CERN
School of Computing

Network Programming

Lecture 2

Building Highly Distributed Systems Within 5 Minutes

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Outline

- **Motivation**
- **Boost.Asio**
- **Message Passing**
- **ØMQ**
- **Apache Thrift**

TCP in C code

- **The BSD socket API is minimalistic**
  - No intrinsic multithreading support
    - Handling multiple connections typically via fork()
  - No data management (messaging)
  - Configuration a bit awkward
- **There is no exception handling or OOP in C**
- **There is no C++ socket API in the std library**
  - std::socket will never come

```
#include <stdio.h>
#include <netinet/in.h>
#include <sys/socket.h>
#include <sys/types.h>

int main( int argc, char *argv[] ) {
   int sockfd, newsockfd, portno, clilen;
   char buffer[256];
   struct sockaddr_in serv_addr, cli_addr;
   int  n;

   sockfd = socket(AF_INET, SOCK_STREAM, 0);

   bzero((char *) &serv_addr, sizeof(serv_addr));
   portno = 1324;
   serv_addr.sin_family = AF_INET;
   serv_addr.sin_addr.s_addr = INADDR_ANY;
   serv_addr.sin_port = htons(portno);
   bind(sockfd, (struct sockaddr *) &serv_addr,
                  sizeof(serv_addr));
   listen(sockfd,5);
   clilen = sizeof(cli_addr);
   while (1) {
      newsockfd = accept(sockfd,
            (struct sockaddr *) &cli_addr, &clilen);
      pid = fork();
      if (pid == 0) {
         close(sockfd);
         dosomething(newsockfd);
         exit(0);
      } else {
         close(newsockfd);
      }
   }
}
```

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- Motivation
- **Boost.Asio**
  - Asynchronous operations
  - Concurrency without threads
  - Multithreading
- Message Passing
- ØMQ
- Apache Thrift

Boost.Asio

- Boost.Asio is a C++ library for low-level I/O programming with a consistent **asynchronous** model including a **BSD** socket interface

BSD Socket API (Linux)	Equivalents in Boost.Asio
socket descriptor – int	For TCP: ip::tcp::socket For UDP: ip::udp::socket
sockaddr_in, sockaddr_in6	For TCP: ip::tcp::endpoint For UDP: ip::udp::endpoint
accept()	For TCP: ip::tcp::acceptor::accept()
bind()	For TCP: ip::tcp::socket::bind() For UDP: ip::udp::socket::bind()
...	...

