Principles of Tapir

Tao B. Schardl William S. Moses Charles E. Leiserson

LLVM Performance Workshop
February 4, 2017

CSAIL
MIT COMPUTER SCIENCE AND ARTIFICIAL INTELLIGENCE LABORATORY

Outline

- What is Tapir?
- Tapir's debugging methodology
- Tapir's optimization strategy

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);
}
```

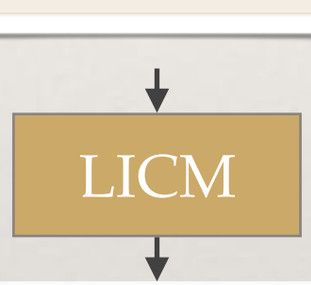
Test: random vector, n = 64M. Machine: Amazon AWS c4.8xlarge.

Running time: 0.312 s

A Crucial Compiler Optimization

```
__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);
}
```




```
__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;
}
```

Example: Normalizing a Vector in Parallel

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);
}
```

A parallel loop replaces the original serial loop.

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

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

Running time on 18 cores: $T_{18} = 180.657$ s

Running time on 1 core: $T_1 = 2600.287$ s

Terrible ***work efficiency***:
$T_S / T_1 = 0.312 / 2600$
$\sim 1 / 8300$

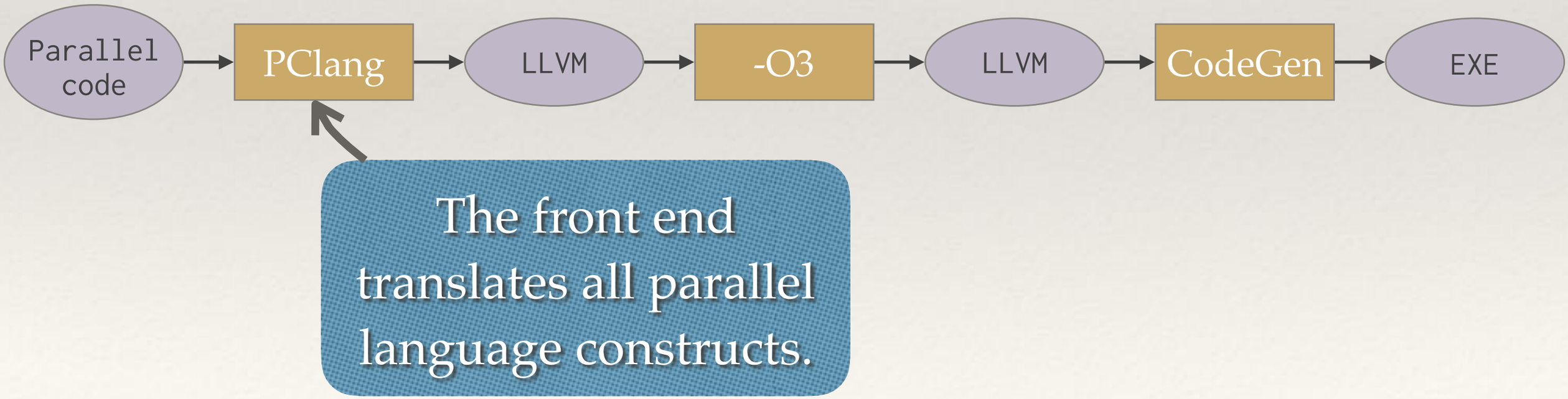
The story for OpenMP is similar, but more complicated.

Parallel code compiled using GCC 6.2. Cilk Plus/LLVM produces worse results.

Compiling Parallel Code Today

LLVM pipeline

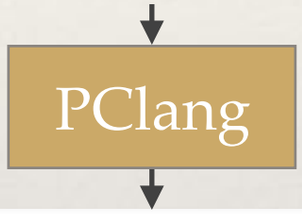
LLVM pipeline for parallel code



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);
}
```




```
__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.

