Boost Asynchronous

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Preface

Note: Asynchronous is not part of the Boost library. It is planed to be offered for Review at the end of 2013. At the moment it is still in heavy development.

Herb Sutter wrote in an article "The Free Lunch Is Over", meaning that developpers will be forced to learn to develop multi-threaded applications. This, however, brings a fundamental issue: multithreading is hard, it's full of ugly beasts waiting hidden for our mistakes: races, deadlocks, all kinds of subtle bugs. Worse yet, these bugs are hard to find because they are never reproducible when you are looking for them, which leaves us with backtrace analysis, and this is when we are lucky enough to have a backtrace in the first place.

This is not even the only danger. CPUs are a magnitude faster than memory, I/O operations, network communications, which all stall our programms and degrade our performance, which means long sessions with coverage or analysis tools.

Well, maybe the free lunch is not completely over yet, or at least maybe we can still get one a bit longer for a bargain. This is what Boost Asynchronous is helping solve.

Boost Asynchronous is a library making it easy to write asynchronous code similar to the Proactor pattern. To achieve this, it offers tools for asynchronous designs: ActiveObject, threadpools, servants, proxies, queues, algorithms, etc.

Asynchronous programming has the advantage of making it easier to design your code nonblocking, single-threaded while still getting your cores to work at full capacity. And all this while forgetting what a mutex is. Incorrect mutex usage is a huge source of bugs and Asynchronous helps you avoid them.

However, the goal of this library is not to help you write massively parallel code. There are other solutions for this. This library is for the other 99% of us who happen to work on 4-12 cores hardware because 1000 cores are not affordable, but would still like to get the best of it while avoiding ugly bugs, get better diagnostic of what our application is doing and planing ourselves what our cores are doing. Asynchronous is not:

- std/boost::async: both are asynchronous in a very limited way. One posts asynchronously some work, but then? Well, then the choice is between blocking for the future result (taboo) or polling from time to time, as in the (bad) old times. Furthermore, one has no control on the scheduler.
- Intel TBB: this is a wonderful parallel library. But it's not asynchronous as one needs to wait for the end of a parallel_ call. Sure, you have pipelines, but when your application is complex, good luck to understand the code. Again, one has limited control on the scheduler.
- N3428: this is an interesting approach as it was at least recognized that std::async is not asynchronous. So now, you get a kind of state machine hidden behind a .then, when_any, when_all, which are a poor man's state machines, besides ugly limitations like finding out which when_all threw an exception. When did we give up writing design diagrams to document and understand our code later? When a 15+ states state machine with guards, event deferring and control flow has to be written with .then, please don't ask me to review the code.

Let's have a quick look at code using futures and .then (taken from N3428):

```
future<int> f1 = async([]() { return 123; });
future<string> f2 = f1.then([](future<int> f) {return f.get().to_string();}); /
f2.get(); // just a "small get" at the end?
```

Saying that there is only a "small get" at the end is, for an application with real-time constraints, equivalent to saying at a lockfree conference something like "what is all the fuss about? Can't we just add a small lock at the end?". Just try it...

This brings us to a central point of Asynchronous: if we build a system with strict real-time constraints, there is no such thing as a small get(). We need to be able to react to any event in the system in a timely manner. And we can't affort to have lots of functions potentially waiting too long everywhere in our code. Therefore, .then is only good for an application of a few hunderds of lines. What about using a timed_wait instead? Nope. Either we wait too long before handling an error (this just limits the amount of time we wate waiting, that's all), or we wait not enough and we poll. In any case, while waiting, our thread cannot react to other events.

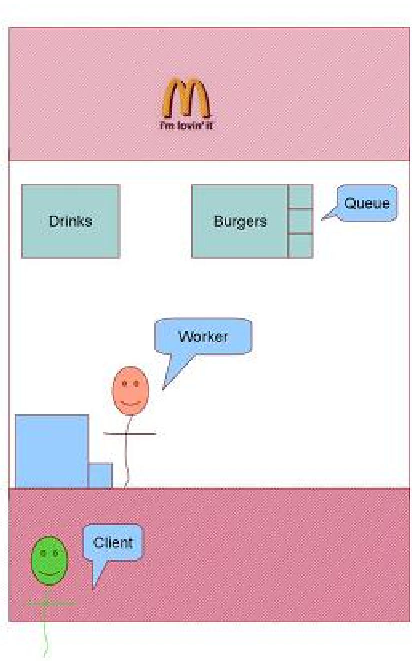
All these libraries also have the disadvantage of working with functions, not classes. But we, normal developers, do use classes. And we want them safe. And you can hardly make a class safe if you simply pass it to another thread. Consider the following example:

```
class Bad : public boost::signals::trackable
{
   int foo();
};
boost::shared_ptr<Bad> b;
future<int> f = async([b](){return b->foo()});
```

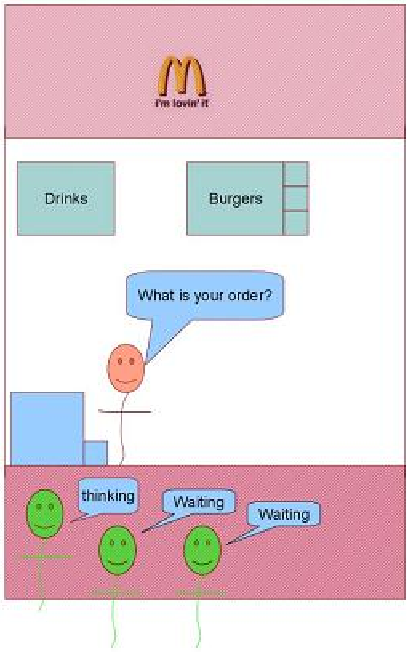
Now you have the ugly problem of not knowing in which thread Bad will be destroyed. And as it's pretty hard to have a thread-safe destructor, you find yourself with a race condition in it. Maybe you'll find a solution for signals, but are you sure nobody is ever going to do something dangerous in the destructor? This clearly is not thinking in the future sense.

Another particularity of Asynchronous is that it's not hiding anything: one gets to pick a pool for a particular application, choose how many threads are to be used, and the type of queue which best corresponds to the job to do, which allows finer tuning.

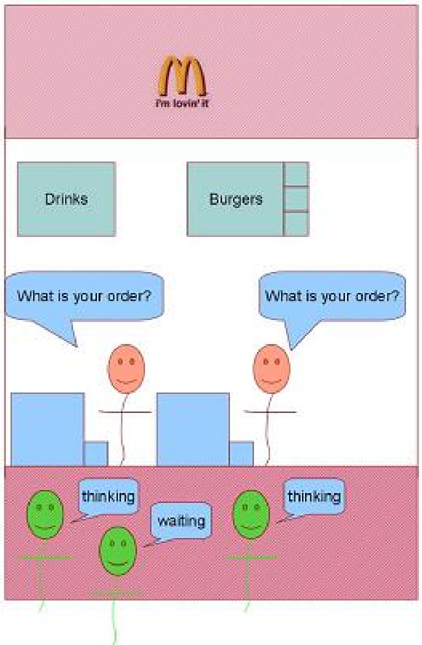
An image being more worth than thousand words, the following story will explain in a few minutes what Asynchronous is about. Consider some fast-food restaurant:



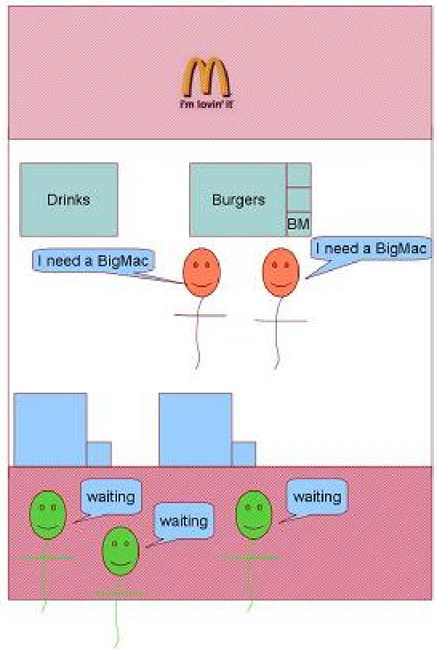
This restaurant has a single employee, Worker, delivers burgers through a burger queue and drinks. A Customer comes. Then another, who waits until the first customer is served.



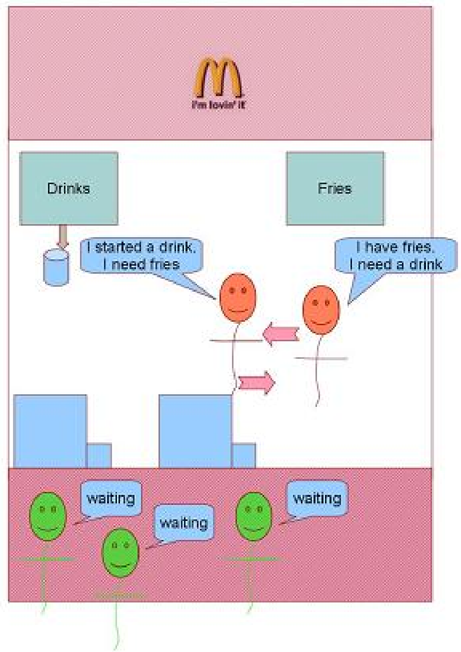
To keep customers happy by reducing waiting time, the restaurant owner hires a second employee:



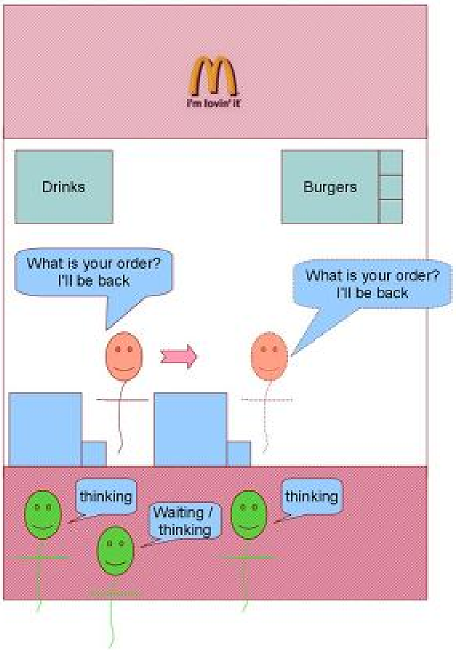
Unfortunately, this brings chaos in the restaurant. Sometimes, employes fight to get a burger to their own customer first:



And sometimes, they stay in each other's way:



