Leveraging LLVM to optimize parallel programs



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CSAIL
MIT COMPUTER SCIENCE AND ARTIFICIAL INTELLIGENCE LABORATORY

Modern Compilers Don’t Understand Parallel Code

OpenMP

CILK ARTS

Modern Compilers Don't Understand Parallel Code

Intel® Threading Building Blocks
C and C++ template library for creating high performance, scalable parallel applications

DESIGNED FOR NVIDIA CUDA™

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

Example: Normalizing a Vector in Parallel

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

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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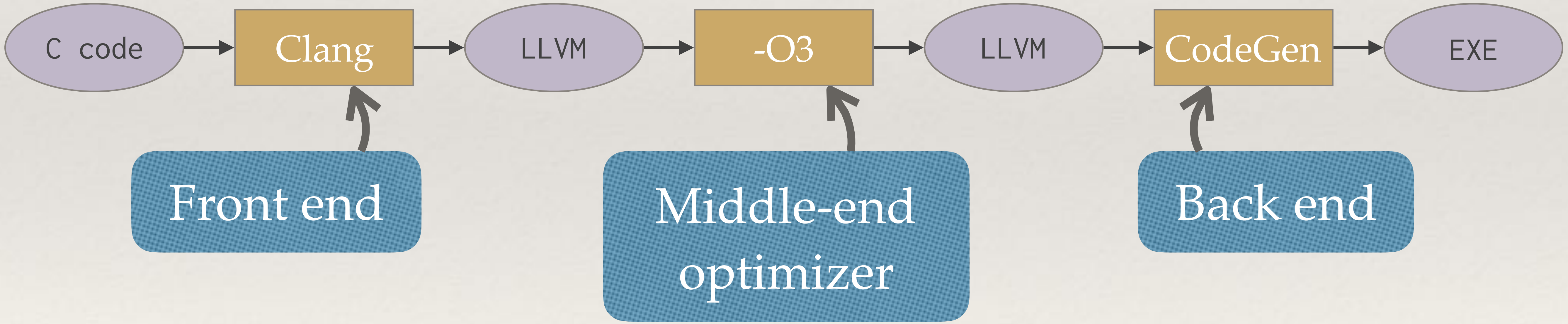
Original serial running time: $T_S = 0.312$ s

18-core running time: 180.657s

1-core running time: 2600.287s

What Happened?

The LLVM Compilation Pipeline



Effect of Compiling Serial Code

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

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  for (int i = 0; i < n; ++i)
    out[i] = in[i] / norm(in, n);
}
```

-O3

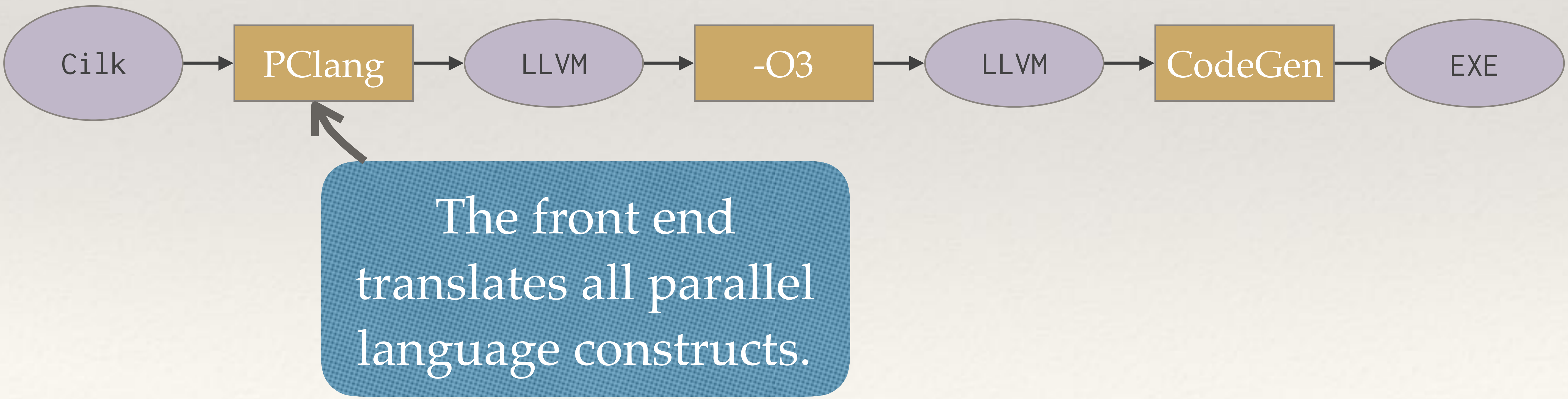
```c
__attribute__((const)) double norm(const double *A, int n);