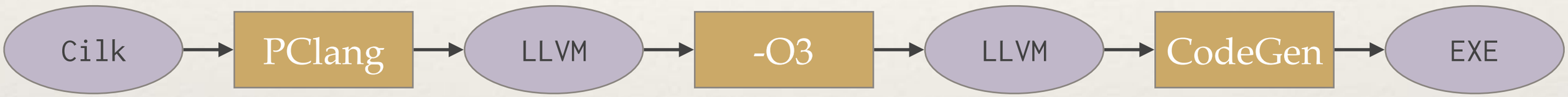
Helper function encodes the loop body.

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

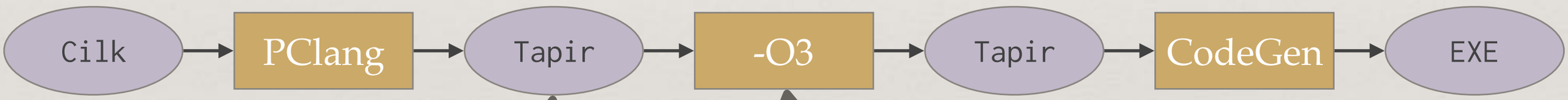
Tapir: Task-based Asymmetric Parallel IR

Tapir embeds parallelism into LLVM 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 optimization passes** work on **parallel code**.

Parallel IR: An Old Idea

Previous work on 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]

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	

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:
$T_S / T_1 = 97\%$

Summary of Performance Results

Compared to handling parallel constructs in the front end:

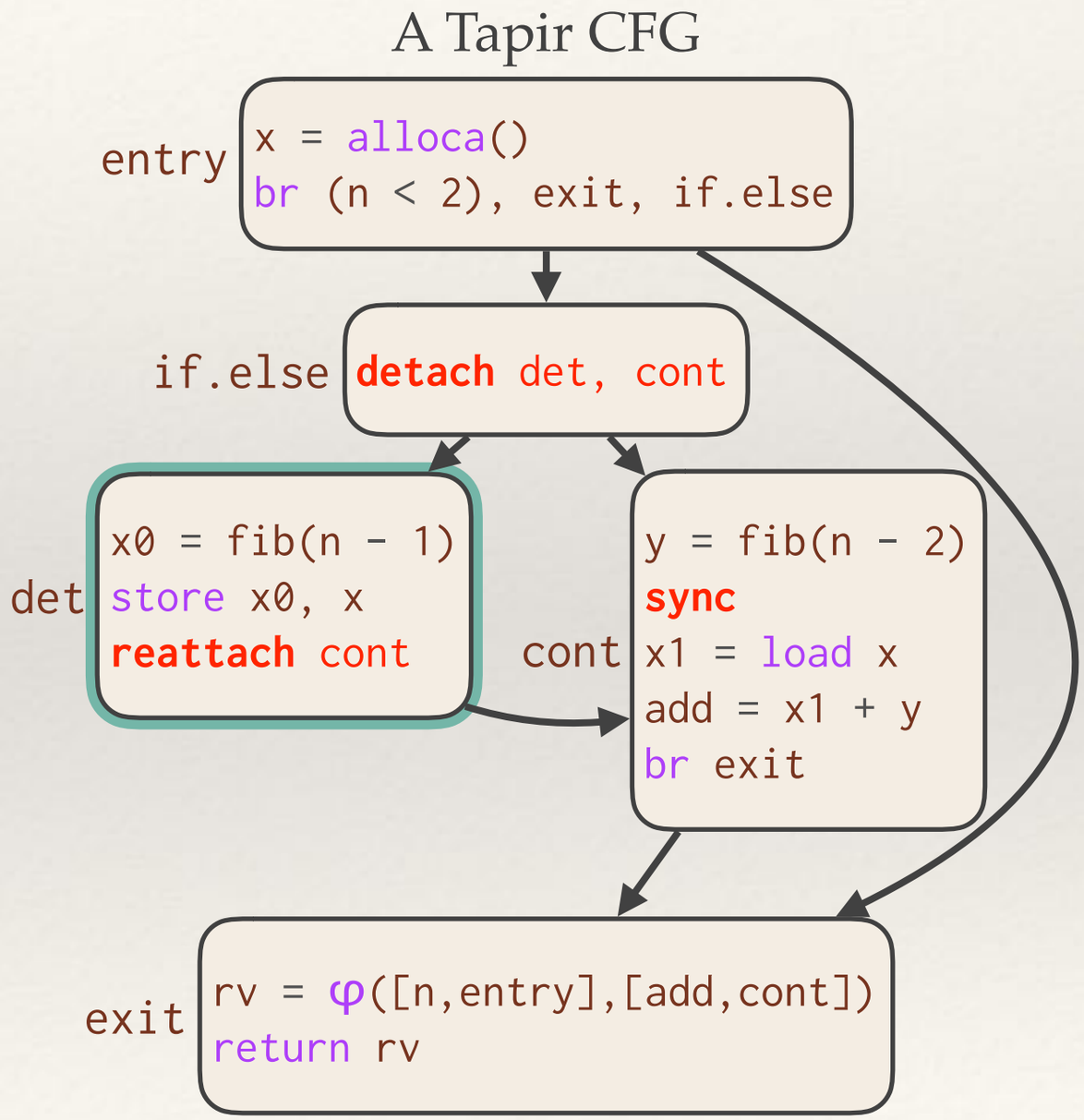
- Tapir/LLVM produces executables with **higher work-efficiency** for 17 of the 20 benchmarks — as much as 10–25% higher on a third of these benchmarks.
- Tapir/LLVM produces executables with at least **99% work-efficiency** on 12 of the benchmarks, whereas the competition does so on 2.
- Tapir/LLVM produces executables with **comparable or better parallel speedup**.