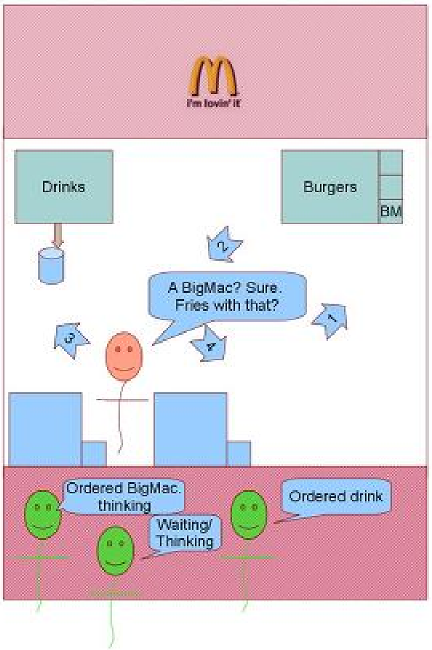
This clearly is a not an optimal solution. Not only the additional employee brings additional costs, but both employees now spend much more time waiting. It also is not a scalable solution if even more customers want to eat because it's lunch-time right now. Even worse, as they fight for resources and stay in each other's way, the restaurant now serves people less fast than before. Customers flee and the restaurant gets bankrupt. A sad story, isn't it? To avoid this, the owner decides to go asynchronous. He keeps a single worker, who moves from cash desk to cash desk:



The worker never waits because it would increase customer's waiting time. Instead, he runs from cash desks to the burger queue, beverage machine using a self-made strategy:

- ask what the customer wants and keep an up-to-date information of the customer's state.
- if we have another customer at a desk, ask what he wants. For both customers, remember the state of the order (waiting for customer choice, getting food, getting drink, delivering, getting payment, etc.)
- as soon as some new state is detected (customer choice, burger in the queue, drink ready), handle it.
- priorities are defined: start the longest-lasting tasks first, serve angry-looking customers first, etc.

The following diagram shows us the busy worker in action:



Of course the owner needs a worker who runs fast, and has a pretty good memory so he can remember what customers are waiting for.

This is what Asynchronous is for. A worker (thread) runs as long as there are waiting customers, following a precisely defined algorithm, and lots of state machines to manage the asynchronous behaviour. In case of customers, we could have a state machine: Waiting -> PickingMenu -> WaitingForFood -> Paying.

We also need some queues (Burger queue, Beverage glass positioning) and some Asynchronous Operation Processor (for example a threadpool made of workers in the kitchen), event of different types (Drinks delivery). Maybe you also want some work stealing (someone in the kitchen serving drinks as he has no more burger to prepare. He will be slower than the machine, but still bring some time gain).

To make this work, the worker must not block, never, ever. And whatever he's doing has to be as fast as possible, otherwise the whole process stalls.

Part I. Concepts

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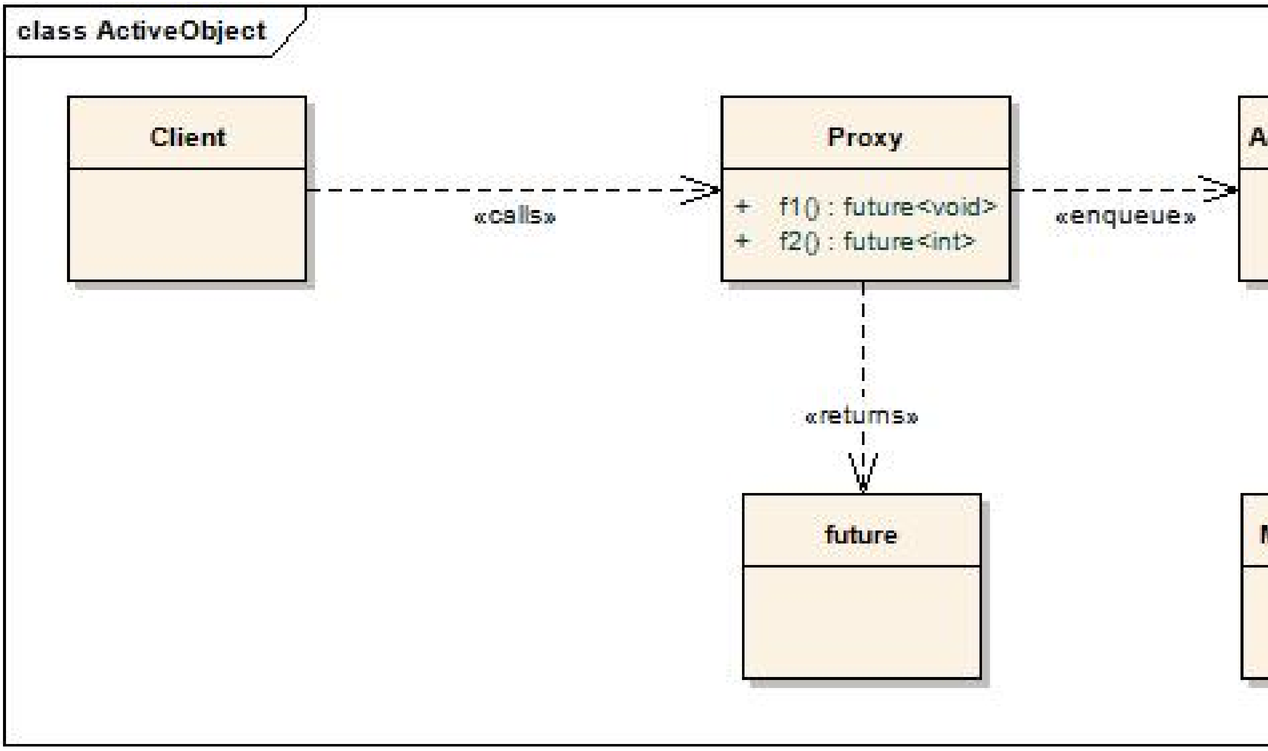
Chapter 1. Related designs: Active Object, Proactor

Active Object

Design



This simplified diagram shows one possible design variant of an Active Object pattern.

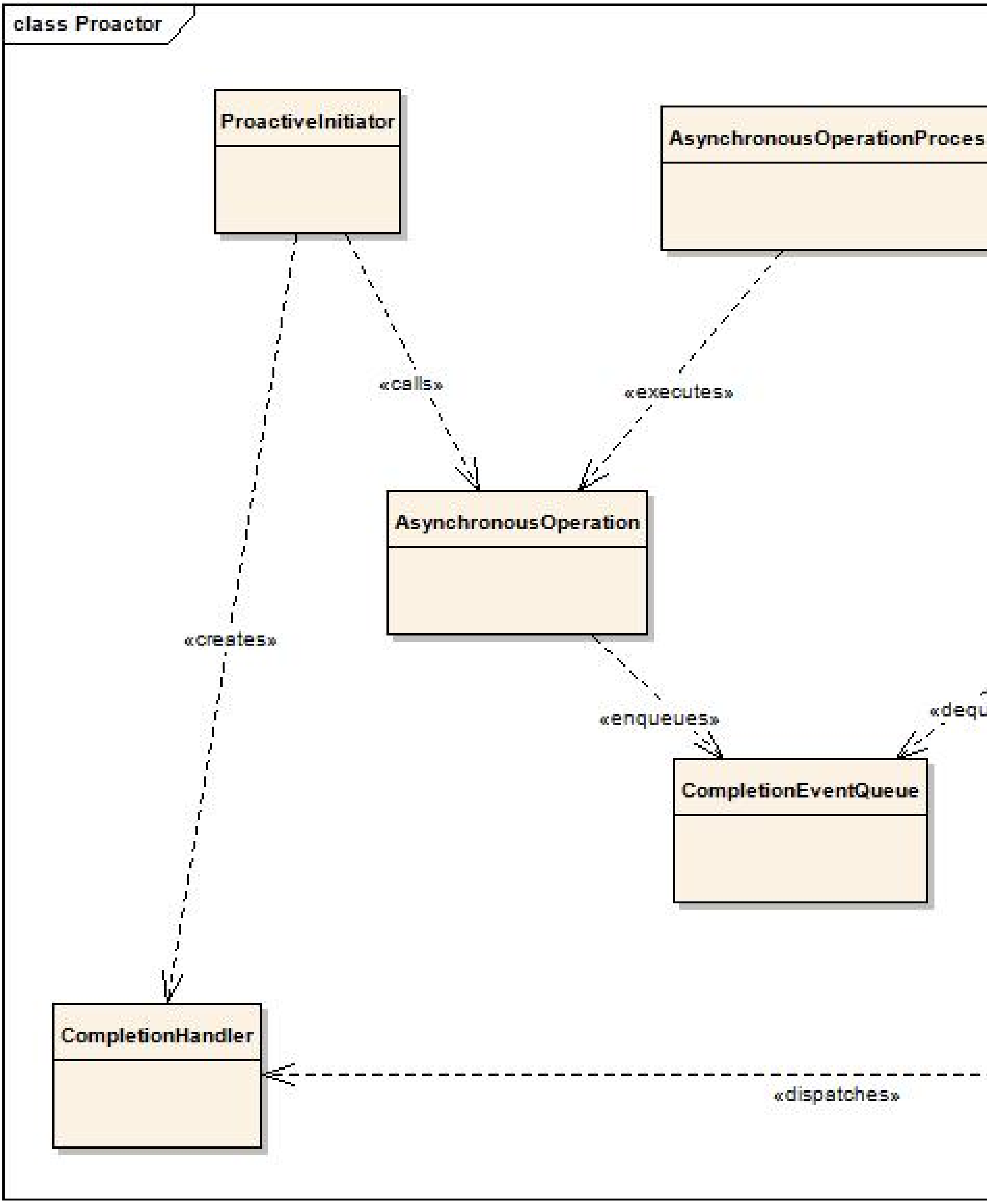
A thread-unsafe Servant is hidden behind a Proxy, which offers the same methods as the Servant itself. This Proxy is called by clients and delivers a future object, which will, at some later point, contain the result of the corresponding member called on the servant. The Proxy packs a MethodRequest corresponding to a Servant call into the ActivationQueue. The Scheduler waits permanently for MethodRequests in the queue, dequeues them, and executes them. As only one scheduler waits for requests, it serializes acces to the Servant, thus providing thread-safety.

However, this pattern presents some liabilities:

- Performance overhead: depending on the system, data moving and context switching can be a performance drain.
- Memory overhead: for every Servant, a thread has to be created, consuming resources.
- Usage: getting a future doesn't bring you as much asynchronous behaviour as one might think. Usually, docs tell you to do something else and check it later. But most cases simply mean that the client will earlier or later block until the future is ready. This also applies to std/boost::async.