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



Effect of Compiling Parallel Code

```
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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.

Tapir: Task-based Asymmetric Parallel IR

Cilk Plus/LLVM pipeline

Tapir/LLVM pipeline

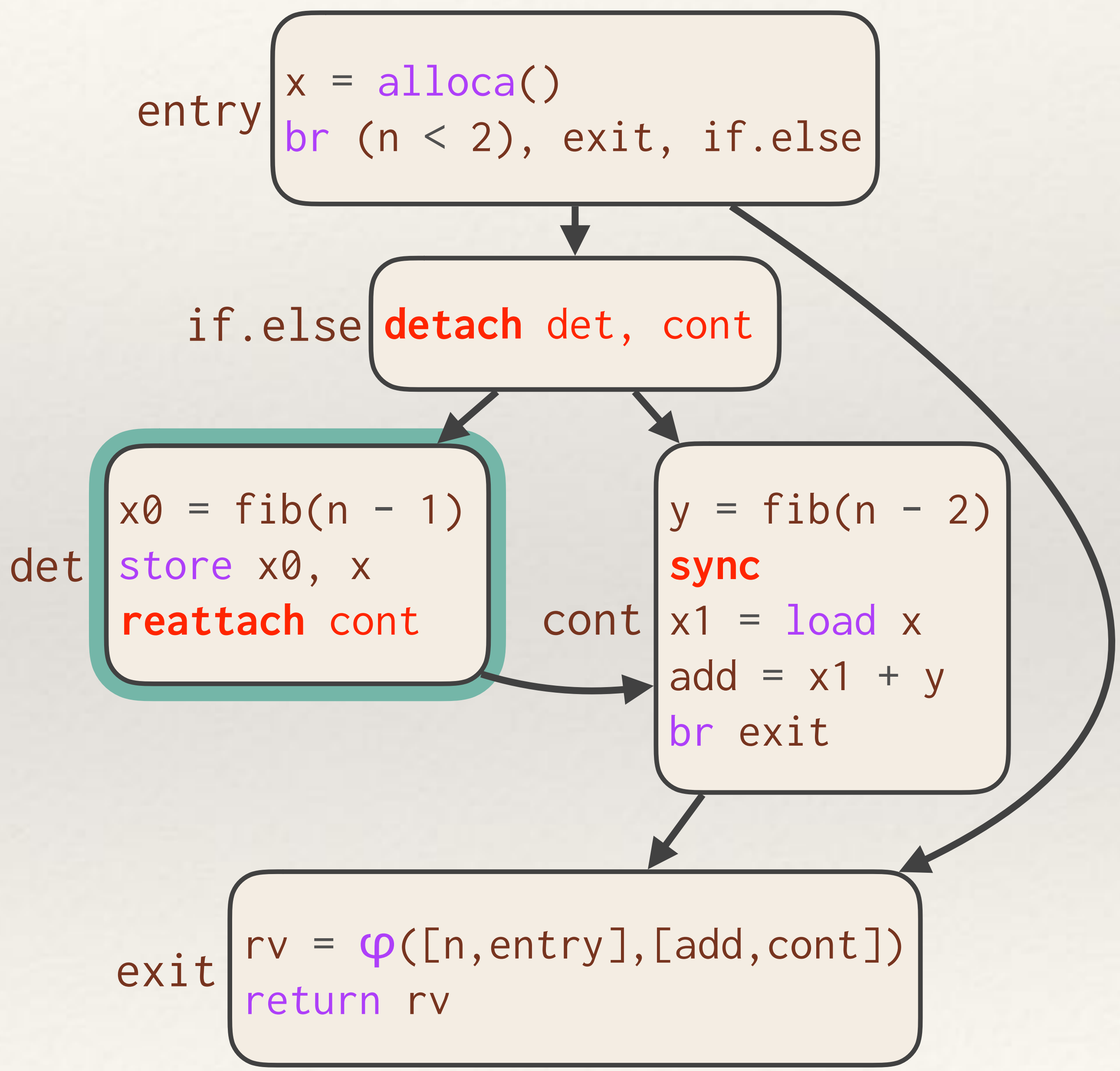