For More on Tapir…

Come to the PPoPP talk!

Tuesday, February 7
Room 400/402

Or ask me and Billy after this talk.



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What Is Parallel Programming?

- Pthreads
- Message passing
- Vectorization
- Task parallelism
- Data parallelism
- Dataflow
- Multicore
- HPC
- GPU's
- Heterogeneous computing
- Shared memory
- Distributed memory
- Clients and servers
- Concurrency
- Races and locks
- Memory models
- Scheduling and load balancing
- Work efficiency
- Parallel speedup
- Etc.

Tapir does NOT directly address ALL of these.

Focus of Tapir

Tapir strives to make it easy for **average programmers** to write **efficient** programs that achieve **parallel speedup**.

- Multicores
- Task parallelism
- Simple and extensible
- Deterministic debugging
- Serial semantics
- Simple execution model
- Work efficiency
- Parallel speedup
- Composable performance
- Parallelism, not concurrency

Focus of Tapir

Tapir strives to make it easy for **average programmers** to write **efficient** programs that achieve **parallel speedup**.

- Multicores
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- **Deterministic debugging**
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- **Composable performance**
- Parallelism, not concurrency

Outline

- What is Tapir?
- Tapir's debugging methodology
- Tapir's optimization strategy

Race Bugs

Parallel programming is strictly harder than serial programming because of **race bugs**.

Example: A buggy `norm()` function

```
__attribute__((const))
double norm(const double *A, int n) {
  double sum = 0.0;
  #pragma omp parallel for
  for (int i = 0; i < n; ++i)
    sum += A[i] * A[i];
  return sqrt(sum);
}
```

Concurrent updates to sum can **nondeterministically** produce **different results**.

How do I spot these bugs in my million-line codebase?

How do I find a race if I'm "lucky" enough to never see different results?

What if the **compiler** creates the race?

A Compiler Writer's Nightmare

Bug 55555 - Transformation puts race into race-free code

Attachments
Parallel test case (text/plain) 2017-02-04, Angry Hacker
Add an attachment

Angry Hacker 2017-02-04

Created attachment 12345
Parallel test case

My parallel code is race free, but the compiler put a race in it!!
>:(

Compiled program

1 run ✔

10 runs ✔

1000 runs ✔

Despite the programmer's assertion, multiple runs indicate no problem.

- Is the compiler buggy?
- Is the programmer wrong?

Debugging Tapir/LLVM

Tapir/LLVM contains a **provably good** race detector for **verifying** the existence of race bugs **deterministically**.