Proactor

Design


class Proactor
ProactiveInitiator
AsynchronousOperationProces
«calls»
«executes»
AsynchronousOperation
«creates»
«enqueues»
«dequ
CompletionEventQueue
CompletionHandler
«dispatches»

TODO

Chapter 2. Features

Active Component

Extending Active Objects with more servants within a thread context

A commonly cited drawback of Active Objects is that it's awfully expensive. A thread per object is really a waste of ressources. Boost.Asynchronous extends this concept by allowing an unlimited number of objects to live within a single thread context, thus amortizing the costs.

This brings another difference with ActiveObjects. As many objects are potentially living in a thread "world", none should be allowed to process long-lasting tasks as it would reduce reactivity of the whole component. In this aspect, Asynchronous' philosophy is closer to a Proactor.

As long-lasting tasks do happen, Boost.Asynchronous provides several implementations of Threadpools and the infrastructure to make it safe to post work to threadpools and get aynchronously a callback. It also provides safe mechanisms to shutdown Active Components and Threadpools.

Shutting down

Shutting down a thread turns out to be harder in practice than expected, as shown by several posts of surprise when Boost.Thread tried to match the C++ Standard. Asynchronous hides all these ugly details. What users see is a proxy object, which can be shared by any number of objects executing within any number of threads.

When the last instance of the inner-ActiveComponent scheduler object is destroyed, the scheduler thread is stopped. When the last instance of a scheduler proxy is destroyed, the scheduler thread is joined. That's as simple as that.

Object lifetime

There are more subtle bugs when living in a multithreaded world. Consider the following class:

```
struct Unsafe
{
void foo()
{
  m_mutex.lock();
  // do something while locked
  m_mutex.unlock();
}
private:
void foobar()
{
  //do something while unlocked
}
boost::mutex m_mutex;
};
```

This is called a thread-safe interface pattern. What is public is locked, what is private no. Simple enough, right? Well, first you have the risk of deadlock if a private member calls a public one. Plus, let's face it, for any complex class, where there's a mutex, there is a race...

But even worse, this simply doesn't work. It supposes that a class can protect itself. Well, no, it can't. Why? You can't protect the destructor. If the object (and the mutex) gets destroyed when a thread waits for it in foo(), we're toast. Ok, then we can use a shared_ptr, and all is good, right? Then you have no destructor if someone keeps the object alive. Then you still have a risk of a signal, callback, etc. What you need is protect your object with a shared_ptr and have no other way to access the object. Asynchronous provides just this.

There are more lifetime issues, even without mutexes. If you have ever used Boost.Asio, a common mistake and an easy one is when a callback is called in the proactor thread after an asynchronous operation, but the object called is long gone and the callback invalid. Asynchronous provides a `trackable_servant` (TODO link) which makes sure that a callback is not called if the object which called the asynchronous operation is gone. It also prevents a task posted in a threadpool to be called if this condition occurs.

Interrupting

Or how to catch back if you're drowning.

Let's say you posted so many tasks to your threadpool that all your cores are full, still, your application is slipping more and more behind plan. You need to give up some tasks to catch back a little.

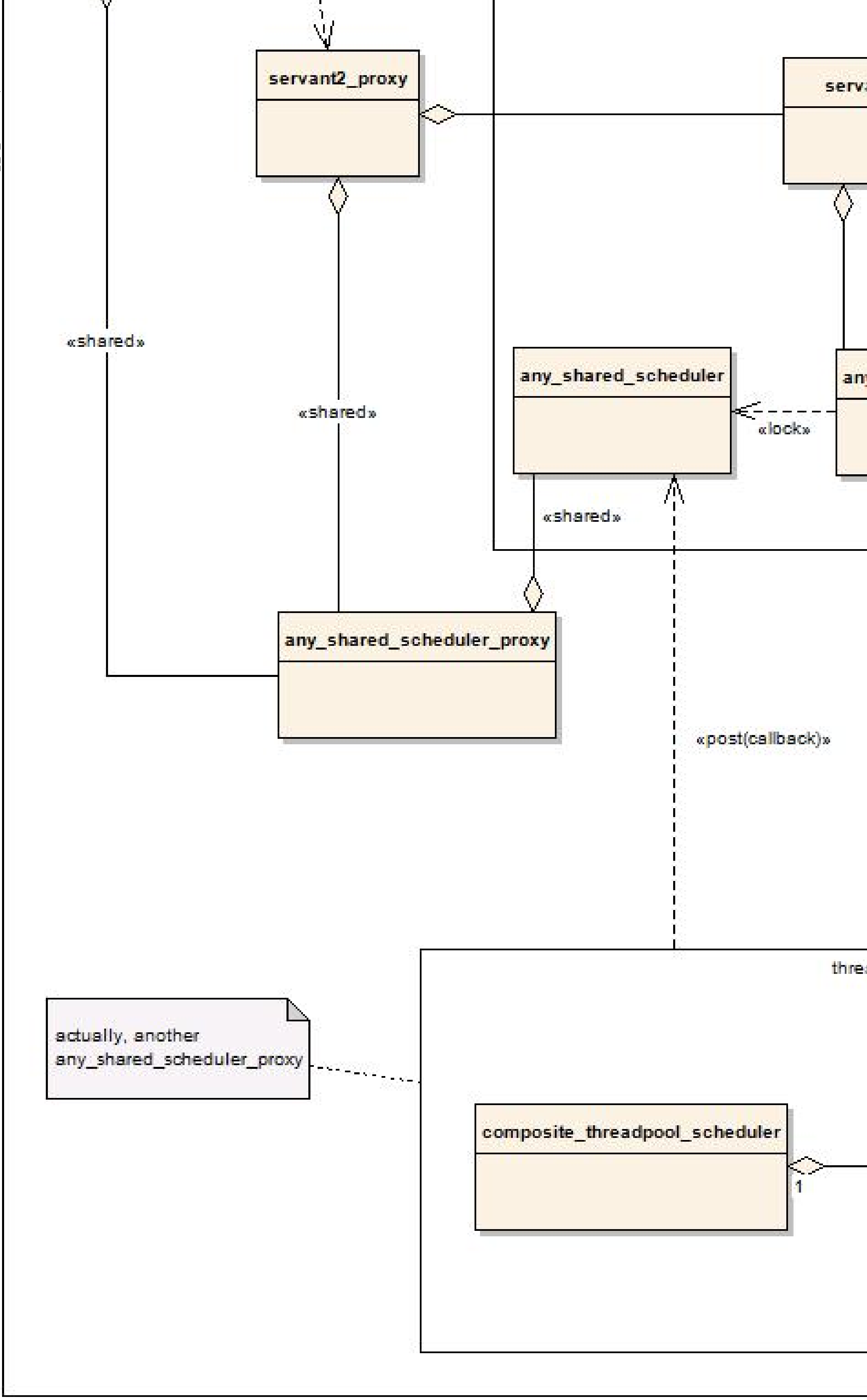
Asynchronous can give you an interruptible cookie when you post a task to a scheduler, and you can use it to stop a posted task. If not running yet, the task will not start, if running, it will stop at the next interruption point, which are documented in the Boost.Thread documentation [http://www.boost.org/doc/libs/1_54_0/doc/html/thread/thread_management.html#thread.thread_management.tutorial.interruption].

Diagnostics

Finding out how good your software is doing is not an easy task. You need to add lots of logging to find out which function call takes too long and becomes a bottleneck. Finding out the minimum required hardware to run your application is even harder.

Asynchronous design helps here too. By logging the required time and the frequency of tasks, it is easy to find out how many cores are needed. Bottlenecks can be found by logging what the Active Component is doing and how long. Finally, designing the asynchronous Active Component as state machines and logging state changes will allow a better understanding of your system and make visible potential for concurrency. Even for non-parallel algorithms, finding out, using a state machine, the earliest point a task can be thrown to a threadpool will give some easy concurrency. Throw enough tasks to the threadpool and manage this with a state machine and you might use your cores with little effort. In a second step, it is still possible to parallelize algorithms and profit from smaller tasks divided among more cores. To find out if a task is small enough to be parallelized, look at the diagnostics.

Desig


servant2_proxy
«shared»
«shared»
any_shared_scheduler
«lock»
«shared»
any_shared_scheduler_proxy
«post(callback)»
actually, another
any_shared_scheduler_proxy
composite_threadpool_scheduler
1

This diagram shows an overview of the design behind Asynchronous. A Servant object lives in a single-theaded world, communicating with the outside world only with one or several queues, from which the single-threaded scheduler pops tasks. Tasks are pushed by calling a member on a proxy object.

Like an Active Object, a client uses a proxy (a shared object type), which offers the same members as the real servant, with the same parameters, the only difference being the return type, a boost::future<R>, with R being the return type of the servant's member. All calls to a servant from the client side are posted, which includes the servant constructor and destructor. When the last instance of a servant is destroyed, be it used inside the Active Component or outside, the servant destructor is posted.

any_shared_scheduler is the part of the Active Object scheduler living inside the Active Component. Servants do not hold it directly but hold an any_weak_scheduler instead. The library will use it to create a posted callback when a task executing in a worker threadpool is completed.

Shutting down an Active Component is done automatically by not needing it. It happens in the following order:

- While a servant proxy is alive, no shutdown
- When the last servant proxy goes out of scope, the servant destructor is posted.
- if jobs from servants are running in a threadpool, they get a chance to stop earlier by running into an interruption point or will not even start.
- threadpool(s) is (are) shut down.
- The Active Component scheduler is stopped and its thread terminates.
- The last instance of any_shared_scheduler_proxy goes out of scope with the last servant proxy and joins.

