Exploring Tradeoffs in Parallel Implementations of C++ using Futures

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Introduction

Motivation

Need for standardized parallelism in C++

1. Hardware concurrency constantly increasing
2. C++ is a high-level language for writing efficient code

Standard solution: futures and async tasks

Benefits of Futures:

1. Synchronization operations cannot introduce data races on future objects
2. Support an easily maintained and composable functional style
3. Support object-oriented programming
4. Can express other parallel constructs with futures

C++ Futures Today

Desired properties:

1. Safe, maintainable, programmable, portable
2. Low-overhead, scalable

Current implementations satisfy first set of criteria but not second

Thesis Statement

A combination of compile-time and run-time approaches is the most effective means of implementing parallel futures in C++.

Contributions

1. Parallel C++ futures implementation: Fibertures
2. Source-to-source compiler transformations to facilitate code migration
3. A quantitative comparison of several implementations of parallel futures in C++

Background

Async Tasks and Futures in the C++ Standard Template Library

Contained in header `<future>`

- `std::promise<T>`: placeholder for a value of type `T`
- `std::future<T>`: represents a future value of type `T`
- `std::async()`: executes a task asynchronously, returns future return value

Future Synchronization Operations

A future references the shared state of a promise object

Wait for a future to be ready using

- `get()`
- `wait()`
- `wait_for()`
- `wait_until()`

Can only call `get()` once unless future is converted to a shared future with `share()`

Example: Promise and Future

```
std::promise<int> int_promise;
std::future<int> int_future = int_promise.get_future();
//int_future.get();
int_promise.set_value(14);
std::cout << int_future.get();
```

Example: Async Tasks and Futures

```
int square(int n) { return n * n; }
int main() {
  std::future<int> square_future = std::async(square, 3);
  std::future<int> cube_future = std::async([](int n) {
    return n * n * n;
  }, 2);
  std::cout << (square_future.get() + cube_future.get());
}
```

Async Task Launch Policy

User may specify a launch policy for an async task:

- `std::launch::async`
- `std::launch::deferred`
- `std::launch::async | std::launch::deferred`

A task marked async is invoked in a new thread

A task marked deferred is invoked the first time its value is used (lazy evaluation)

We are interested only in the parallel overloads

Pitfalls of `std::async()` and `std::future`

- Threads have high overhead for creation and context-switching
- Synchronization is blocking

HClib (https://github.com/habanero-rice/hclib)

- A high-level, lightweight, task-based programming model for intra-node parallelism in C and C++
- Uses a cooperative work-stealing strategy, implemented using Boost Context
- API includes a variety of parallel constructs, including async tasks with futures
- Supports integration of task parallelism with multiple distributed runtimes, including MPI, UPC++, and OpenSHMEM
- Supports data-driven futures (DDFs) and data-driven tasks (DDTs)

Example: Parallel Recursive Fibonacci Function using HClib

```
uint64_t fibonacci(uint64_t n) {
  if (n < 2) return n;
  hclib::future_t<uint64_t> n1 = hclib::async_future([] {
    return fibonacci(n - 1);
  });
  hclib::future_t<uint64_t> n2 = hclib::async_future([] {
    return fibonacci(n - 2);
  });
  return n1.get() + n2.get();
}
int main(int argc, char* argv[]) {
  hclib::launch([]() {
    std::cout << fib(10) << '\n';
  };
}
```

Our Approach: Fibertures

Problem Statement

- Pthreads are inefficient for applications using many tasks with possibly varying run time
- Want to utilize the programmability and portability of `std::future` while enabling scalable parallel performance
- Several implementations of C++ futures exist, using a variety of compiler- and library-based approaches
- We implemented Fibertures on top of the libfib runtime library
- We compare these approaches to C++ futures by programmability, portability, and efficiency

`Swapstack` Calling Convention

`Swapstack`:

- A calling convention used for switching between continuations
- Calls exchange the current stack for that of the invoked continuation
- Saves the address where execution should continue when the calling continuation resumes

libfib (https://github.com/stedolan/libfib)

A cooperative work-stealing runtime scheduler for C++ built using `Swapstack`

- Spawn lightweight tasks (fibers)
- Rapidly context-switch between fibers
- Cooperatively yield a fiber's worker thread for another fiber to use