Tapir adds **three instructions** to LLVM IR that encode **fork-join parallelism**.

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

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

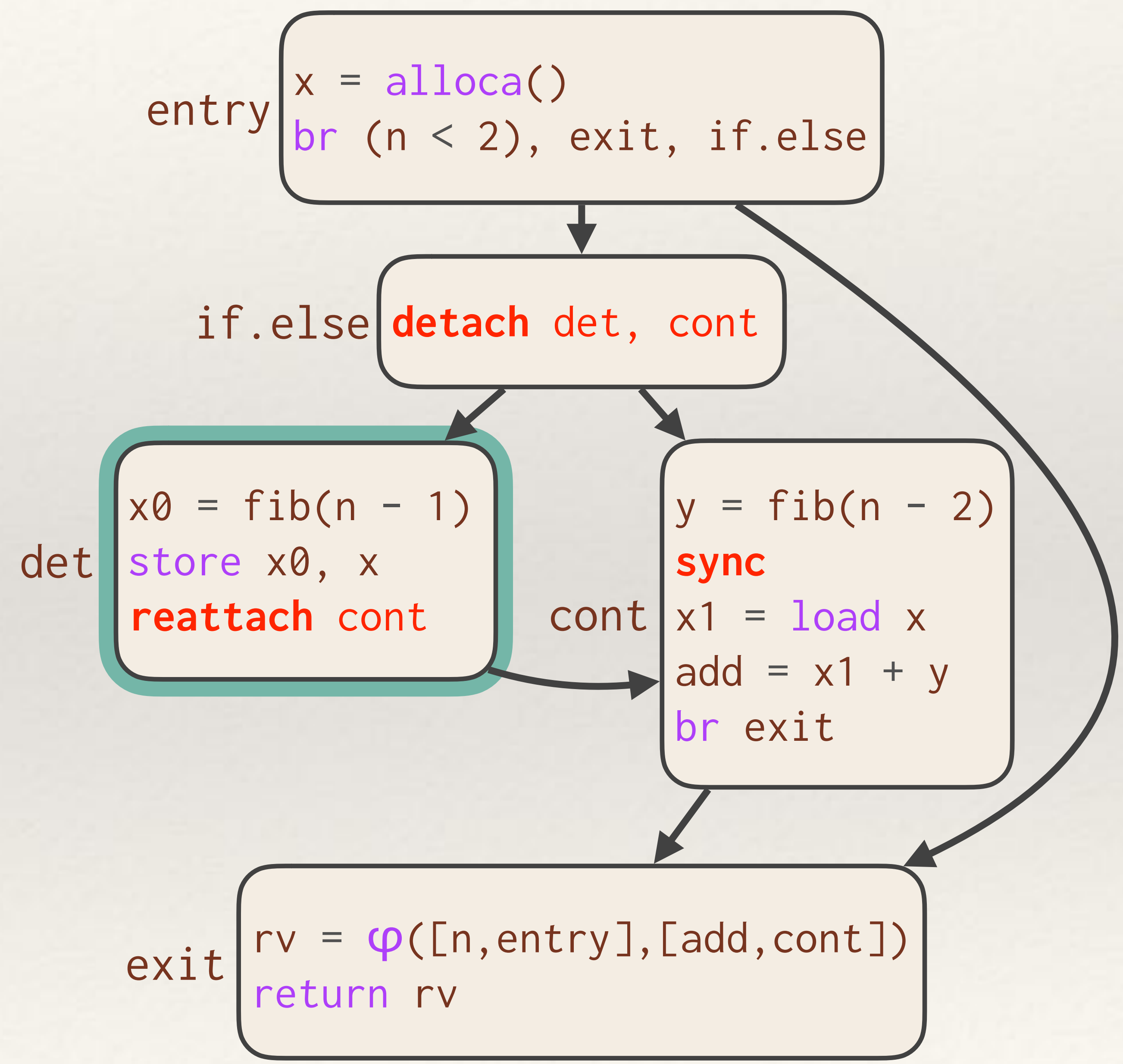
Tapir CFG



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

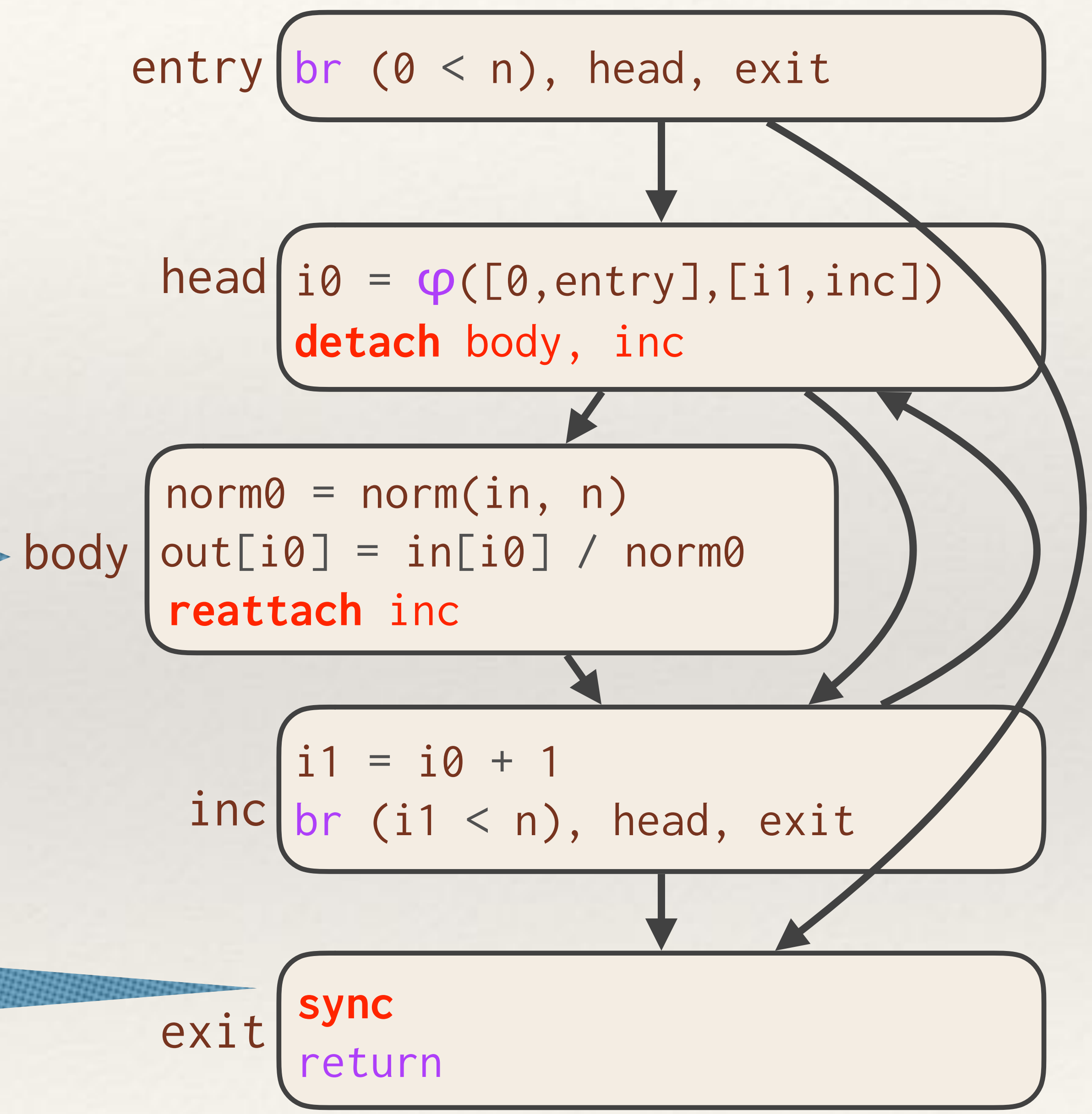


Parallel Loops in Tapir