- Given a program and an input — e.g., a regression test — the race-detection algorithm **guarantees** to find a race if one exists or **certify** that no races exist [FL99, UAFL16].
- The race-detection algorithm introduces **approximately constant overhead**.
- We used the race detector together with `opt` to **pinpoint optimization passes** that incorrectly introduce races.

What about Thread Sanitizer?

Efficient race detectors have been developed, including FastTrack [FF09] and Thread Sanitizer [KPIV11].

- These detectors are **best effort**: they are **not** guaranteed to find a race if one exists.
- These detectors are designed to handle **a few** parallel threads, comparable to the number of processors.
- Task-parallel languages are designed to get parallel speedup by exposing **orders of magnitude more** parallel tasks than processors.

Outline

- What is Tapir?
- Tapir's debugging methodology
- Tapir's optimization strategy

Example: Normalizing a Vector with OpenMP

OpenMP code for `normalize()`

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

void normalize(double *restrict out, const double *restrict in, int n) {
  #pragma omp parallel for
  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 LLVM 4.0, running time on 1 core: $T_1 = 0.329$ s

Compiled with LLVM 4.0, running time on 18 cores: $T_{18} = 0.205$ s

Great work efficiency without Tapir?

Work Analysis of Serial Normalize

$T(\texttt{norm}) = O(n)$

```
__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);
}
```

$T(\texttt{normalize}) = n * T(\texttt{norm}) + O(n) = O(n^2)$

Work Analysis After LICM

$T(\texttt{norm}) = O(n)$

```
__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;
}
```

$T(\texttt{normalize}) = T(\texttt{norm}) + O(n) = O(n)$

Compiling OpenMP Normalize

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

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

PClang → -O3

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

void normalize(double *restrict out, const double *restrict i
  __kmpc_fork_call(omp_outlined, n, out, in);
}

void omp_outlined(int n, double *restrict out,
                  const double *restrict in) {
  int local_n = n; double *local_out = out, *local_in = in;
  __kmpc_for_static_init(&local_n, &local_out, &local_
  double tmp = norm(in, n);
  for (int i = 0; i < local_n; ++i)
    local_out[i] = local_in[i] / tmp;
  __kmpc_for_static_fini();
}
```

Each processor runs the helper function once.

Helper function contains a serial copy of the original loop.

Work Analysis of OpenMP Normalize

How much **work** (total computation outside of scheduling) does this code do?

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

void normalize(double *restrict out, const double *restrict in, int n) {
  __kmpc_fork_call(omp_outlined, n, out, in);
}

void omp_outlined(int n, double *restrict out,
                  const double *restrict in) {
  int local_n = n; double *local_out = out, *local_in = in;
  __kmpc_for_static_init(&local_n, &local_out, &local_in);
  double tmp = norm(in, n);
  for (int i = 0; i < local_n; ++i)
    local_out[i] = local_in[i] / tmp;
  __kmpc_for_static_fini();
}
```

$T_1(\text{norm}) = O(n)$

$T_1(\text{omp\_outlined}) = T_1(\text{norm}) + O(\text{local\_n}) = O(n)$

$T(\text{normalize}) = P * T_1(\text{omp\_outlined}) = O(n * P)$

Let P be the number of processors.

What Does This Analysis Mean?

$T(\texttt{normalize}) = O(\texttt{n} * P)$

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

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

Original serial running time: $T_S = 0.312$ s

1-core running time: $T_1 = 0.329$ s

18-core running time: $T_{18} = 0.205$ s

- This code is only work-efficient on **one processor**.
- **Only minimal** parallel speedup is possible.
- The problem **persists** whether `norm` is serial or parallel.
- This code **slows down** when not all processors are available.

Tapir's Optimization Strategy

Tapir strives to optimize parallel code according the **work-first principle**:

- **First** optimize the **work**, not the parallel execution.
- Sacrifice **minimal** work to support parallel execution.

The work-first principle helps to ensure that parallel codes can achieve speedup in **all runtime environments**.