Our Extension to libfib: Fibertures

- libfib supports fibers but not futures
- Same safety and programmability downsides of using STL threads
- Fibertures
  - Defines an async task function that returns `std::futures`, uses fibers
  - Modifies libfib scheduler to support improved future synchronization

Fibertures Task Type

```
// in namespace fibertures
struct Task {
  // The callback function.
  std::function<result_t()> f;
    // The promise used to create and set the future.
  std::promise<result_t> p;
  // Constructor.
  Task(std::function<function_t>&& f, args_t... args)
    : f{std::bind(f, args...)}
  {}
};
```

Replacement for std::async(): fibertures::async()

```
// in namespace fibertures
std::future<result_t> async(function_t&& f, args_t... args)
{
  auto task = new Task{move(f), forward<args_t>(args)...};
  std::size_t task_address = (std::size_t)task;
  auto fiber_lambda = [](std::size_t task_address) {
    auto task = (Task<function_t, args_t>*)task_address;
    auto value = task->f();
    task->p.set_value(std::move(value));
    delete task;
  };
  auto future_result = task->p.get_future();
  worker::current().new_fiber(fiber_lambda, task_address);
  return future_result;
}
```

Capturing and Passing Parameters with Fibertures

Cannot pass lambdas and multiple arguments directly to libfib

- Supports a limited number of parameters (just one, in our port)
- Does not support lambdas with captures

Solution

- Capture parameters and store callback in a new `fibertures::Task`
- Convert task address to an integer type
- Pass task address into a capture-less lambda inside `fibertures::async()`
- During task execution, convert task address back into a task pointer and invoke the original callback

Source-to-source Transformations

- Designed to make using Fibertures with existing standard C++ trivial
- Currently applied manually but could be automated

Runtime Library Inclusion and Initialization

- Include the header `"fibertures.h"` in each source file containing a parallel async task
- In `main()`, initialize runtime with `worker::spawn_workers(nworkers)`
- `nworkers` could be determined based on hardware concurrency or chosen by the user

Asynchronous Call Transformations

- Transform calls to the parallel overloads of `std::async()` to calls to `fibertures::async()`
- Same function signature and return type as `std::async()`
- `fibertures::async()` does not support deferred evaluation
- Must not apply if tasks uses thread-local data

Asynchronous Call Transformations

Source Code

```
std::future<T> fut = std::async(f, ...);
```

```
std::future<T> fut = std::async(std::launch::async, f, ...);
```

```
std::future<T> fut = std::async
  (std::launch::async | std::launch::deferred, f, ...);
```

Transformed Code

```
std::future<T> fut = fibertures::async(f, ...);
```

Synchronization Transformations

- Need to prevent synchronization operations from blocking
- While future is not ready, yield current fiber and look for more work
- No worker thread is ever blocked unless there is no work to be done

Task Scheduling with Yield-loops

- Worker threads should perform useful work when available
- Want to avoid staying in the yield-loop waiting for a future to become unblocked
- libfib scheduler prioritizes doing local work over stealing
- Problem: A worker thread that generates a yield-loop never steals
- Solution: Modified libfib scheduler to prioritize stealing work

get() Transformation

Source Code

```
T val = fut.get();
```

Transformed Code

```
while (fut.wait_for(std::chrono::seconds(0))
       != std::future_status::ready) {
  worker::current().yield();
}
T val = fut.get();
```

wait() transformation.

Source Code

```
fut.wait();
```

Transformed Code

```
while (fut.wait_for(std::chrono::seconds(0))
        != std::future_status::ready) {
  worker::current().yield();
}
```

wait_for() transformation.

Source Code

```
future_status status = fut.wait_for(duration);
```

Transformed Code

```
future_status status = future_status::ready;
{ auto start = high_resolution_clock::now();
  while (fut.wait_for(std::chrono::seconds(0))
         != future_status::ready) {
    if (high_resolution_clock::now() - start > duration) {
      status = future_status::timeout; break;
    }
    worker::current().yield();
  } }
```

wait_until() Transformation

Source Code

```
future_status status = fut.wait_until(time_point);
```

Transformed Code

```
future_status status = std::future_status::ready;
while (fut.wait_for(std::chrono::seconds(0))
       != future_status::ready) {
  if (time_point::clock::now() >= time_point) {
    status = future_status::timeout;
    break;
  }
  worker::current().yield();
}
```