```
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.

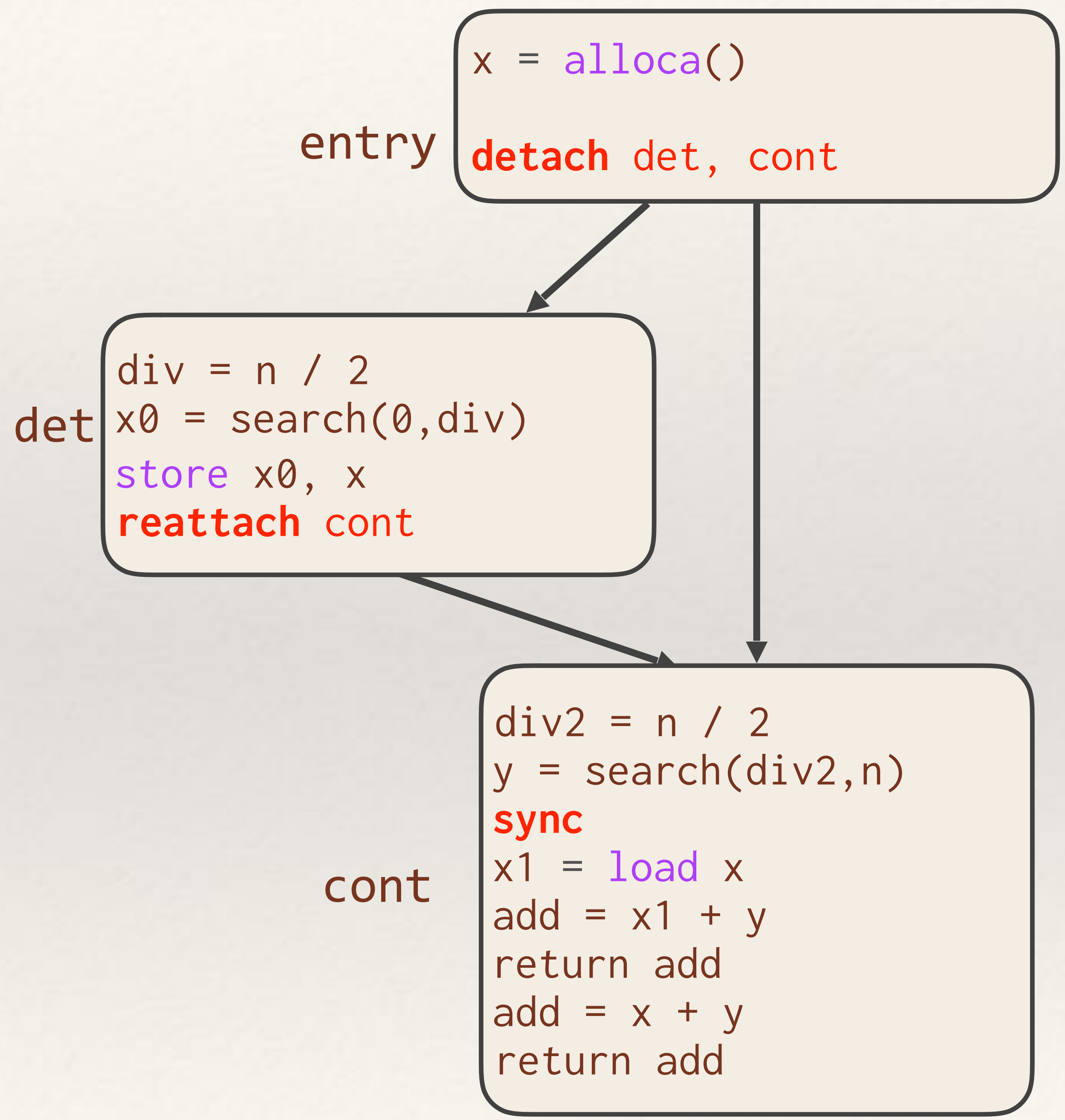


Most Serial Optimizations “Just Work” on Parallel Code!

