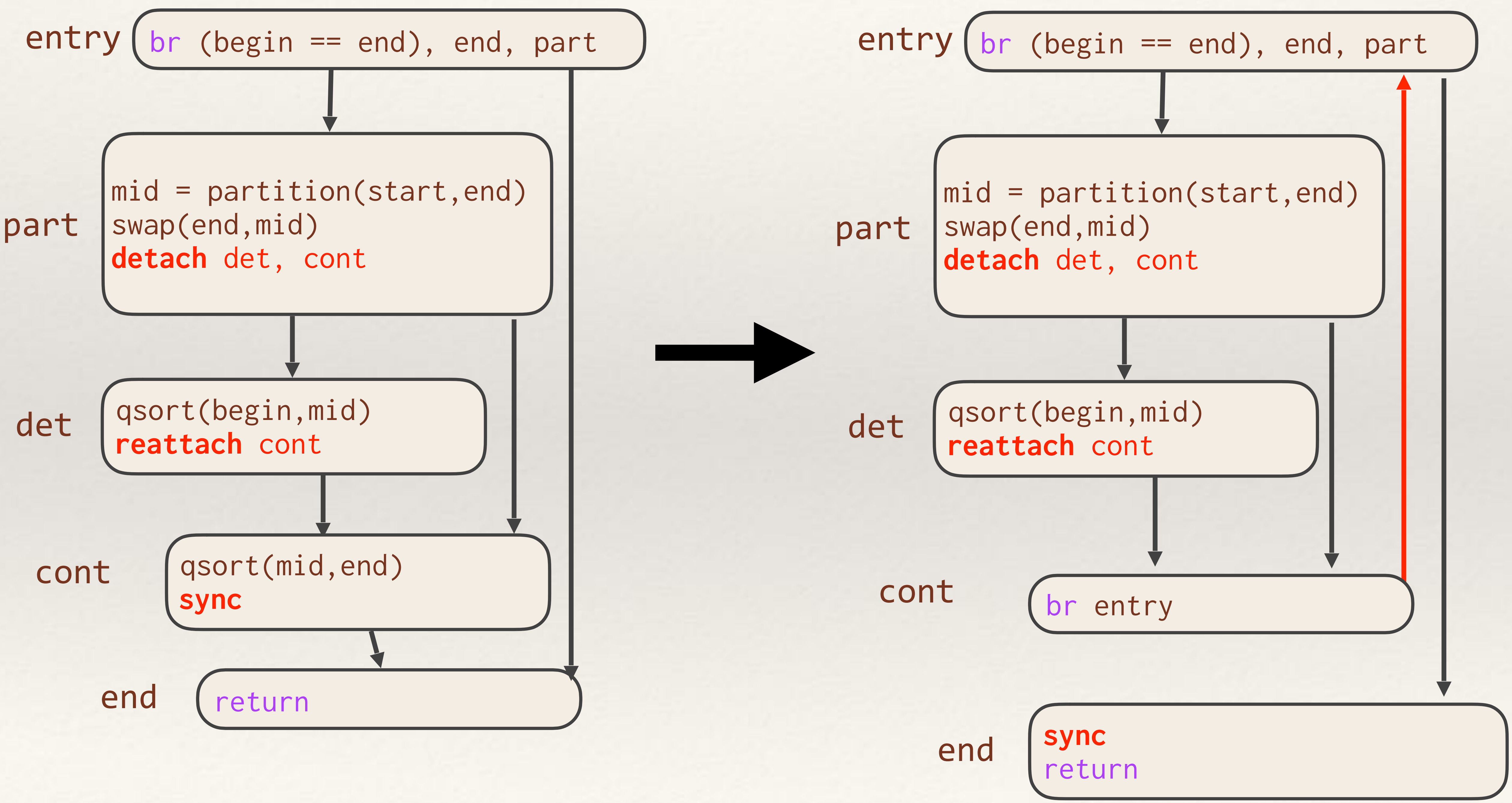

Conclusion

- Tapir enables existing serial optimizations to operate on fork-join parallel code
- Tapir requires minimal compiler modifications
- Tapir opens the door for parallel optimizations
- Ongoing development (bug fixes, new optimizations, etc).
- Available on GitHub!
  https://github.com/wsmoses/Parallel-IR.git