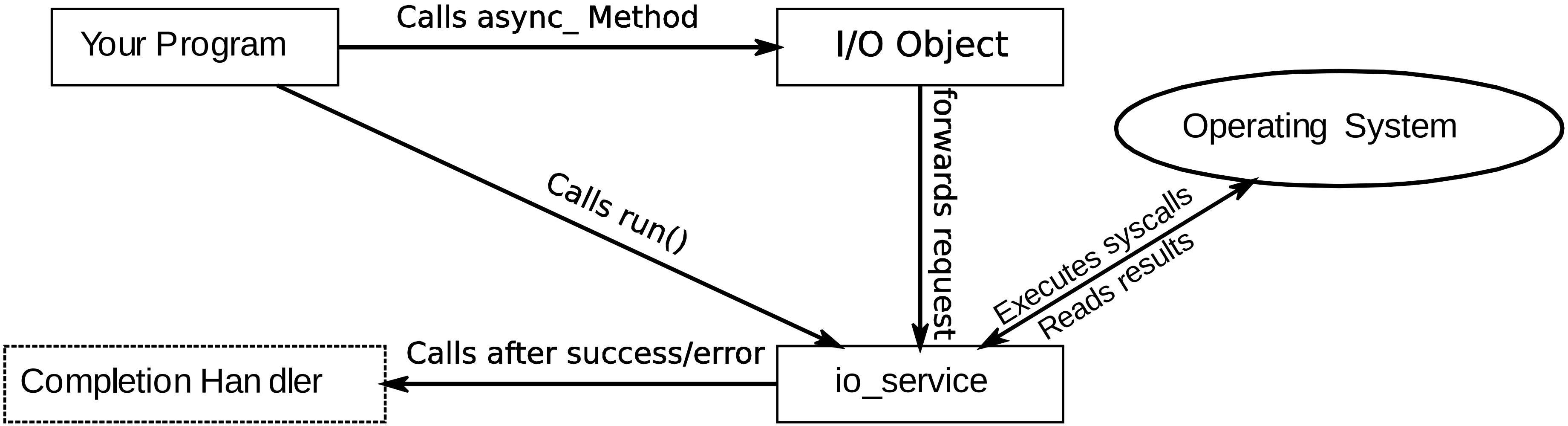
Boost.Asio

- **Boost.Asio uses an object as an interface to the operating system: io_service**
- **The io_service object is passed to I/O objects like tcp::socket**
- **The I/O objects will forward requests to the io_service object**
  - io_service runs the required syscalls

```
boost::asio::io_service io_service;
boost::asio::ip::tcp::socket socket(io_service);
boost::asio::ip::tcp::resolver resolver(io_service); // gethostbyname wrapper
socket.connect(*resolver.resolve({hostname, portNum}));
socket.send(boost::asio::buffer("message"));
```

Boost.Asio: Asynchronous operations

- **I/O objects implement non-blocking/asynchronous operations**
  - E.g. boost::asio::ip::tcp::socket::async_connect
- **Completion handler function passed to async_ functions**
- **io_service.run() calls the completion handler as soon as results of async_ functions are available**



Boost.Asio: Asynchronous operations

- **Simple TCP connection example:**

```
void MyClass::handle_connect(const boost::system::error_code& error)  {
        if (!error) { doSomething(); }
}
...
socket.async_connect(socket, *resolver.resolve({hostname, portNum}),
   boost::bind(&MyClass::handle_connect, this, boost::asio::placeholders::error));
workWhileConnecting();
io_service.run(); // Runs handle_connect as soon as the connection is established
```

- **Even simpler with C++11 using a lambda function:**

```
socket.async_connect(*resolver.resolve({hostname, portNum}),
        [this](boost::system::error_code error, tcp::resolver::iterator) {
                if (!error) { doSomething(); }
        });
workWhileConnecting();
io_service.run();
```

Concurrency without threads
Handling multiple TCP connections

- **One io_service can handle several I/O objects and async_ operations**
- **io_service::run() will block until all requests have been handled**

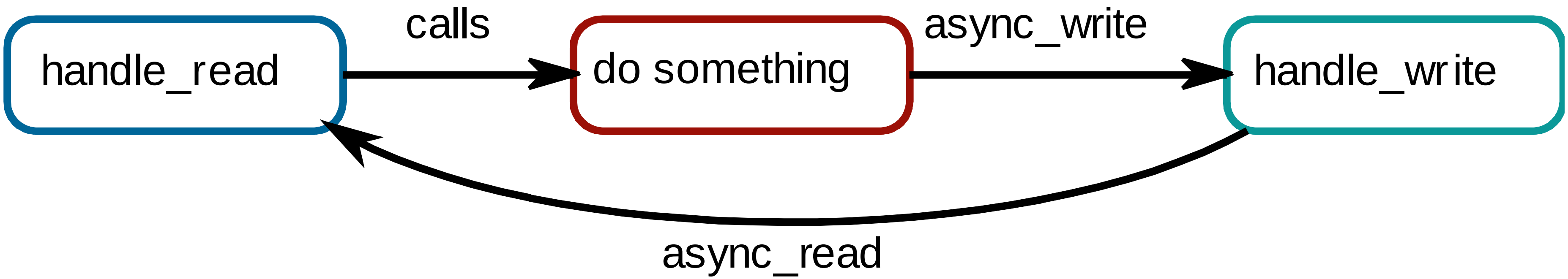
```
sock1.async_read_some(readBuffer, [](boost::system::error_code error, std::size_t){
		if (!error) {std::cout << "Socket 1 received something" << std::endl;}
});

sock2.async_read_some(readBuffer, [](boost::system::error_code error, std::size_t){
		if (!error) {std::cout << "Socket 2 received something" << std::endl;}
});

io_service.run();
cout << “Both sockets received something” << endl;
```

Multithreading

- **io_service::run() can be called by multiple threads simultaneously**
- **async_ operations will be distributed among these threads**
- **A common approach is to launch a thread pool running the whole lifetime**
  - N threads spawned at the beginning handling all async_ operations
  - Recursive calls of async_ operations (io_service::run() never returns)



Server with a Thread Pool

```
boost::asio::io_service io_service;
EchoServer s(io_service, 1234); // calls socket.async_read...

std::vector<std::thread> threadPool;
for (std::size_t i = 0; i < std::thread::hardware_concurrency(); ++i) {
	threadPool.push_back(
		std::thread(
			[&]() {
				io_service.run();
		})
	);
}
for(auto& thread : threadPool){
	 thread.join();
}
```