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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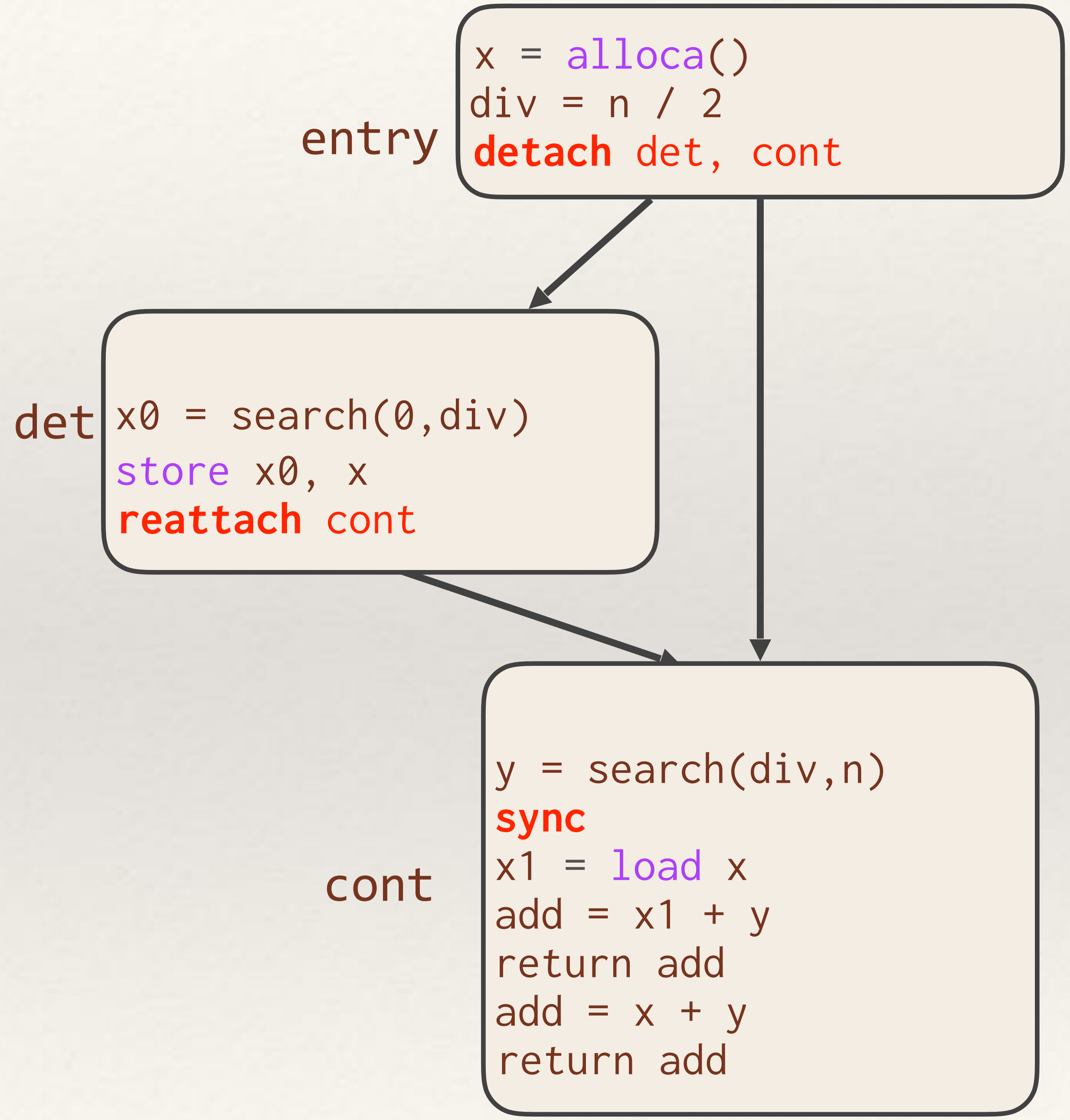