Handling Return Values

Three cases:

- If the return value is assigned to a variable in the source code, do the same in the transformed code
- If the return value of a synchronization operation is unused, omit the assignment
- If the return value is used in a temporary expression, introduce a new variable with an unused name

Transformation Example: Source Program

```
#include <future>
int f(); // Some lengthy computation
int main() {
  // Spawn a new thread to compute f().
  std::future<int> fut = std::async(std::launch::async, f);
  // Wait for the spawned thread to finish.
  fut.wait();
  return 0;
}
```

Transformation Example: Transformed Program

```
#include <future>
#include "fibertures.h"
int f(); // Some lengthy computation
int main() {
  // Spawn 8 worker threads.
  worker::spawn_workers(8);
  // Spawn a new fiber to compute f().
  std::future<int> fut = fibertures::async(f);
  // Wait for the spawned fiber to finish.
  while (fut.wait_for(std::chrono::seconds(0))
         != std::future_status::ready) {
    worker::current().yield();
  }
  return 0;
}
```

Micro-benchmark Results

Micro-benchmark: Task Creation Overhead

Measure the cost of `std::thread` and libfib fiber creation

```
constexpr int nthreads = 100000;
for (int i = 0; i < nthreads; ++i) {
  std::thread{[] {}}.detach();
}
```

```
constexpr int nthreads = 100000;
for (int i = 0; i < nthreads; ++i) {
  worker::current().new_fiber([](size_t) {}, 0);
}
```

Experimental Setup

All performance results obtained on Intel Ivy Bridge architecture

- 8 GB of memory
- Intel Core i7-3770K processor
- Four cores and eight hardware threads
- Default optimization level

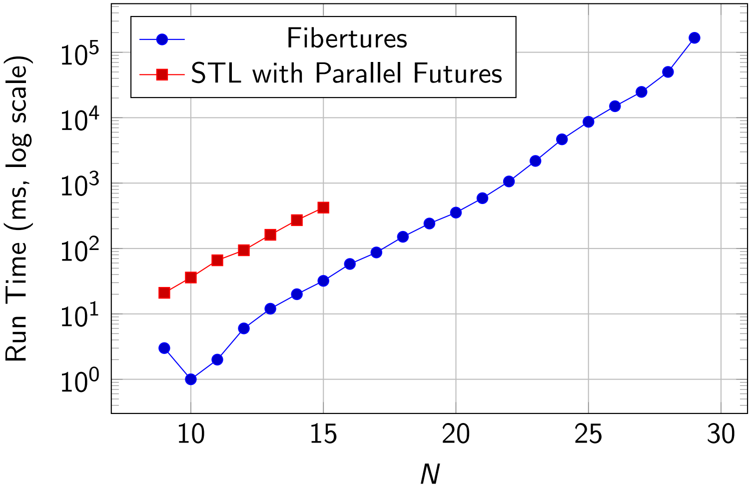
Task Creation Time for STL Threads and libfib Fibers

Task Type		Mean Task Creation Time (ns)
STL thread		3,230
libfib fiber	2 threads	185
	4 threads	262
	8 threads	332
	16 threads	655

Micro-benchmark: Parallel Recursive Fibonacci Function

- Creates an extremely large number of asynchronous tasks
- Not a realistic problem
- Good stress test for parallel runtime systems