Outline

- Motivation
- Boost.Asio
- **Message Passing**
- ØMQ
- Apache Thrift

Message passing via TCP

- **TCP only offers a continuous data stream**
  - Although data is typically sent to sockets in chunks, the receiver may see different chunks (scaling window)
  - The application layer program has to split the stream into messages

- **There are three possible approaches to indicate messages in the stream:**
  - Protocol defines the message length **implicitly**
  - The message length is **explicitly** specified in a message header
  - **Line-Based**: Messages in the stream are separated by delimiters

Message passing via TCP

- **Line-Based approach easily implemented with Boost.Asio:**

```
boost::asio::read_until(socket, msgBuffer, "\r\n");
```

- **Other approaches are much more efficient**
  - But also hard work to implement

No need to reinvent the wheel!

- **ØMQ implements fast message passing using the explicit format**

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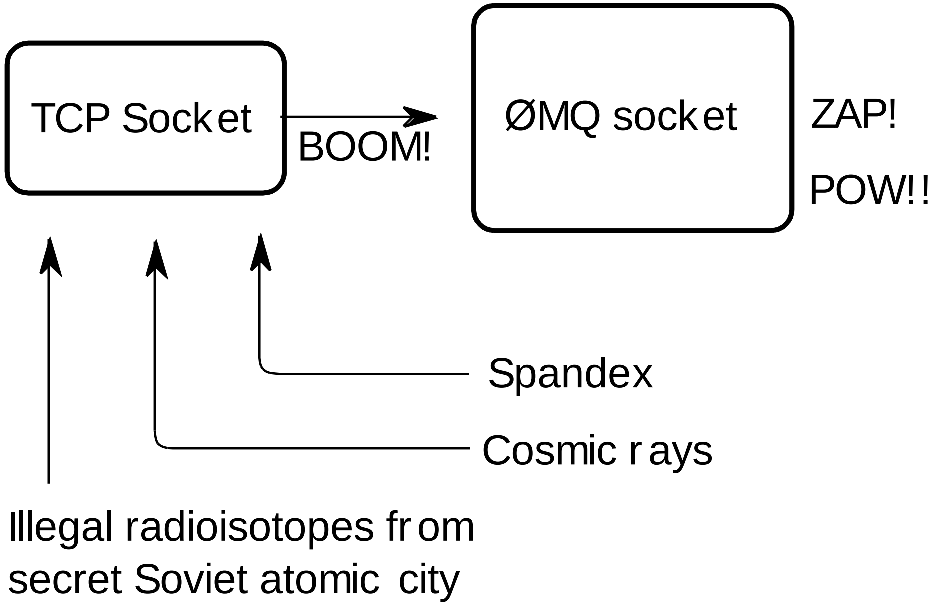
- Motivation
- Boost.Asio
- Message Passing
- **ØMQ**
  - Messaging Patterns
  - Broker
  - Multithreading
- Apache Thrift

ØMQ

- **What ØMQ says about their socket library (http://zguide.zeromq.org/page:all):**

We took a normal TCP socket, injected it with a mix of radioactive isotopes stolen from a secret Soviet atomic research project, bombarded it with 1950-era cosmic rays (...) It's sockets on steroids.



ØMQ

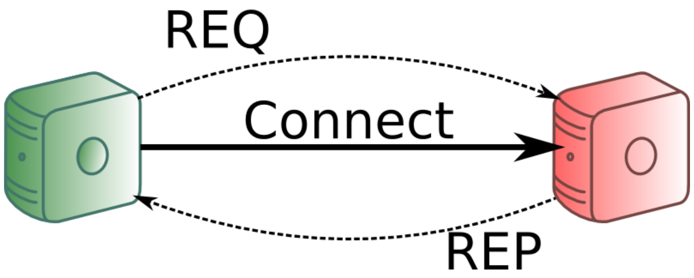
- **ØMQ offers a uniform API (ØMQ sockets) to transport messages over different channels:**
  - TCP, multicast, IPC (process to process), inproc (thread to thread)
- **Cross Platform (Linux, Windows, Mac, etc...)**
- **Implementations in many(!!!) different languages:**
  - C/C++, Java, Python, Ruby, PHP, Perl, Node.js, C#, Clojure, CL, Delphi, Erlang, F#, Felix, Go, Haskell, Haxe, Lua, Objective-C, Q, Racket, Scala...
- **OpenSource**