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Normalizing a Vector in Parallel with Tapir

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

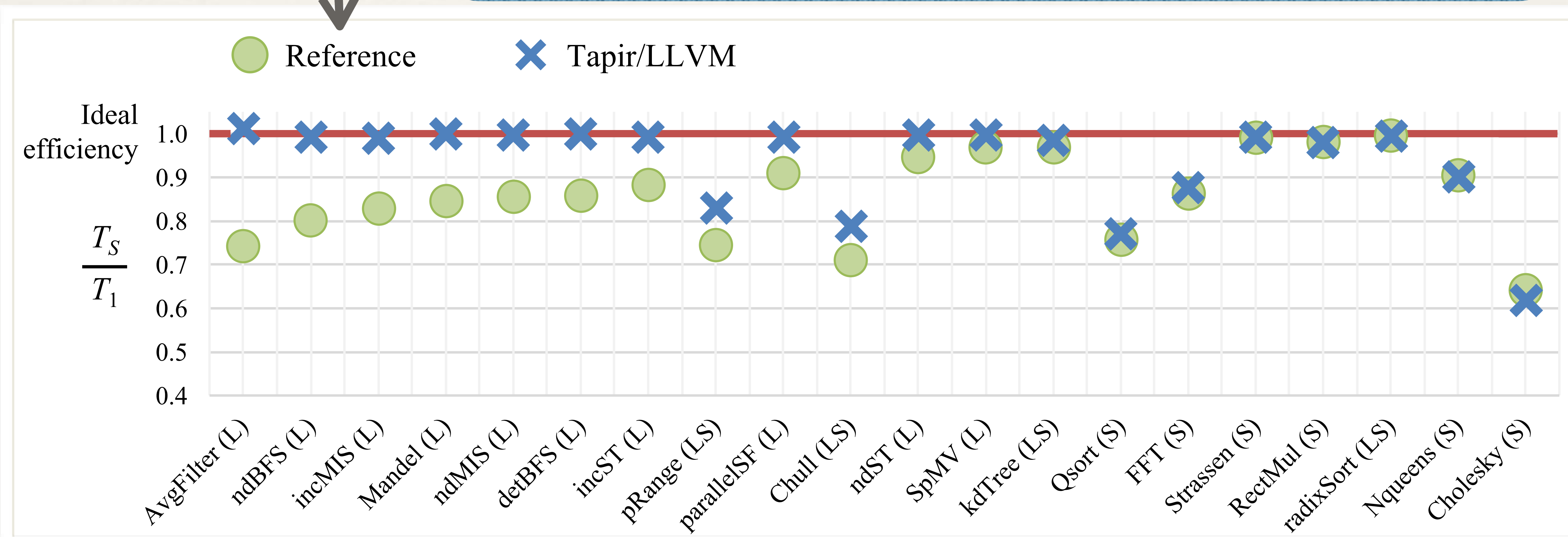
Compiled with Tapir/LLVM, running time on 1 core: $T_1 = 0.321$ s