Part II. User Guide

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Chapter 3. Using Asynchronous

Hello, asynchronous world

The following code shows a very basic usage (a complete example here [examples/example_post_future.cpp]), this is not really asynchronous yet:

```
#include <boost/asynchronous/scheduler/threadpool_scheduler.hpp>
#include <boost/asynchronous/queue/threadsafe_list.hpp>
#include <boost/asynchronous/scheduler_shared_proxy.hpp>
#include <boost/asynchronous/post.hpp>
struct void_task
{
    void operator()()const
    {
        std::cout << "void_task called" << std::endl;
    }
};
struct int_task
{
    int operator()()const
    {
        std::cout << "int_task called" << std::endl;
        return 42;
    }
};

// create a threadpool scheduler with 3 threads and communicate with it using a
// we use auto as it is easier than boost::asynchronous::any_shared_scheduler_p
auto scheduler = boost::asynchronous::create_shared_scheduler_proxy(
                            new boost::asynchronous::threadpool_scheduler<
                                boost::asynchronous::threadsafe_list<> >(3));
// post a simple task and wait for execution to complete
boost::shared_future<void> fuv = boost::asynchronous::post_future(scheduler, vo
fuv.get();
// post a simple task and wait for result
boost::shared_future<int> fui = boost::asynchronous::post_future(scheduler, int
int res = fui.get();
```

Of course this works with C++11 lambdas:

```
auto scheduler = boost::asynchronous::create_shared_scheduler_proxy(
                            new boost::asynchronous::threadpool_scheduler<
                                boost::asynchronous::threadsafe_list<> >(3));
// post a simple task and wait for execution to complete
boost::shared_future<void> fuv =
                boost::asynchronous::post_future(scheduler, [](){std::cout << "
fuv.get();
// post a simple task and wait for result
boost::shared_future<int> fui =
                boost::asynchronous::post_future(scheduler, [](){std::cout << "
int res = fui.get();
```

boost::asynchronous::post_future posts a piece of work to a threadpool scheduler with 3 threads and using a simple threadsafe_list. We get a boost::future<the type of the task return type>.

This looks like std::async, but we're just getting started. Let's move on to something more useful.

A servant proxy

We now want to create a single-threaded scheduler, populate it with some servant(s), and exercise some members of the servant from an outside thread. We first need a servant:

```
struct Servant
{
    // optional: the servant has such an easy constructor, no need to post it
    typedef int simple_ctor;
    Servant(int data): m_data(data){}
    int doIt()const
    {
        std::cout << "Servant::doIt with m_data:" << m_data << std::endl;
        return 5;
    }
    void foo(int& i)const
    {
        std::cout << "Servant::foo with int:" << i << std::endl;
        i = 100;
    }
    void foobar(int i, char c)const
    {
        std::cout << "Servant::foobar with int:" << i << " and char:" << c <<std
    }
    int m_data;
};
```

We now create a proxy type to be used in other threads:

```
class ServantProxy : public boost::asynchronous::servant_proxy<ServantProxy,Serv
{
public:
    // forwarding constructor. Scheduler to servant_proxy, followed by arguments
    template <class Scheduler>
    ServantProxy(Scheduler s, int data):
        boost::asynchronous::servant_proxy<ServantProxy,Servant>(s, data)
    {}
    // the following members must be available "outside"
    // foo and foobar, just as a post (no interesting return value)
    BOOST_ASYNC_POST_MEMBER(foo)
    BOOST_ASYNC_POST_MEMBER(foobar)
    // for doIt, we'd like a future
    BOOST_ASYNC_FUTURE_MEMBER(doIt)
};
```

Let's use our newly defined proxy:

```
int something = 3;
{
    // with c++11
    auto scheduler = boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::single_thread_scheduler<
                          boost::asynchronous::threadsafe_list<> >);

    {
        // arguments (here 42) are forwarded to Servant's constructor
```

```
        ServantProxy proxy(scheduler,42);
        // post a call to foobar, arguments are forwarded.
        proxy.foobar(1,'a');
        // post a call to foo. To avoid races, the reference is ignored.
        proxy.foo(something);
        // post and get a future because we're interested in the result.
        boost::shared_future<int> fu = proxy.doIt();
        std::cout<< "future:" << fu.get() << std::endl;
    }// here, Servant's destructor is posted
}// scheduler is gone, its thread has been joined
std::cout<< "something:" << something << std::endl; // something was not change
```

We can call members on the proxy, almost as if they were called on Servant. The library takes care of the posting and forwarding the arguments. When required, a future is returned. Stack unwinding works, and when the servant proxy goes out of scope, the servant destructor is posted. When the scheduler goes out of scope, its thread is stopped and joined. The queue is processed completely first. Of course, as many servants as desired can be created in this scheduler world. Please have a look at the complete example [examples/example_simple_servant.cpp].

Using a threadpool

If you remember the principles of Asynchronous, blocking a single-thread scheduler is taboo as it blocks the thread doing all the management of a system. But what to do when one needs to execute long tasks? Asynchronous provides a whole set of threadpools. A servant posts something to a threadpool, provides a callback, then gets a result. Wait a minute. Callback? Is this not thread-unsafe? Why not threadpools with futures, like usual? Because in a perfectly asynchronous world, waiting for a future means blocking a servant scheduler. One would argue that it is possible not to block on the future, and instead ask if there is a result. But then, what if not? Is the alternative to poll? Like in the "good" all times?

Ok, ok, we buy the story with the future, but what about thread-safety? Asynchronous takes care of this. A callback is never called from a threadpool, but instead posted back to the queue of the scheduler which posted the work. All the servant has to do is to do nothing and wait until the callback is executed. Clearly, this brings some new challenges as the flow of control gets harder to follow. This is why a servant is often written using state machines. The (biased) author suggests to have a look at the Meta State Machine library [http://svn.boost.org/svn/boost/trunk/libs/msm/doc/HTML/index.html] , which plays nicely with Asynchronous.

But then, as someone at the back of the room shouts, I'll get the usual proactor-class issues of crashing when the servant has long been destroyed when the callback is posted. No you won't. Asynchronous provides `trackable_servant` which will ensure that a callback is not called if the servant is gone. Better even, if the servant has been destroyed, an unstarted posted task will not be executed.

Again, from the back of the room comes an issue. And what if I post a task, say a lambda, which captures a shared_ptr to an object per value, and this object is a boost::signal? Then when the task object has been executed and is destroyed, I'll get a race on the signal deregistration. Good point, but again no. Asynchronous ensures that a task created within a scheduler context gets destroyed in this context.

This is about the best protection you can get. What Asynchronous cannot protect you from are self-made races within a task (if you post a task with a pointer to the servant, you're on your own and have to protect your servant). A good rule of thumb is to consider data passed to a task as moved. To support this, Asynchronous does not copy tasks but move them.

Armed with these protections, let's give a try to a threadpool, starting with the most basic one, `threadpool_scheduler` (more to come):

```
struct Servant : boost::asynchronous::trackable_servant<>
{
```

```
    Servant(boost::asynchronous::any_weak_scheduler<> scheduler)
        : boost::asynchronous::trackable_servant<>(scheduler,
                                                // threadpool with 3 threads and
                                                boost::asynchronous::create_shar
                                                    new boost::asynchronous::thr
                                                            boost::asynchronous:
    // call to this is posted and executes in our (safe) single-thread schedule
    void start_async_work()
    {
       //ok, let's post some work and wait for an answer
       post_callback([](){std::cout << "Long Work" << std::endl;}, //work
                     [this](){...}// callback. Safe to use this as if callback i
                     );
    }
    };
```

We now have a servant, ready to be created in its own thread, which posts some long work to a 3 thread-threadpool and gets a callback, but only if still alive. Similarly, the long work will be executed by the threadpool only if Servant is alive. Everything else stays the same, one creates a proxy for the servant and posts calls to its members, so we'll skip it for conciseness, the complete example can be found here [examples/example_post_trackable_threadpool.cpp].

A servant using another servant proxy

Often, in a layered design, you'll need that a servant in a single-threaded scheduler calls a member of a servant living in another one. And you'll want to get a callback, not a future like in our previous example, because you absolutely refuse to block waiting for a future (and you'll be very right of course!). Ideally, except for main(), you won't want any of your objects to wait for a future. There is another servant_proxy macro for this, `BOOST_ASYNC_UNSAFE_MEMBER`(unsafe because you get no thread-safety from if and you'll take care of this yourself, or better, `trackable_servant` will take care of it for you):

```
// Proxy for a basic servant
class ServantProxy : public boost::asynchronous::servant_proxy<ServantProxy,Ser
{
public:
    template <class Scheduler>
    ServantProxy(Scheduler s, int data):
        boost::asynchronous::servant_proxy<ServantProxy,Servant>(s, data)
    {}
    BOOST_ASYNC_UNSAFE_MEMBER(foo)
    BOOST_ASYNC_UNSAFE_MEMBER(foobar)
};

// Servant using the first one
struct Servant2 : boost::asynchronous::trackable_servant<>
{
    Servant2(boost::asynchronous::any_weak_scheduler<> scheduler,ServantProxy w
        :boost::asynchronous::trackable_servant<>(scheduler)
        ,m_worker(worker) // the proxy allowing access to Servant
    boost::shared_future<void> doIt
    {
         call_callback(m_worker.get_proxy(), // Servant's outer proxy, for post
                       m_worker.foo(), // what we want to call on Servant
                      // callback functor, when done.
                      [](boost::shared_future<int> result){...} );
    }
};
```

Call of `foo()` will be posted to `Servant`'s scheduler, and the callback lambda will be posted to `Servant2` when completed. All this thread-safe of course. Destruction is also safe. When `Servant2` goes out of scope, it will shutdown `Servant`'s scheduler, then will his scheduler be shutdown (provided no more object is living there), and all threads joined. The complete example [examples/example_two_simple_servants.cpp] shows a few more calls too.