Status of Tapir

- Try Tapir/LLVM yourself!
  `git clone –recursive https://github.com/wsmoses/Tapir-Meta.git`
- We have a **prototype front end** for Tapir/LLVM that is substantially compliant with the Intel Cilk Plus language specification.
- Tapir/LLVM achieves **comparable or better performance** with GCC, ICC, and Cilk Plus/LLVM, and is becoming **comparably robust**.
- Last fall, a **software performance-engineering class** at MIT with ~100 undergrads used Tapir/LLVM as their compiler.
- Tapir's **race detector** is available for debugging parallel programs.
- We're continuing to enhance Tapir/LLVM with bug fixes, new compiler optimizations, and other new features.

Question?

Recap: Foci of Tapir

- Multicores
- Task parallelism
- Simple and extensible
- Deterministic debugging
- Serial semantics
- Simple execution model
- Work efficiency
- Parallel speedup
- Composable performance
- Parallelism, not concurrency

Backup Slides

Multicores Are The Bargain Component

Multicores are **pervasive** in today's computing ecosystem.

Smartphones

Laptops

Servers in the cloud

Average programmers are writing code for multicores.

Multicores Are Powerful

GraphChi: How a Mac Mini outperformed a 1,636 node Hadoop cluster

By Christian Prokopp | 2014-04-29 | Big Data · Big Data Republic · Cloud Computing · Machine Learning · MapReduce · Published · Semantikoz
Tags: big data · graph · graphchi · graphlab · hadoop · machine learning · mapreduce

Last year ~~GraphChi~~, a spin-off of GraphLab, a distributed graph-based high performance computation framework, did something remarkable. GraphChi

But getting performance out of a multicore today requires **software performance engineering**.

knowledge and understanding of the general benefits and disadvantages of single machine performance the processing steps can be designed. A single computer has usually two characteristics, firstly a large graph problem does not fit into the fast RAM (Random Access Memory), and secondly it has a large disk, which is large enough to hold the data. The traditional disks are only performant on sequential and not on random reads. Modern computers may come with solid state disks for faster random read and write though they are still significantly slower than RAM. Consequently, any algorithm aiming to solve graph problems on single machine commodity hardware has to utilise the disk and minimise the random access to data.

Divide and Conquer

Task Parallelism

Task parallelism provides **simple linguistics** for **average programmers** to write parallel code.

Example: parallel quicksort

```
void pqsort(int64_t array[], size_t l,
            size_t h) {
  if (h - l < COARSENING)
    return qsort_base(array, l, h);
  size_t part = partition(array, l, h);
  cilk_spawn pqsort(array, l, part);
  pqsort(array, part, h);
  cilk_sync;
}
```

The child function is *allowed* (but not required) to execute in parallel with the parent caller.

Control cannot pass this point until all spawned children have returned.

Advantages of Fork-Join

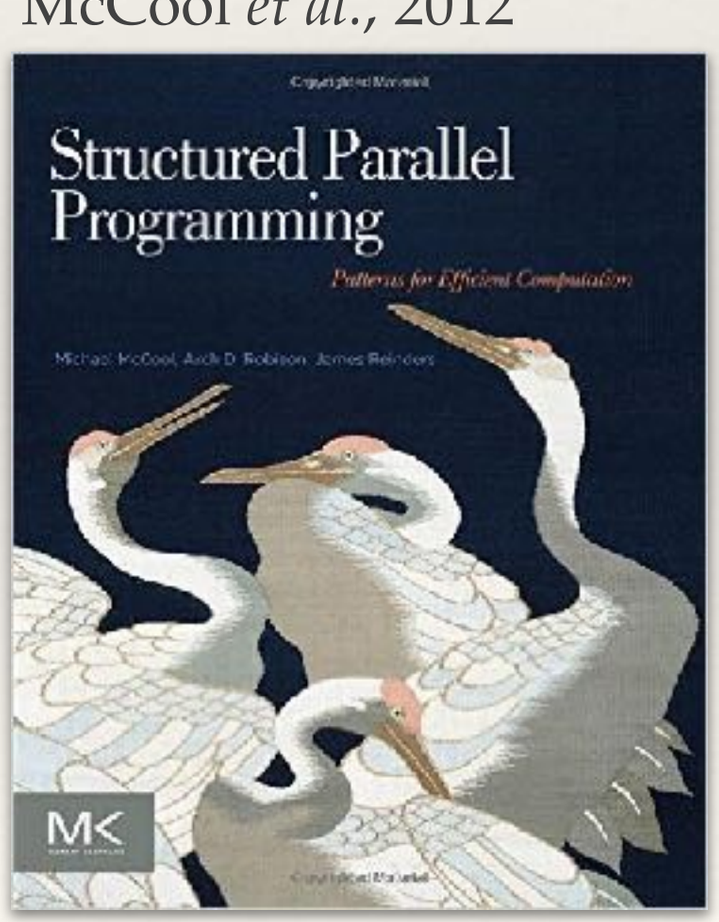
Fork-join parallelism provides a **simple**, **low-level** model of parallelism.