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
Optimizations	152,229	380
Parallelism lowering	0	3,782
Other	3,803,831	460
Total	4,083,843	6,010

1,768

Rhino: The Parallel Compiler Dream

Parallel Optimizations

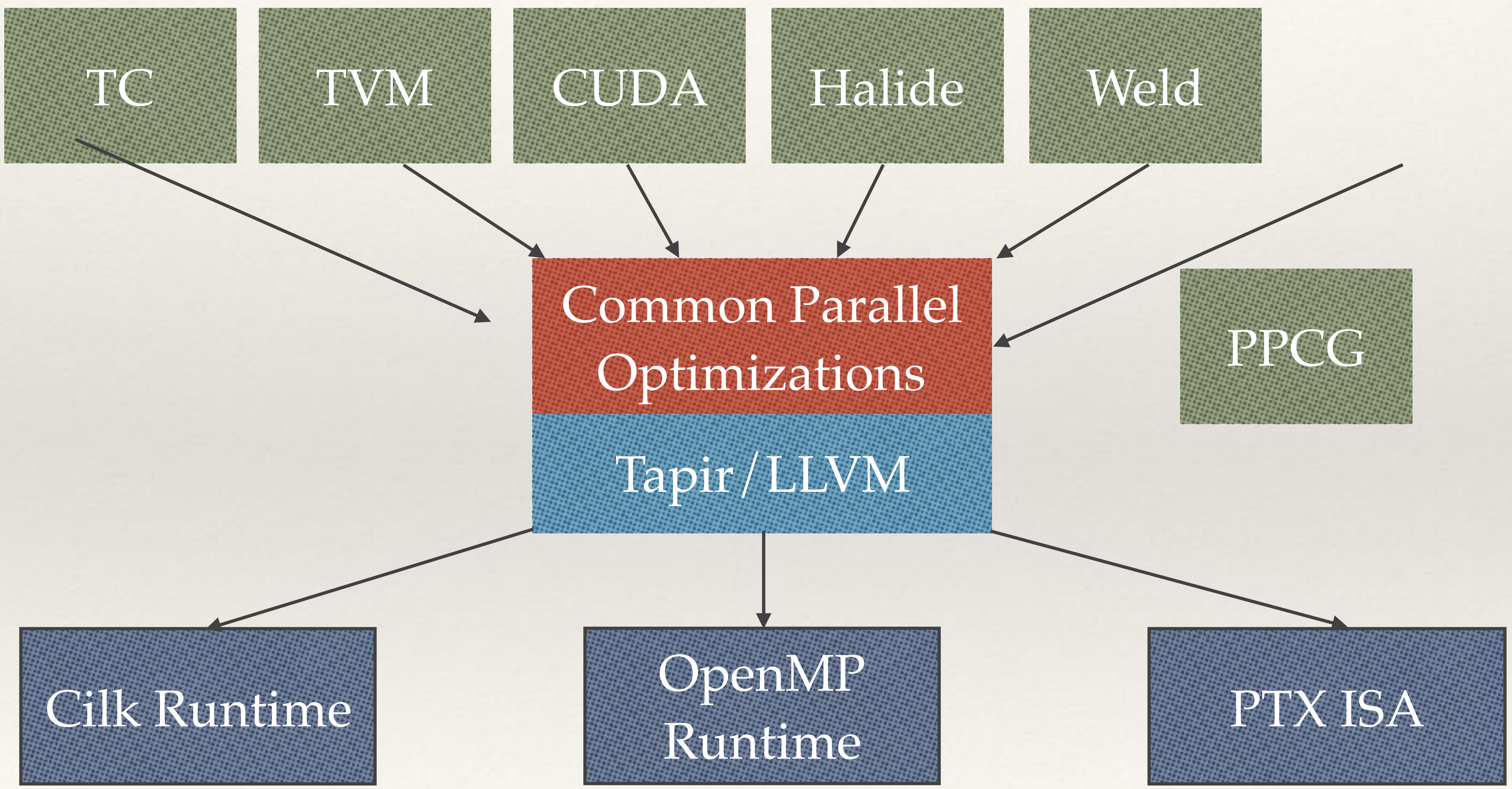
- There is ample opportunity for parallel-specific optimizations
  - Scheduling has potential for big boosts!