Interrupting tasks

Imagine a manager object (a state machine for example) posted some long-lasting work to a threadpool, but this long-lasting work really takes too long. As we are in an asynchronous world and non-blocking, the manager object realizes there is a problem and decides the task must be stopped otherwise the whole application starts failing some real-time constraints. This is also possible, one uses another version of posting, gets some handle, on which one can require interruption. As Asynchronous does not kill threads, it means that we'll have to use one of Boost.Thread predefined interruption points. Supposing we have well-behaved tasks, they will be interrupted at the next interruption point if they started, or if they did not start yet because they are waiting in a queue, then they will never start. In this example [examples/example_interrupt.cpp], we have very little to change but the post call:

```
struct Servant : boost::asynchronous::trackable_servant<>
{
     ... // as usual
    void start_async_work()
    {
        // start long interruptible tasks
        // we get an interruptible handler representing the task
        boost::asynchronous::any_interruptible interruptible =
        interruptible_post_callback(
                // interruptible task
               [](){
                    std::cout << "Long Work" << std::endl;
                    boost::this_thread::sleep(boost::posix_time::milliseconds(1
               ,
               // callback functor.
               [](boost::shared_future<void> ){std::cout << "Callback will most
        );
        // let the task start (not sure but likely)
        // if it had no time to start, well, then it will never.
        boost::this_thread::sleep(boost::posix_time::milliseconds(100));
        // actually, we changed our mind and want to interrupt the task
        interruptible.interrupt();
        // the callback will never be called as the task was interrupted
    }
};
```

Logging tasks

Developers are notoriously famous for being bad at guessing which part of their code is inefficient or has potential for long execution time. This is bad in itself, but even worse for a control class like our post-callback servant as it reduces responsiveness. Knowing how long a posted call or a callback lasts is therefore very useful. Knowing how long take tasks executing in the threadpools is also essential to plan what hardware one needs for an application(4 cores? Or 100?). We need to know what our program is doing. Asynchronous provides some logging per task to help there. Let's have a look at some code. It's also time to start using our template parameters, in case you wondered why they are here.

```
// we will be using loggable jobs internally
typedef boost::asynchronous::any_loggable<boost::chrono::high_resolution_clock>
```

```
// the type of our log
typedef std::map<std::string,std::list<boost::asynchronous::diagnostic_item<boos
// we log our scheduler and our threadpool scheduler (both use servant_job)
struct Servant : boost::asynchronous::trackable_servant<servant_job,servant_job
{
    Servant(boost::asynchronous::any_weak_scheduler<servant_job> scheduler) //s
        : boost::asynchronous::trackable_servant<servant_job,servant_job>(sched
                                                boost::asynchronous::create_shar
                                                    // threadpool with 3 threads
                                                    // Furthermore, it logs post
                                                    new boost::asynchronous::thr
                                                            //servant_job is our
                                                            boost::asynchronous:
    void start_async_work()
    {
         post_callback(
               // task posted to threadpool
               [](){...},
               // the lambda calls Servant, just to show that all is safe, Serv
               [this](boost::shared_future<int> res){...},// callback functor.
               // the task / callback name for logging
               "int_async_work"
        );
    }
    // we happily provide a way for the outside world to know what our threadpo
    // get_worker is provided by trackable_servant and gives the proxy of our t
    diag_type get_diagnostics() const
    {
        return (*get_worker()).get_diagnostics();
    }
};
```

The proxy is also slightly different, as it uses a LOG macro and an argument representing the name of the task.

```
class ServantProxy : public boost::asynchronous::servant_proxy<ServantProxy,Ser
{
public:
    template <class Scheduler>
    ServantProxy(Scheduler s):
        boost::asynchronous::servant_proxy<ServantProxy,Servant,servant_job>(s)
    {}
    // the _LOG macros do the same as the others, but take an extra argument, t
    BOOST_ASYNC_FUTURE_MEMBER_LOG(start_async_work,"proxy::start_async_work")
    BOOST_ASYNC_FUTURE_MEMBER_LOG(get_diagnostics,"proxy::get_diagnostics")
    };
```

We now can get diagnostics from both schedulers, the single-threaded and the threadpool (as external code has no access to it, we ask Servant to help us there through a get_diagnostics() member).

```
// create a scheduler with logging
auto scheduler = boost::asynchronous::create_shared_scheduler_proxy(
                                new boost::asynchronous::single_thread_schedule
                                    boost::asynchronous::threadsafe_list<servan
// create a Servant
ServantProxy proxy(scheduler);
...
// let's ask the single-threaded scheduler what it did.
diag_type single_thread_sched_diag = (*scheduler).get_diagnostics();
```

```
for (auto mit = single_thread_sched_diag.begin(); mit != single_thread_sched_di
{
     std::cout << "job type: " << (*mit).first << std::endl;
     for (auto jit = (*mit).second.begin(); jit != (*mit).second.end();++jit)
     {
          std::cout << "job waited in us: " << boost::chrono::nanoseconds((*jit
          std::cout << "job lasted in us: " << boost::chrono::nanoseconds((*jit
          std::cout << "job interrupted? "  << std::boolalpha << (*jit).is_inte
     }
     }
```

It goes similarly with the threapool scheduler, with the slight difference that we ask the Servant to deliver diagnostic information through a proxy member. The complete example [examples/example_log.cpp] shows all this, plus an interrupted job (you might have noticed in the previous listing that a diagnostic offers an `is_interrupted` member).

Queue container with priority

Sometimes, all jobs posted to a scheduler do not have the same priority. For threadpool schedulers, `composite_threadpool_scheduler` is an option. For a single-threaded scheduler, Asynchronous does not provide a priority queue but a queue, which itself contains any number of queues, of different type if needed. This has several advantages:

- Priority is defined simply by posting to the queue with the desired priority, so there is no need for expensive priority algorithms.
- Ones gets also reduced contention if many threads of a threadpool post something to the queue of a single-threaded scheduler. If no priority is defined, one queue will be picked, according to a configurable policy.
- It is possible to mix queues to get the best of each.
- One can build a queue container of queue containers, etc.

Note: This applies of course to any scheduler. We'll start with single-threaded schedulers used by managing servants for simplicity, but it is possible to have composite schedulers using queue containers for finest granularity and least contention.

First, we need to create a single-threaded scheduler with several queues for our servant to live in, for example, one threadsafe list and and lockfree queues:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
                           boost::asynchronous::create_shared_scheduler_proxy(
                                new boost::asynchronous::single_thread_schedule
                                          boost::asynchronous::any_queue_containe
                        (boost::asynchronous::any_queue_container_config<boost:
                         boost::asynchronous::any_queue_container_config<boost:
                         ));
```

`any_queue_container` takes as constructor arguments a variadic sequence of `any_queue_container_config`, with a queue type as template argument, and in the constructor the number of objects of this queue (in the above example, one `threadsafe_list` and 3 `lockfree_queue` instances, then the parameters that these queues require in their constructor (100 is the capacity of the underlying `boost::lockfree_queue`). This means, that our `single_thread_scheduler` has 4 queues:

- a threadsafe_list at index 1
- lockfree queues at indexes 2,3,4

- >= 4 means the queue with the least priority.
- 0 means "any queue" and is the default

The scheduler will handle these queues as having priorities: as long as there are work items in the first queue, take them, if there are no, try in the second, etc. If all queues are empty, the thread gives up his time slice and sleeps until some work item arrives. If no priority is defined by posting, a queue will be chosen (by default randomly, but you can configure this with a policy). This has the advantage of reducing contention of the queue, even when not using priorities. The servant defines the priority of the tasks it provides. While this might seem surprising, it is a design choice to avoid someone using a servant proxy interface to think about it, as you will see in the second listing. To define a priority for a servant proxy, there is a second field in the macros:

```
class ServantProxy : public boost::asynchronous::servant_proxy<ServantProxy,Serv
{
public:
    template <class Scheduler>
    ServantProxy(Scheduler s):
        boost::asynchronous::servant_proxy<ServantProxy,Servant>(s)
    {}
    BOOST_ASYNC_SERVANT_POST_CTOR(3)
    BOOST_ASYNC_SERVANT_POST_DTOR(4)
    BOOST_ASYNC_FUTURE_MEMBER(start_async_work,1)
};
```

BOOST_ASYNC_FUTURE_MEMBER and other similar macros can be given an optional priority parameter, in this case 1, which is our threadsafe list. Notice how you can then define the priority of the posted servant constructor and destructor.

```
ServantProxy proxy(scheduler);
                boost::shared_future<boost::shared_future<int> > fu = proxy.sta
```

Calling our proxy member stays unchanged because the macro defines the priority of the call.

We also have an extended version of `post_callback`, called by a servant posting work to a threadpool:

```
post_callback(
               [](){return 42;}// work
                ,
               [this](boost::shared_future<int> res){}// callback functor.
               ,"",
               2,2
               );
```

Note the two added priority values: the first one for the task posted to the threadpool, the second for the priority of the callback posted back to the servant scheduler. The string is the log name of the task, which we choose to ignore here.

The priority is in any case an indication, the scheduler is free to ignore it if not supported. In the example [examples/example_queue_container.cpp], the single threaded scheduler will honor the request, but the threadpool has a normal queue and cannot honor the request, but a threadpool with an `any_queue_container` or a `composite_threadpool_scheduler` can. The same example [examples/example_queue_container_log.cpp] can be rewritten to make use of the logging mechanism.

`any_queue_container` has two template arguments. The first, the job type, is as always, a callable (`any_callable`) job. The second is the policy which Asynchronous usses to find the desired queue for a job. The default is `default_find_position`, which is as described above, 0 means any position, all other values map to a queue, priorities >= number of queues means last queue. Any position is by default random (`default_random_push_policy`), but you might pick `sequential_push_policy`, which keeps an atomic counter and always adds to the next queue.

If your idea is to build a queue container of queue containers, you'll probably want to provide your own policy.

Multiqueue Schedulers' priority

TODO

Threadpool Schedulers with several queues

A queue container has advantages (different queue types, priority for single threaded schedulers) but also disadvantages (takes jobs from one end of the queue, which means potential cache misses, more typing work). If you don't need different queue types for a threadpool but want to reduce contention, multiqueue schedulers are for you. A normal `threadpool_scheduler` has x threads and one queue, serving them. A `multiqueue_threadpool_scheduler` has x threads and x queues, each serving a worker thread. Each thread looks for work in its queue. If it doesn't find any, it looks for work in the previous one, etc. until it finds one or inspected all the queues. As all threads steal from the previous queue, there is little contention. The construction of this threadpool is very similar to the simple `threadpool_scheduler`:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                // 4 threads and 4 lockfree queues of 10 capacity
                new boost::asynchronous::multiqueue_threadpool_scheduler<boost:
```

The first argument is, as usual, the number of worker threads, which is at the same time the number of queues. As for every scheduler, if the queue constructor takes arguments, they come next and are forwarded to the queue.

This is the advised scheduler for standard cases as it offers lesser contention and task stealing between the queues it uses for task transfer.

There is a limitation, these schedulers cannot have 0 thread like their single-queue counterparts.

composite_threadpool_scheduler

When a project becomes more complex, having a single threadpool for the whole application does not offer enough flexibility in load planning. It is pretty hard to avoid either oversubscription (more busy threads than available hardware threads) or undersubscription. One would need one big threadpool with exactly the number of threads available in the hardware. Unfortunately, if we have a hardware with, say 12 hardware threads, parallelizing some work using all 12 might be slowlier than using only 8. One would need different threadpools of different number of threads for the application. This, however, has the serious drawback that there is a risk that some threadpools will be in overload, while others are out of work unless we have work stealing between different threadpools.

The second issue is task priority. One can define priorities with several queues or a queue container, but this ensures that only highest priority tasks get executed if the system is coming close to overload. Ideally, it would be great if we could decide how much compute power we give to each task type.