ØMQ – Messaging Patterns

- **ØMQ sockets express several messaging patterns**
  - **REQ** and **REP**
  - **PUB** and **SUB**
  - **PUSH** and **PULL**
  - REQ and ROUTER
  - DEALER and REP
  - DEALER and ROUTER
  - DEALER and DEALER
  - ROUTER and ROUTER
  - PAIR and PAIR

ØMQ – REQ-REP

- **Clients “connect” to a service and send a REQuest message**
- **The server REPlies to each request with a single message**
- **Sending is done asynchronously in the background**
  - User writes simple non-blocking code
  - If the remote endpoint is down the message will be sent later
- **This represents a remote procedure call pattern**



ØMQ – Simple REQ Client

```
int main() {
    zmq::context_t context(1); // Similar to io_service
    zmq::socket_t socket(context, ZMQ_REQ);
    socket.connect("tcp://REPServerHostName:5555");

    zmq::message_t request(6);
    memcpy((void *) request.data(), "Hello", 5);
    socket.send(request);

    zmq::message_t reply;
    socket.recv(&reply);
    return 0;
}
```

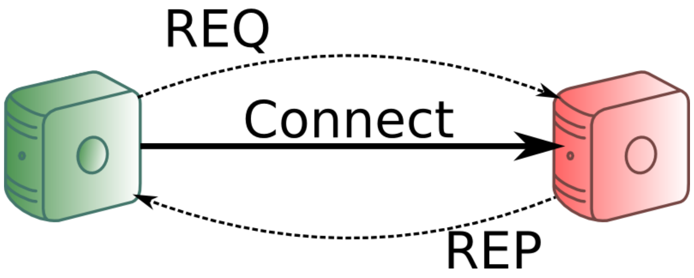
ØMQ – Simple REP Server

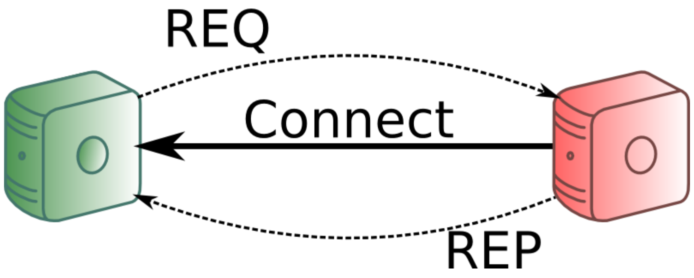
```
int main() {
    zmq::context_t context(1); // Similar to io_service
    zmq::socket_t socket(context, ZMQ_REP);
    socket.bind("tcp://*:5555");

    while (true) {
        zmq::message_t request;
        socket.recv(&request);

        zmq::message_t reply(5);
        memcpy((void *) reply.data(), "World", 5);
        socket.send(reply);
    }
    return 0;
}
```

ØMQ – REQ-REP Notes

- **The REQ-REP socket pair is in lockstep**
  - Server and client have to call send and recv alternately
  - Server automatically sends to the node it got the last message (recv) from
    - All the connection handling is done by ØMQ

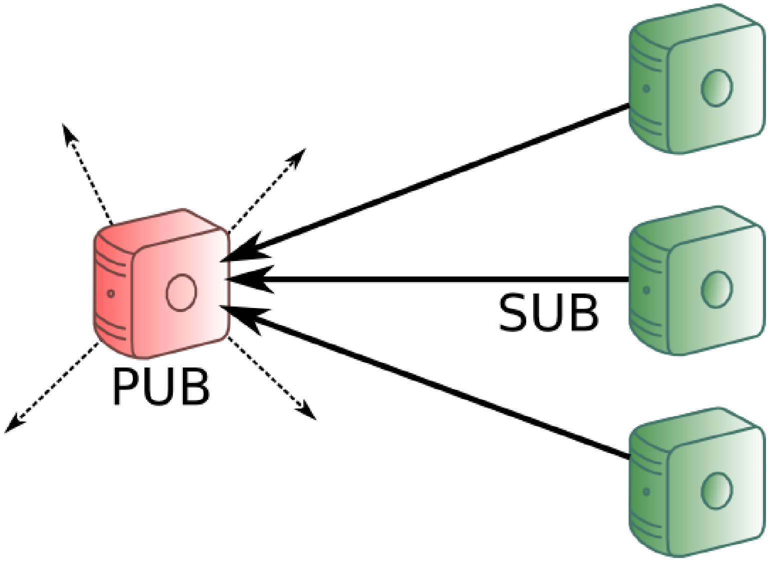
- **The connection can be established from both sides (true for all patterns)**