Rhino: The Parallel Compiler Dream

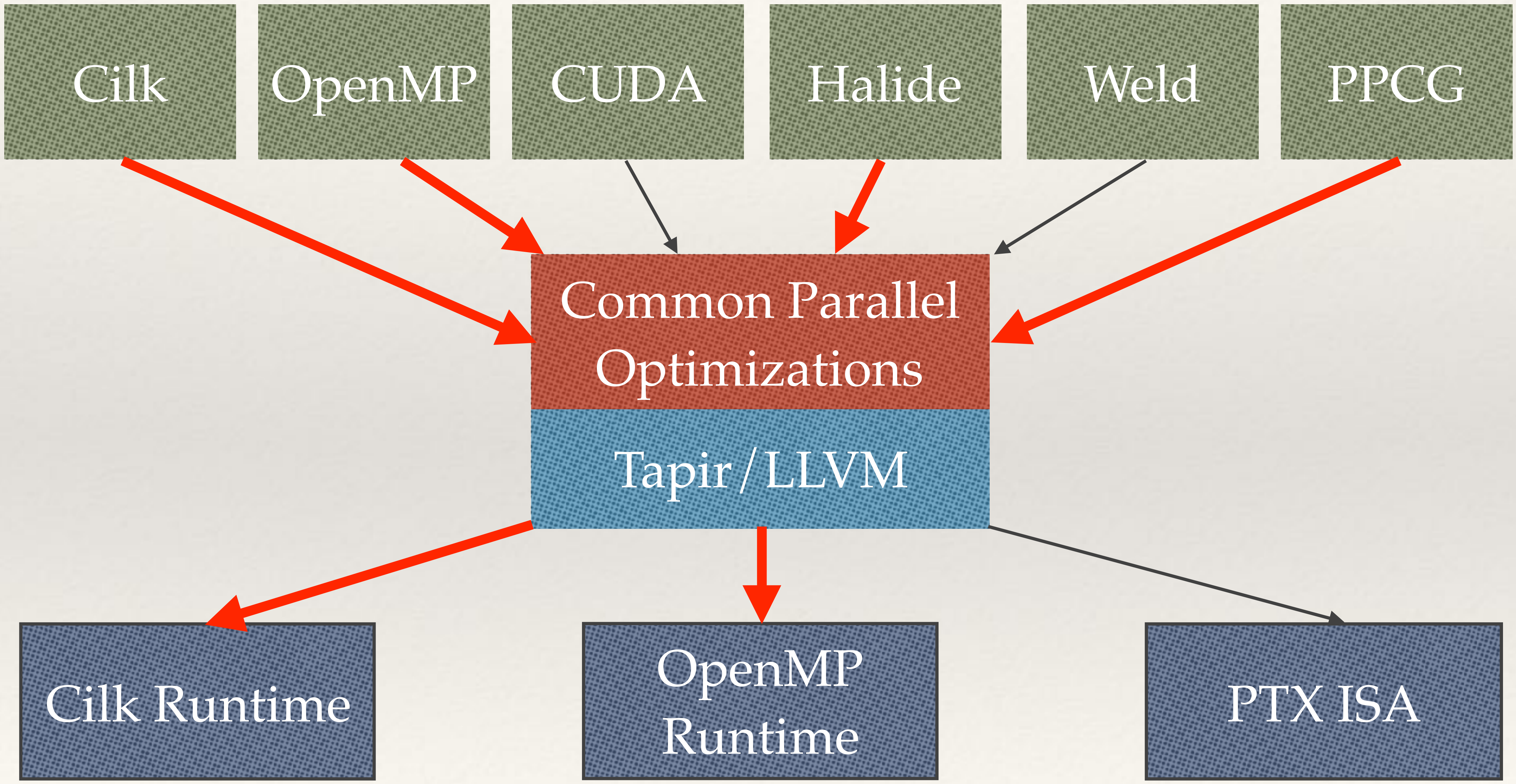
Parallel Optimizations

- In order to maintain some level of parallel performance, each high-level framework has its own set of parallel optimizations
- Done at a high-level, this requires both duplicating low-level code (i.e. LICM) and duplicating from framework to framework

Rhino: The Parallel Compiler Dream



Rhino: The Parallel Compiler Dream



Conclusion

- Tapir/LLVM enables existing serial optimizations to operate on fork-join parallel code, with minimal modification
- Using Tapir as a common parallel framework, you allow high-level parallel frameworks to share optimizations and allow library transformation
- Ongoing development (bug fixes, new optimizations, etc).
- Available on GitHub! https://github.com/wsmoses/Parallel-IR.git