Time to Compute the N^{th} Fibonacci Number using STL and Fibertures, Log Scale

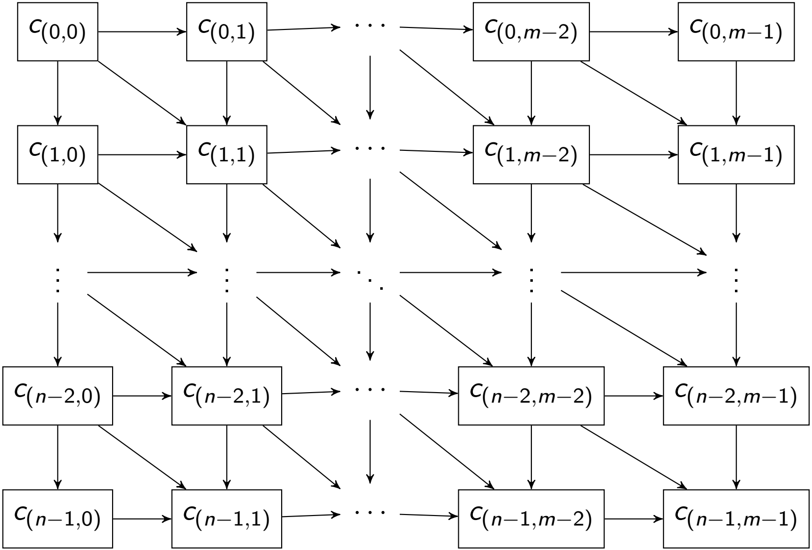


Case Study: Local Sequence Alignment using Smith-Waterman

Local Sequence Alignment using Smith-Waterman

- Identifies the maximally homologous subsequences between two input gene sequences
- Constructs a rectangular scoring matrix
- Non-border cells computed as a function of left, upper-left, and upper neighbors
- High degree of ideal parallelism

Smith-Waterman Inter-cell Data Dependence Graph



Execution Times of Smith-Waterman by Runtime System

Runtime System		Execution Time (ms) Mean	Execution Time (ms) Std. Dev.	Number of Tiles
Sequential STL		26,335	34	N/A
STL with Parallel Futures		6,349	18	552
HClib	1 thread	26,650	17	2,208
	2 threads	13,540	40	
	4 threads	7,113	83	
	8 threads	6,463	58	
	16 threads	7,126	221	
Fibertures	1 thread	25,510	11	552
	2 threads	13,153	64	
	4 threads	7,284	34	
	8 threads	6,218	26	
	16 threads	6,780	74	

Execution times of Smith-Waterman by Runtime System, 2,208 tiles

Runtime System		Execution Time (ms)	
		Mean	Std. Dev.
Sequential STL		26,335	34
Parallel STL		N/A	N/A
HClib	1 thread	26,650	17
	2 threads	13,540	40
	4 threads	7,113	83
	8 threads	6,463	58
	16 threads	7,126	221
Fibertures	1 thread	25,534	10
	2 threads	13,461	45
	4 threads	7,615	36
	8 threads	6,343	26
	16 threads	6,319	32

Related Work

Qthreads (`http://www.cs.sandia.gov/qthreads/`)

- Provides support for lightweight tasks in C, comparable to fibers
- Support the use of full/empty bits (FEBs) for synchronization
- Does not support futures but could be used as a building block for futures

Folly Futures (`https://github.com/facebook/folly/tree/master/folly/futures`)

- Promise and future library for C++11
- Supports callback chaining with `then()` and `onError()`
- The C++ standard does not currently support callback chaining; however, the Concurrency TS does support chaining
- Different API from `<future>`
- Requires user-specified `Executor` for async tasks
- Offers more control over execution policy but requires more manual effort

Boost Fiber (http://www.boost.org/doc/libs/1_64_0/libs/fiber/doc/html/fiber/overview.html)

- A fiber runtime that supports futures
- Future synchronization does not block the worker thread
- Different future type from `std::future`, but APIs are similar
- User can specify scheduler (defaults to round-robin)
- Provides moderate level of compatibility with existing STL-only code

HPX (`https://github.com/STEllAR-GROUP/hpx`)

- Distributed and intra-node parallel runtime library for C++
- High level of compatibility with STL and Boost
- Extends futures with continuation chaining and locality awareness
- Relatively easy to translate existing code to HPX

Conclusions and Future Work

Conclusions

- C++ must support expressive and efficient means of expressing parallelism
- C++ futures confer programmability and safety benefits but can have significant performance drawbacks
- Drawbacks particularly apparent in applications requiring large numbers of async tasks
- Third-party libraries using compiler transformations and/or a runtime scheduler can effectively solve these problems
- We implemented Fibertures to improve the performance of parallel futures in C++ through use of fibers
  - Performs well compared to the STL and other futures libraries in some benchmarks
  - Easy transition from STL to Fibertures due to matching APIs and source-to-source transformations

Future Work

- Fix libfib to support compilation under higher optimization levels and reevaluate performance of libraries
- Integrate dependences directly into fibers
- Automate source-to-source transformations using a compiler tool such as LibTooling
- Explore ways to infer the best stack size automatically, perhaps per call rather than per program

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