This is what `composite_threadpool_scheduler` solves. This pool supports, like any other pool, the `any_shared_scheduler_proxy`concept so you can use it in place of the ones we used so far. The pool is composed of other pools (`any_shared_scheduler_proxy` pools). It implements work stealing between pools if a) the pools support it and b) the queue of a pool also does. For example, if we define as worker of a servant inside a single-threaded scheduler:

```
// create a composite threadpool made of:
```

```
// a multiqueue_threadpool_scheduler, 1 thread, with a lockfree_queue of capaci
// This scheduler does not steal from other schedulers, but will lend its queue
boost::asynchronous::any_shared_scheduler_proxy<> tp = boost::asynchronous::cre
              new boost::asynchronous::multiqueue_threadpool_scheduler<boost::a

// a stealing_multiqueue_threadpool_scheduler, 3 threads, each with a threadsaf
// this scheduler will steal from other schedulers if it can. In this case it w
boost::asynchronous::any_shared_scheduler_proxy<> tp2 = boost::asynchronous::cr
                   new boost::asynchronous::stealing_multiqueue_threadpool_sch

// a multiqueue_threadpool_scheduler, 4 threads, each with a lockfree_spsc_queu
// this works because there will be no stealing as the queue can't, and only th
boost::asynchronous::any_shared_scheduler_proxy<> tp3 = boost::asynchronous::cr
              new boost::asynchronous::multiqueue_threadpool_scheduler<boost::a

// create a composite pool made of the 3 previous ones
boost::asynchronous::any_shared_scheduler_proxy<> tp_worker =
            boost::make_shared<boost::asynchronous::composite_threadpool_sched
```

We can use this pool:

- As a big worker pool. In this case, the priority argument we use for posting refers to the (1-based) index of the subpool (post_callback(func1,func2,"task name",**1**,0);). "1" means post to the first pool. But the second pool could steal the work.
- As a pool container, but different parts of the code will get to see only the subpools. For example, the pools tp, tp2 and tp3 can still be used independently as a worker pool. Calling composite_threadpool_scheduler<>::get_scheduler(std::size_t index_of_pool) will also give us the corresponding pool (1-based, as always).

A good example of why to use this pool is if you have a threadpool for an asio-based communication. Using such a pool inside the composite pool will allow the threads of this pool to help (steal) other pools if they have nothing to do.

Stealing is done with priority. A stealing poll first tries to steal from the first pool, then from the second, etc.

The following example [examples/example_composite_threadpool.cpp] shows a complete servant implementation, and the ASIO section will show how an ASIO pool can steal (TODO link).

The threadpool schedulers we saw so far are not stealing from other pools. The single-queue schedulers are not stealing, and the multiqueue schedulers steal from the queues of other threads of the same pool. The stealing schedulers usually indicate this by appending a `stealing_` to their name:

- `stealing_threadpool_scheduler` is a `threadpool_scheduler` which steals from other pools.
- `stealing_multiqueue_threadpool_scheduler` is a `multiqueue_threadpool scheduler` which steals from other pools.
- `asio_scheduler steals`.

The only difference with their not stealing equivalent is that they need a composite_scheduler to tell them from which queues they can steal.

Not all schedulers offer a queue to steal from. A `single_thread_scheduler` does not as it would likely bring race conditions in active objects. If you do want to allow stealing, use a threadpool with 1 thread. An `asio_scheduler` also offers no queue to steal from although it can steal from other queues because Boost.Asio does not offer this in its interface. Future extensions will overcome this.

TODO priority posting

asio_scheduler

Asynchronous supports the possibility to use Boost.Asio as a threadpool provider. This has several advantages:

- asio_scheduler is delivered with a way to access Asio's io_service from a servant object living inside the scheduler.
- asio_scheduler handles the necessary work for creating a pool of threads for multithreaded-multi-io_service communication.
- asio_scheduler threads implement work-stealing from other Asynchronous schedulers. This allows communication threads to help other threadpools when no I/O communication is happening. This helps reducing thread oversubscription.
- One has all the usual goodies of Asynchronous: safe callbacks, object tracking, servant proxies, etc.

Let's create a simple but powerful example to illustrate its usage. We want to create a TCP client, which connects several times to the same server, gets data from it (in our case, the Boost license will do), then checks if the data is coherent by comparing the results two-by-two. Of course, the client has to be perfectly asynchronous and never block. We also want to guarantee some threads for the communication and some for the calculation work. We also want to communication threads to "help" by stealing some work if necessary.

Let's start by creating a TCP client using Boost.Asio. A slightly modified version of the async TCP client from the Asio documentation will do. All we change is pass it a callback which it will call when the requested data is ready. We now pack it into an Asynchronous trackable client:

```
// Objects of this type are made to live inside an asio_scheduler,
// they get their associated io_service object from TLS
struct AsioCommunicationServant : boost::asynchronous::trackable_servant<>
{
    AsioCommunicationServant(boost::asynchronous::any_weak_scheduler<> schedule
                             const std::string& server, const std::string& path
        : boost::asynchronous::trackable_servant<>(scheduler)
        , m_client(*boost::asynchronous::get_io_service<>(),server,path)
    {}
    void test(std::function<void(std::string)> cb)
    {
        // just forward call to asio asynchronous http client
        // the only change being the (safe) callback which will be called when 
        m_client.request_content(cb);
    }
private:
    client m_client; //client is from Asio example
};
```

The main noteworthy thing to notice is the call to **boost::asynchronous::get_io_service**<>**()**, which, using thread-local-storage, gives us the io_service associated with this thread (one io_service per thread). This is needed by the Asio TCP client. Also noteworthy is the argument to `test()`, a callback when the data is available.

Wait a minute, is this not unsafe (called from an asio worker thread)? It is but it will be made safe in a minute.

We now need a proxy so that this communication servant can be safely used by others, as usual:

```
class AsioCommunicationServantProxy: public boost::asynchronous::servant_proxy<
```

```
{
public:
    // ctor arguments are forwarded to AsioCommunicationServant
    template <class Scheduler>
    AsioCommunicationServantProxy(Scheduler s,const std::string& server, const s
        boost::asynchronous::servant_proxy<AsioCommunicationServantProxy,AsioCo
    {}
    // we offer a single member for posting
    BOOST_ASYNC_POST_MEMBER(test)
};
```

A single member, `test`, is used in the proxy. The constructor takes the server and relative path to the desired page. We now need a manager object, which will trigger the communication, wait for data, check that the data is coherent:

```
struct Servant : boost::asynchronous::trackable_servant<>
{
    Servant(boost::asynchronous::any_weak_scheduler<> scheduler,const std::stri
        : boost::asynchronous::trackable_servant<>(scheduler)
        , m_check_string_count(0)
    {
        // as worker we use a simple threadpool scheduler with 4 threads (0 wou
        auto worker_tp = boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::threadpool_scheduler<boost::asynch

        // for tcp communication we use an asio-based scheduler with 3 threads
        auto asio_workers = boost::asynchronous::create_shared_scheduler_proxy(

        // we create a composite pool whose only goal is to allow asio worker t
        m_pools = boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::composite_threadpool_scheduler<> (

        set_worker(worker_tp);
        // we create one asynchronous communication manager in each thread
        m_asio_comm.push_back(AsioCommunicationServantProxy(asio_workers,server
        m_asio_comm.push_back(AsioCommunicationServantProxy(asio_workers,server
        m_asio_comm.push_back(AsioCommunicationServantProxy(asio_workers,server
    }
... //to be continued
```

We create 3 pools:

- A worker pool for calculations (page comparisons)
- An asio threadpool with 3 threads in which we create 3 communication objects.
- A composite pool which binds both pools together into one stealing unit. You could even set the worker pool to 0 thread, in which case the worker will get its work done when the asio threads have nothing to do. Only non- multiqueue schedulers support this. This composite pool is now made to be the worker pool of this object using `set_worker()`.

We then create our communication objects inside the asio pool.

Note: at the moment, asio pools can steal from other pools but not be stolen from. Let's move on to the most interesting part:

```
void get_data()
{
```

```
    // provide this callback (executing in our thread) to all asio servants as t
    std::function<void(std::string)> f =
...
    m_asio_comm[0].test(make_safe_callback(f));
    m_asio_comm[1].test(make_safe_callback(f));
    m_asio_comm[2].test(make_safe_callback(f));
    }
```

We skip the body of f for the moment. f is task which will be posted to each communication servant so that they can do the same work:

- call the same http get on an asio servants
- at each callback, check if we got all three callbacks
- if yes, post some work to worker threadpool, compare the returned strings (should be all the same)
- if all strings equal as they should be, cout the page

All this will be doine in a single functor. This functor is passed to each communication servant, packed into a make_safe_callback, which, as its name says, transforms the unsafe functor into one which posts this callback functor to the manager thread and also tracks it to check if still alive at the time of the callback. By calling `test()`, we trigger the 3 communications, and f will be called 3 times. The body of f is:

```
std::function<void(std::string)> f =
                [this](std::string s)
                {
                   this->m_requested_data.push_back(s);
                   // poor man's state machine saying we got the result of our a
                   if (this->m_requested_data.size() == 3)
                   {
                       // ok, this has really been called for all servants, comp
                       // but it could be long, so we will post it to threadpoo
                       std::cout << "got all tcp data, parallel check it's corre
                       std::string s1 = this->m_requested_data[0];
                       std::string s2 = this->m_requested_data[1];
                       std::string s3 = this->m_requested_data[2];
                       // this callback (executing in our thread) will be calle
                       auto cb1 = [this,s1](boost::future<bool> res)
                       {
                          if (res.get())
                              ++this->m_check_string_count;
                          else
                              std::cout << "uh oh, the pages do not match, data
                          if (this->m_check_string_count ==2)
                          {
                              // we started 2 comparisons, so it was the last on
                              std::cout << "data has been confirmed, here it is
                              std::cout << s1;
                          }
                       };
                       auto cb2=cb1;
                       // post 2 string comparison tasks, provide callback where
                       this->post_callback([s1,s2](){return s1 == s2;},std::move
                       this->post_callback([s2,s3](){return s2 == s3;},std::move
                   }
                };
```

We start by checking if this is the third time this functor is called (this, the manager, is nicely serving as holder, kind of poor man's state machine counting to 3). If yes, we prepare a call to the worker pool to compare the 3 returned strings 2 by 2 (cb1, cb2). Again, simple state machine, if the callback is called twice, we are done comparing string 1 and 2, and 2 and 3, in which case the page is confirmed and cout'ed. The last 2 lines trigger the work and post to our worker pool (which is the threadpool scheduler, or, if stealing happens, the asio pool) two comparison tasks and the callbacks.