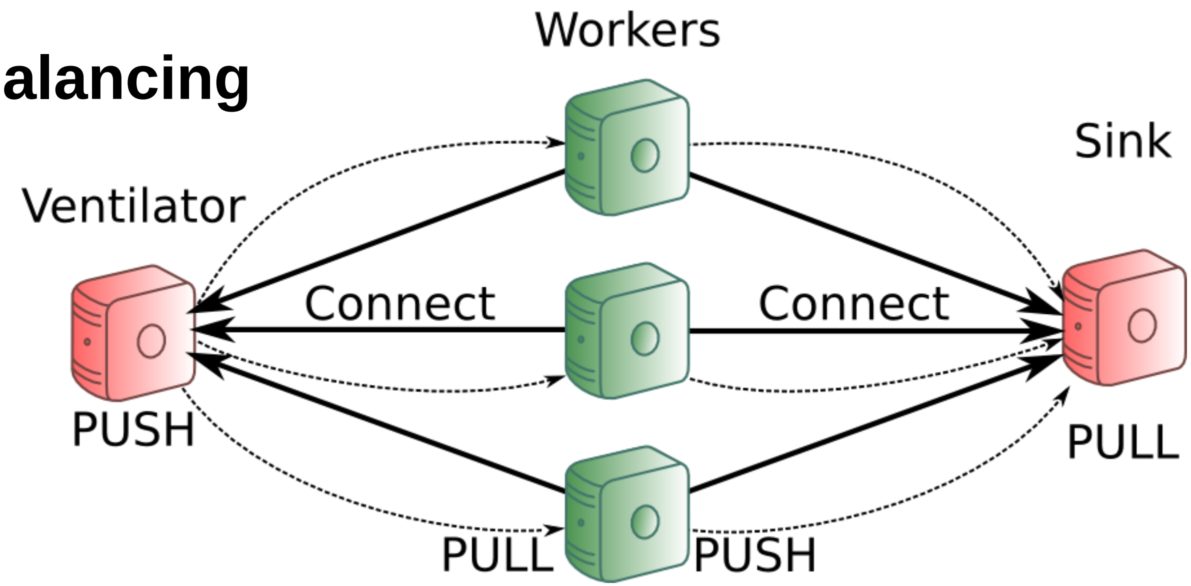
ØMQ – PUB-SUB

- Server PUBlishes data to all connected clients
- Clients SUBscribe to the data by connecting to the server
- Subscription to messages by data prefix (filter)
- If no client is connected the data will be lost



ØMQ – Pipeline

- **Ventilator: Produces task that can be processed in parallel**
- **These tasks are then PUSHed evenly to the connected Workers**
- **After processing the tasks the Workers push the results to a Sink**
- **Basic load balancing**



ØMQ – Pipeline Worker

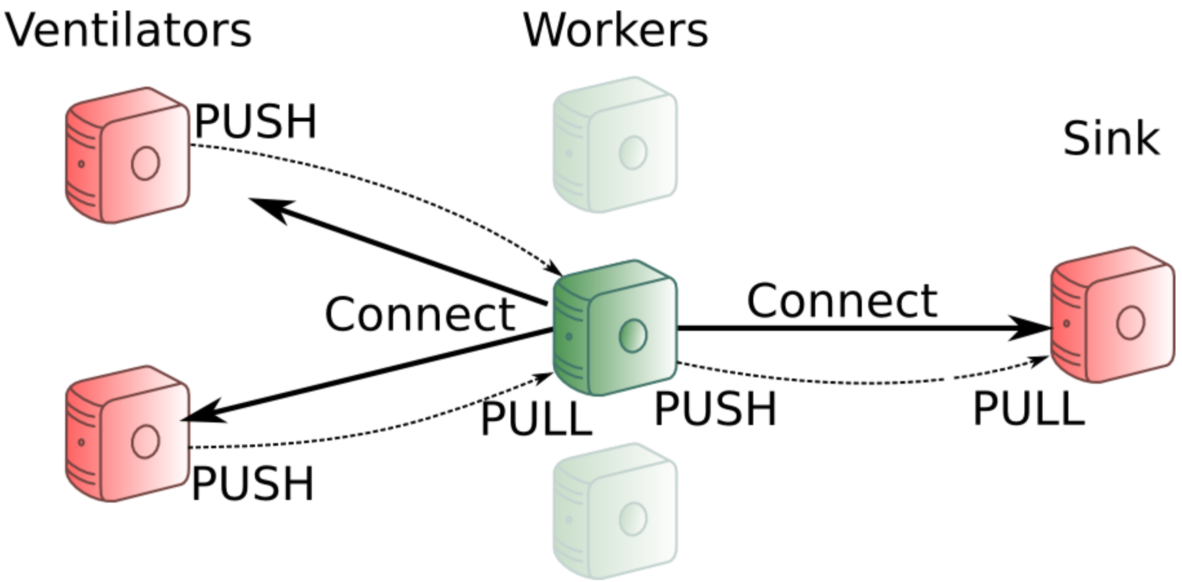
```
int main() {
    zmq::context_t context(1);
    zmq::socket_t ventilatorSocket(context, ZMQ_PULL);
    ventilatorSocket.connect("tcp://ventilator:5557");

    zmq::socket_t sinkSocket(context, ZMQ_PUSH);
    sinkSocket.connect("tcp://sink:5558");

    while (1) {
        zmq::message_t task;
        ventilatorSocket.recv(&task); // PULL
        zmq::message_t result = doSomeWork(task);
        sinkSocket.send(result); // PUSH
    }
}
```