Many higher-level parallel constructs can be encoded in the fork-join model [MRR12].

- Map
- Reduction
- Stencil
- Recursion
- Scan

Efficient parallel runtimes exist that support fork-join parallelism.

McCool *et al.*, 2012



What About Everything Else?

Fork-join doesn't cover all parallel patterns, but it can be extended (e.g., [LLSSZ15]).

Tapir itself is meant to be **extensible**.

- For now, a front-end can still insert runtime calls to handle parallel constructs that don't have explicit IR support.
- New extensions for additional parallel constructs should be able interoperate with Tapir.

How Can We Be Sure?

We are currently developing **formal semantics** for Tapir.

- An early draft of Tapir's semantics can be found in Tao B. Schardl's Ph.D. thesis.
- *Current Goal:* Prove that all serial code transformations are **safe** to perform on both race-free and racy Tapir programs.

Three Traits of Parallel Programs

- A parallel program has **serial semantics** if a 1-processor execution of the program is valid.
- A parallel program is a **faithful extension** of a serial program if eliding the parallel constructs yields a serial program with the original program's serial semantics.
- A parallel program is **deterministic** if all (serial and parallel) executions have the same semantics.

Serial Semantics vs. Faithful Extension

Example: OpenMP code with `private` construct

```
int main(void)
{
  int i = 0;
#pragma omp parallel for private(i)
  for (int j = 1; j < 10; ++j) {
    i += j * j;
    printf("i = %d\n", i);
  }
  printf("i = %d\n", i);

  return 0;
}
```

The `private` construct ensures that updates to `i` are not retained after the loop.

Some languages, such as OpenMP, allow programs that are not faithful extensions.