Our manager is now ready, we still need to create for it a proxy so that it can be called from the outside world asynchronously, then create it in its own thread, as usual:

```
class ServantProxy : public boost::asynchronous::servant_proxy<ServantProxy,Serv
{
public:
    template <class Scheduler>
    ServantProxy(Scheduler s,const std::string& server, const std::string& path
        boost::asynchronous::servant_proxy<ServantProxy,Servant>(s,server,path)
    {}
    // get_data is posted, no future, no callback
    BOOST_ASYNC_POST_MEMBER(get_data)
};
...
auto scheduler = boost::asynchronous::create_shared_scheduler_proxy(
                                new boost::asynchronous::single_thread_schedule
                                     boost::asynchronous::threadsafe_list<> >);
{
   ServantProxy proxy(scheduler,"www.boost.org","/LICENSE_1_0.txt");
   // call member, as if it was from Servant
   proxy.get_data();
   // if too short, no problem, we will simply give up the tcp requests
   // this is simply to simulate a main() doing nothing but waiting for a termi
   boost::this_thread::sleep(boost::posix_time::milliseconds(2000));
}
```

As usual, here the complete, ready-to-use example [examples/example_asio_http_client.cpp] and the implementeation of the Boost.Asio HTTP client [examples/asio/asio_http_async_client.cpp].

Timers

Very often, an Active Object servant acting as an asynchronous dispatcher will post tasks which have to be done until a certain point in the future, or which will start only at a later point. State machines also regularly make use of a "time" event.

For this we need a timer, but a safe one:

- The timer callback has to be posted to the Active Object thread to avoid races.
- The timer callback shall not be called in the servant making the request has been deleted (it can be an awfully long time until the callback).

Asynchronous itself has no timer, but Boost.Asio has, so the library provides a wrapper around it and will allow us to create a timer using an io_service running in its own thread or in an asio threadpool, also provided by the library.

Constructing a timer

One first needs an `asio_scheduler` with at least one thread:

```
boost::asynchronous::any_shared_scheduler_proxy<> asio_sched = boost::asynchrono
```

The Servant living in its ActiveObject thread then creates a timer (as attribute to keep it alive as destroying the object will cancel the timer) using this scheduler and a timer value:

```
boost::asynchronous::asio_deadline_timer_proxy m_timer (asio_sched,boost::posi
```

It can now start the timer using `trackable_servant` (its base class)`::async_wait`, passing it a functor call when timer expires / is cancelled:

```
async_wait(m_timer,
           [](const ::boost::system::error_code& err)
           {
               std::cout << "timer expired? "<< std::boolalpha << (bool)err <<
           }
           );
```

Canceling the timer means destroying (and possibly recreating) the timer object:

```
m_timer =  boost::asynchronous::asio_deadline_timer_proxy(get_worker(),boost::
```

The following example [examples/example_asio_deadline_timer.cpp] displays a servant using an asio scheduler as a thread pool and creating there its timer object. Not how the timer is created using `trackable_servant` (its base class)`::get_worker()`.

Continuation tasks

A common limitation of threadpools is support for recursive tasks: tasks start other tasks, which start other tasks, until all threads in the threadpool are busy waiting. At this point, one could add more threads, but threads are expensive. Similarly, you might post a task which posts more tasks and wait for them to complete to do a merge of the result. Of course you can achieve this with a controller object or state machine in a single-threaded scheduler waiting for callbacks, but for very small tasks, using callbacks might just be too expensive. In such cases, Asynchronous provides continuations: a task executes, does something then creates a continuation which will wake up when ready.

A common example of recursive tasks is a parallel fibonacci. Usually, this means a task calculating fib(n) will start a fib(n-1) and fib(n-2) and blocks until both are done. These tasks will start more tasks, etc. until a cutoff number, at which point recursion stops and fibonacci is calculated serially. This approach has some problems: to avoid thread explosion, we would need fibers, which are not available in Boost at the time of this writing, and even in fibers, tasks would block, which means interrupting them is not possible, which we would want to avoid. In any case, blocking simply isn't part of the asynchronous philosophy of the library. Let's have a look how continuation tasks let us implement a parallel fibonacci.

First of all, we need a serial fibonacci to use for the cutoff. This is a classical one:

```
 long serial_fib( long n ) {
    if( n<2 )
        return n;
    else
        return serial_fib(n-1)+serial_fib(n-2);
}
```

We now need a recursive fibonacci task:

```
// our recursive fibonacci tasks. Needs to inherit continuation_task<value type
```

```
struct fib_task : public boost::asynchronous::continuation_task<long>
{
    fib_task(long n,long cutoff):n_(n),cutoff_(cutoff){}
    // called inside of threadpool
    void operator()()const
    {
        // the result of this task, will be either set directly if < cutoff, ot
        boost::asynchronous::continuation_result<long> task_res = this_task_res
        if (n_<cutoff_)
        {
            // n < cutoff => execute immediately
            task_res.set_value(serial_fib(n_));
        }
        else
        {
            // n>= cutoff, create 2 new tasks and when both are done, set our r
            boost::asynchronous::create_continuation<long>(
                        // called when subtasks are done, set our result
                        [task_res](std::tuple<boost::future<long>,boost::future
                        {
                            long r = std::get<0>(res).get() + std::get<1>(res).
                            task_res.set_value(r);
                        },
                        // recursive tasks
                        fib_task(n_-1,cutoff_),
                        fib_task(n_-2,cutoff_));
        }
    }
    long n_;
    long cutoff_;
};
```

This deserves a bit of explanation. Our task need to inherit `boost::asynchronous::continuation_task<R>` where R is the type later returned. This class provides us with `this_task_result()` where we set the task result. This is done either immediately if n < cutoff (first if clause), or (else clause) using a continuation.

If n>= cutoff, we create a continuation task. This is a sleeping task, which will get activated when all required tasks complete. In this case, we have two fibonacci sub tasks. The template argument is the return type of the continuation. We create two sub-tasks, for n-1 and n-2 and when they complete, the completion functor passed as first argument is called.

Note that `boost::asynchronous::create_continuation` is a variadic function, there can be any number of sub-tasks. The completion functor takes as single argument a tuple of futures, one for each subtask. The template argument of the future is the template argument of `boost::asynchronous::continuation_task` of each subtask. In this case, all are long, but it's not a requirement.

When this completion functor is called, we set our result to be result of first task + result of second task and return.

The main particularity of this solution is that a task does not block until sub-tasks complete but instead provides an asynchronous functor.

All what we still need to do is create the first task. In the tradition of Asynchronous, we do it inside an asynchronous servant which posts the first task and waits for a callback:

```
struct Servant : boost::asynchronous::trackable_servant<>
```

```
{
...
   void calc_fibonacci(long n,long cutoff)
   {
      post_callback(
            [n,cutoff]()
            {
                // a top-level continuation is the first one in a recursive ser
                // Its result will be passed to callback
                return boost::asynchronous::top_level_continuation<long>(fib_ta
            }// work
            ,
            // callback with fibonacci result.
            [](boost::future<long> res){...}// callback functor.
        );
   }
   };
```

We call `post_callback`, which, as usual, ensure that the callback is posted to the right thread and the servant lifetime is tracked. The posted task calls `boost::asynchronous::top_level_continuation<task-return-type>` to create the first, top-level continuation, passing it a first fib_task. This is non-blocking, a special version of `post_callback` recognizes a continuation and will call its callback (with a `future<task-return-type>`) only when the calculation is finished.

As usual, calling get on the future is non-blocking, one gets eaither the result or an exception if thrown by a task.

Please have a look at the complete example [examples/example_fibonacci.cpp].

And what about logging? We don't want to give up this feature of course and would like to know how long all these fib_task took to complete. This is done through minor changes. As always we need a job, the same as usual:

```
typedef boost::asynchronous::any_loggable<boost::chrono::high_resolution_clock>
```

We give the logged name of the task in the constructor of fib_task, for example fib_task_xxx:

```
fib_task(long n,long cutoff)
        : boost::asynchronous::continuation_task<long>("fib_task_" + boost::lex
        ,n_(n),cutoff_(cutoff){}
```

And call `boost::asynchronous::create_continuation_log` instead of `boost::asynchronous::create_continuation`:

```
boost::asynchronous::create_continuation_log<long,servant_job>(
                        [task_res](std::tuple<boost::future<long>,boost::future
                        {
                            long r = std::get<0>(res).get() + std::get<1>(res).
                            task_res.set_value(r);
                        },
                        fib_task(n_-1,cutoff_),
                        fib_task(n_-2,cutoff_)
);
```

Inside the servant we might optionally want the version of post_callback with name, and we need to use `top_level_continuation_log` instead of `top_level_continuation`:

```
post_callback(
              [n,cutoff]()
              {
                   return boost::asynchronous::top_level_continuation_log<long,s
              }// work
              ,
              // the lambda calls Servant, just to show that all is safe, Serva
              [this](boost::future<long> res){...},// callback functor.
              "calc_fibonacci"
        );
```

The previous example has been rewritten with logs and a display of all tasks [examples/example_fibonacci_log.cpp] (beware, with higher fibonacci numbers, this can become a long list)..

Chapter 4. In-depth usage.

Which protections you get, which ones you don't.

todo

Tips

todo

Part III. Reference

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Chapter 5. Common concepts

Subtitle of Chapter

Section1 Title

Subtitle of Section 1

TODO

Chapter 6. Queues

Asynchronous provides a range of queues with different trade-offs. Use `threadsafe_list` as default for a quickstart with Asynchronous.

threadsafe_list

This queue is mostly the one presented in Anthony Williams' book, "C++ Concurrency In Action". It is made of a single linked list of nodes, with a mutex at each end of the queue to minimize contention. It is reasonably fast and of simple usage. It can be used in all configurations of pools. Please use this container as default when starting with Asynchronous.

Its constructor does not require any parameter forwarded from the scheduler.

Stealing: from the same queue end as pop. Will be implemented better (from the other end to reduce contention) in a future version.

Declaration:

```
template<class JOB = boost::asynchronous::any_callable>
class threadsafe_list;
```

lockfree_queue

This queue is a light wrapper around a `boost::lockfree::queue`, which gives lockfree behavior at the cost of an extra dynamic memory allocation.

The container is faster than a `threadsafe_list`, provided one manages to set the queue size to an optimum value. A too small size will cause expensive memory allocations, a too big size will significantly degrade performance.

Its constructor requires a default size forwarded from the scheduler.

Stealing: from the same queue end as pop. Stealing from the other end is not supported by `boost::lockfree::queue`. It can be used in all configurations of pools.

Declaration:

```
template<class JOB = boost::asynchronous::any_callable>
class lockfree_queue;
```

lockfree_spsc_queue

This queue is a light wrapper around a `boost::lockfree::spsc_queue`, which gives lockfree behavior at the cost of an extra dynamic memory allocation.

Its constructor requires a default size forwarded from the scheduler.

Stealing: None. Stealing is not supported by `boost::lockfree::spsc_queue`. It can only be used Single-Producer / Single-Consumer, which reduces its typical usage to a queue of a `multiqueue_threadpool_scheduler` as consumer, with a `single_thread_scheduler` as producer.

Declaration:

```
template<class JOB = boost::asynchronous::any_callable>
class lockfree_spsc_queue;
```

lockfree_stack

This queue is a light wrapper around a `boost::lockfree::stack`, which gives lockfree behavior at the cost of an extra dynamic memory allocation. This container creates a task inversion as the last posted tasks will be executed first.

Its constructor requires a default size forwarded from the scheduler.

Stealing: from the same queue end as pop. Stealing from the other end is not supported by `boost::lockfree::stack`. It can be used in all configurations of pools.

Declaration:

```
template<class JOB = boost::asynchronous::any_callable>
class lockfree_stack;
```

Chapter 7. Schedulers

There is not the perfect scheduler. In any case it's a question of trade-off. Here are the schedulers offered by Asynchronous.

single_thread_scheduler

The scheduler of choice for all servants which are not thread-safe. Serializes all calls to a single queue and executes them in order. Using `any_queue_container` as queue will however allow it to support task priority.

This scheduler does not steal from other queues or pools, only stealing_ threadpools do this, and does not get stolen from to avoid races.

Declaration:

```
template<class Queue>
class single_thread_scheduler;
```

Creation:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::single_thread_scheduler<
                          boost::asynchronous::threadsafe_list<> >);

boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::single_thread_scheduler<
                          boost::asynchronous::lockfree_queue<> >(10)); // size
```

Or, using logging:

```
typedef boost::asynchronous::any_loggable<boost::chrono::high_resolution_clock>

boost::asynchronous::any_shared_scheduler_proxy<servant_job> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::single_thread_scheduler<
                          boost::asynchronous::threadsafe_list<servant_job> >);

boost::asynchronous::any_shared_scheduler_proxy<servant_job> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::single_thread_scheduler<
                          boost::asynchronous::lockfree_queue<servant_job> >(10
```

Table 7.1. #include <boost/asynchronous/scheduler/single_thread_scheduler.hpp>

Characteristics	
Number of threads	1
Can be stolen from?	No
Can steal from other threads in this pool?	N/A (only 1 thread)
Can steal from other threads in other pools?	No

threadpool_scheduler

The simplest and easiest threadpool using a single queue, though multiqueue behavior could be done using `any_queue_container`. The advantage is that it allows the pool to be given 0 thread and only be stolen from. The cost is a slight performance loss due to higher contention on the single queue.

This pool does not steal from other pool's queues.

Use this pool as default for a quickstart with Asynchronous.

Declaration:

```
template<class Queue>
class threadpool_scheduler;
```

Creation:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::threadpool_scheduler<
                          boost::asynchronous::threadsafe_list<> >(4)); // 4 th

boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::threadpool_scheduler<
                          boost::asynchronous::lockfree_queue<> >(4,10)); // si
```

Or, using logging:

```
typedef boost::asynchronous::any_loggable<boost::chrono::high_resolution_clock>

boost::asynchronous::any_shared_scheduler_proxy<servant_job> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::threadpool_scheduler<
                          boost::asynchronous::threadsafe_list<servant_job> >(4

boost::asynchronous::any_shared_scheduler_proxy<servant_job> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::threadpool_scheduler<
                          boost::asynchronous::lockfree_queue<servant_job> >(4,
```

Table 7.2. #include <boost/asynchronous/scheduler/threadpool_scheduler.hpp>

Characteristics	
Number of threads	**0**-n
Can be stolen from?	Yes
Can steal from other threads in this pool?	N/A (only 1 queue)
Can steal from other threads in other pools?	No

multiqueue_threadpool_scheduler

This is a `threadpool_scheduler` with multiple queues to reduce contention. On the other hand, this pool requires at least one thread.

This pool does not steal from other pool's queues though pool threads do steal from each other's queues.

Declaration:

```
template<class Queue,class FindPosition=boost::asynchronous::default_find_posit
class multiqueue_threadpool_scheduler;
```

Creation:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::multiqueue_threadpool_scheduler<
                          boost::asynchronous::threadsafe_list<> >(4)); // 4 th

boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::multiqueue_threadpool_scheduler<
                          boost::asynchronous::lockfree_queue<> >(4,10)); // si
```

Or, using logging:

```
typedef boost::asynchronous::any_loggable<boost::chrono::high_resolution_clock>

boost::asynchronous::any_shared_scheduler_proxy<servant_job> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::multiqueue_threadpool_scheduler<
                          boost::asynchronous::threadsafe_list<servant_job> >(4

boost::asynchronous::any_shared_scheduler_proxy<servant_job> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::multiqueue_threadpool_scheduler<
                          boost::asynchronous::lockfree_queue<servant_job> >(4,
```

Table 7.3. #include <boost/asynchronous/scheduler/multiqueue_threadpool_scheduler.hpp>

Characteristics	
Number of threads	**1**-n
Can be stolen from?	Yes
Can steal from other threads in this pool?	Yes
Can steal from other threads in other pools?	No

stealing_threadpool_scheduler

This is a `threadpool_scheduler` with the added capability to steal from other pool's queues within a `composite_threadpool_scheduler`. Not used within a `composite_threadpool_scheduler`, it is a standard `threadpool_scheduler`.

Declaration:

```
template<class Queue,bool /* InternalOnly */ = true >
class stealing_threadpool_scheduler;
```

Creation if used within a `composite_threadpool_scheduler`:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
```

```
                    new boost::asynchronous::stealing_threadpool_scheduler<
                          boost::asynchronous::threadsafe_list<> >(4)); // 4 th
```

However, if used stand-alone, which has little interest outside of unit tests, we need to add a template parameter to inform it:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::stealing_threadpool_scheduler<
                          boost::asynchronous::threadsafe_list<>,true >(4)); //
```

Table 7.4. #include <boost/asynchronous/scheduler/stealing_threadpool_scheduler.hpp>

Characteristics	
Number of threads	**0**-n
Can be stolen from?	Yes
Can steal from other threads in this pool?	N/A (only 1 queue)
Can steal from other threads in other pools?	Yes

stealing_multiqueue_threadpool_scheduler

This is a `multiqueue_threadpool_scheduler` with the added capability to steal from other pool's queues within a `composite_threadpool_scheduler` (of course, threads within this pool do steal from each other queues, with higher priority). Not used within a `composite_threadpool_scheduler`, it is a standard `multiqueue_threadpool_scheduler`.

Declaration:

```
template<class Queue,class FindPosition=boost::asynchronous::default_find_posit
class stealing_multiqueue_threadpool_scheduler;
```

Creation if used within a `composite_threadpool_scheduler`:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::stealing_multiqueue_threadpool_sch
                          boost::asynchronous::threadsafe_list<> >(4)); // 4 th
```

However, if used stand-alone, which has little interest outside of unit tests, we need to add a template parameter to inform it:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::stealing_multiqueue_threadpool_sch
                          boost::asynchronous::threadsafe_list<>,boost::asynchr
```

Table 7.5. #include <boost/asynchronous/stealing_multiqueue_threadpool_scheduler.hpp>

Characteristics	
Number of threads	**1**-n

Characteristics	
Can be stolen from?	Yes
Can steal from other threads in this pool?	Yes
Can steal from other threads in other pools?	Yes

composite_threadpool_scheduler

This pool has no thread by itself. Its job is to contain other pools, accessible by the priority given by posting, and share all queues of its subpools among them. Only the stealing_* pools and `asio_scheduler` will make use of this and steal from other pools though.

For creation we need to create other pool of stealing or not stealing, stolen from or not, schedulers. stealing_xxx pools will try to steal jobs from other pool of the same composite, but only if these schedulers support this. Other threadpools will not steal but get stolen from. `single_thread_scheduler` will not steal or get stolen from.

```
// create a composite threadpool made of:
// a multiqueue_threadpool_scheduler, 0 thread
// This scheduler does not steal from other schedulers, but will lend its queue
auto tp = boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::threadpool_scheduler<boost::asynch

// a stealing_multiqueue_threadpool_scheduler, 3 threads, each with a threadsaf
// this scheduler will steal from other schedulers if it can. In this case it w
auto tp2 = boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::stealing_multiqueue_threadpool_sch

// composite pool made of the previous 2
auto tp_worker = boost::asynchronous::create_shared_scheduler_proxy(new boost::a
```

Declaration:

```
template<class Job = boost::asynchronous::any_callable,
         class FindPosition=boost::asynchronous::default_find_position< >,
         class Clock = boost::chrono::high_resolution_clock  >
class composite_threadpool_scheduler;
```

Table 7.6. #include <boost/asynchronous/scheduler/composite_threadpool_scheduler.hpp>

Characteristics	
Number of threads	0
Can be stolen from?	Yes
Can steal from other threads in this pool?	N/A
Can steal from other threads in other pools?	No

asio_scheduler

This pool brings the infrastructure and access to io_service for an integrated usage of Boost.Asio. Furthermore, if used withing a `composite_threadpool_scheduler`, it will steal jobs from other pool's queues.

Declaration:

```
template<class FindPosition=boost::asynchronous::default_find_position< boost::a
class asio_scheduler;
```

Creation:

```
boost::asynchronous::any_shared_scheduler_proxy<> scheduler =
    boost::asynchronous::create_shared_scheduler_proxy(
                    new boost::asynchronous::asio_scheduler<>(4)); // 4 threads
```

Table 7.7. #include <boost/asynchronous/extensions/asio/asio_scheduler.hpp>

Characteristics	
Number of threads	**1**-n
Can be stolen from?	No*
Can steal from other threads in this pool?	Yes
Can steal from other threads in other pools?	Yes

Chapter 8. Compiler

C++ 11

Asynchronous is C++11-only. Please check that your compiler has C++11 enabled (-std=c++0x or -std=c++11 in different versions of gcc)

Supported compilers

At the moment, Asynchronous has only be tested with gcc versions 4.5 to 4.7.