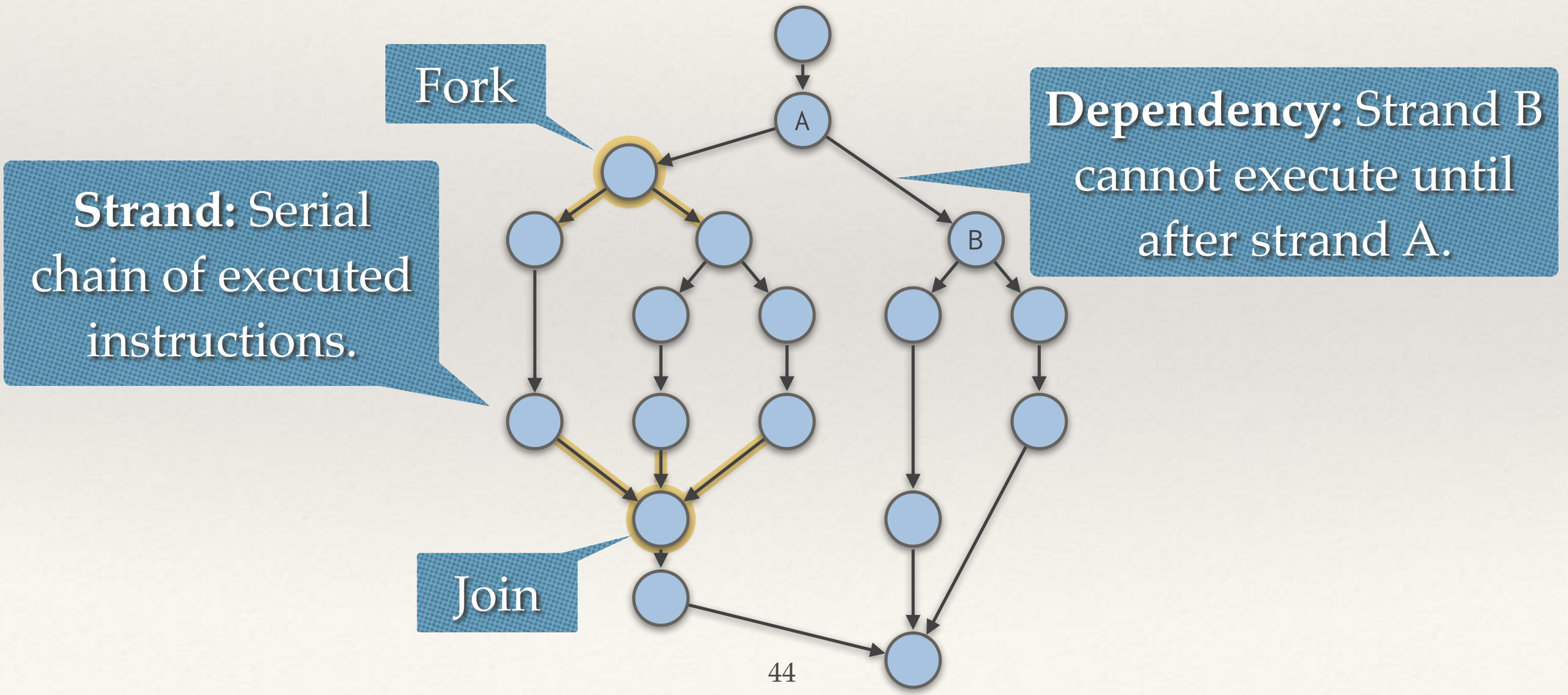
- Tapir **doesn't care** about whether the program source is a faithful extension.

Serial Semantics vs. Determinism

- A Tapir program can contain races, even though it has serial semantics.
- If the execution of a Tapir program contains no **determinacy races** [FL99], then it is **deterministic**.
- When optimizing a Tapir program, the compiler strives to **preserve** the program's serial semantics and **avoid** introducing new races.

Simple Model of Computation

The logical control structure of a Tapir program execution can be modeled as a **directed acyclic graph**, or **dag**.

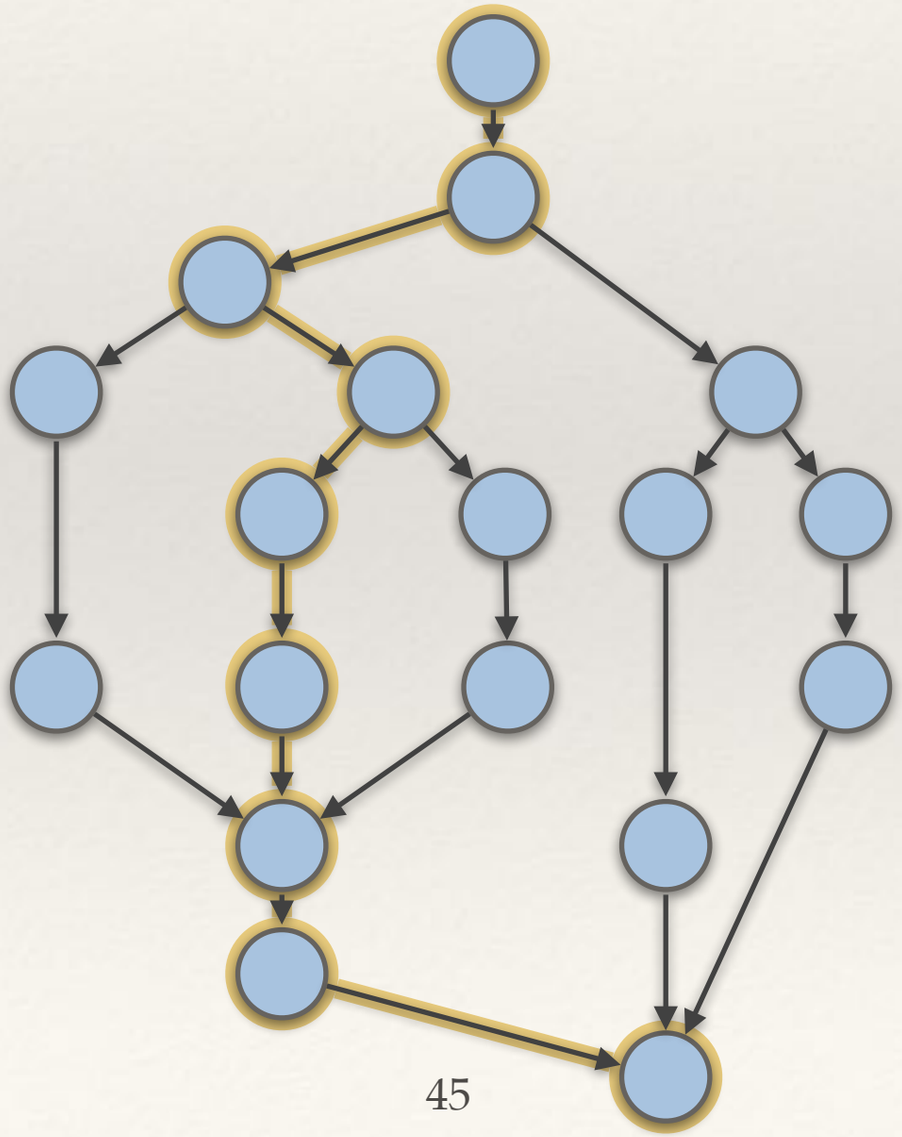


Work/Span Analysis

Using the dag model, **parallel performance** can be understood in terms of **work** and **span**.

Work, T_1, is the serial running time of the program.

Example:
$T_1 = 18$



Span, T_∞, is the length of a longest path in the dag.

Example:
$T_\infty = 9$

Parallel Speedup

Parallel speedup on P processors can be understood in terms of work and span.

- **Work Law:** $T_P \geq T_1/P$
- **Span Law:** $T_P \geq T_\infty$
- Modern parallel runtime systems are **guaranteed** to execute a parallel program on P processors in time $T_P \leq T_1/P + O(T_\infty)$ [BL99].

Concurrency Is Complicated

Interactions between threads can **confound** traditional compiler optimizations.

Thread 1

```
a = 1;
```

Thread 2

```
if (x.load(RLX))
  if (a)
    y.store(1, RLX);
```

Thread 3

```
if (y.load(RLX))
  x.store(1, RLX);
```

This program produces different results under the C11 memory model if Threads 1 and 2 are sequentialized [VBCMN15].

Parallelism Sans Concurrency

Conceptually, Tapir introduces **task-parallelism** for speeding up a **single thread of control**.

C code for `normalize()`

```
__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);
}
```

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);
}
```

Same control, but `cilk_for` indicates an opportunity to speed up execution using parallel processors.

Weak Memory Models and Tapir

Tapir's task-parallel model, with a serial elision, helps ensure that **standard optimizations** are **legal**.

C11 optimization example, written in Cilk pseudocode

```
cilk_spawn { a = 1; }

cilk_spawn {
  if (x.load(RLX))
    if (a)
      y.store(1, RLX);
}

cilk_spawn {
  if (y.load(RLX))
    x.store(1, RLX);
}
```

The serial semantics of cilk_spawn ensures that sequentialization is **always allowed.**

A Sweet Spot for Compiler Optimizations

- When optimizing **across threads**, standard compiler optimizations are **not always legal**.
- By enabling parallelism for a **single thread of control**, Tapir's model is **amenable** to standard compiler optimizations.
- **Vectorization** is another example of where compilers use parallelism to speed up a single thread of control.