ØMQ – N-to-M communication

- **So far we had N workers pulling from one ventilator**
- **It is possible to connect one ØMQ socket to several endpoints**

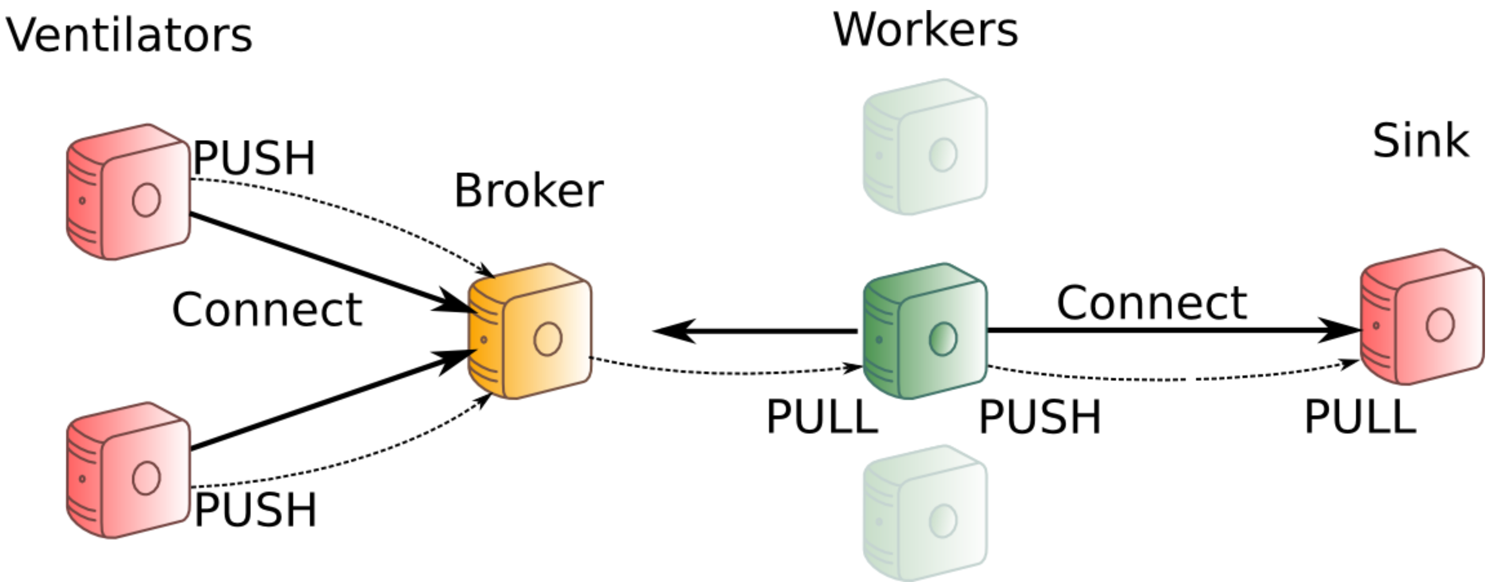
```
ventilatorSocket.connect("tcp://ventilator1:5557");
ventilatorSocket.connect("tcp://ventilator2:5557");
```

- **The messages will be scheduled fairly from all ventilators**



ØMQ – Broker

- **With the last design the workers need to know all ventilators (hostnames)**
- **If a new ventilator is added all the workers have to connect (evtl. Restart)**
- **One easy design to fix this: Add a central broker**



ØMQ – Broker

- **This is easily implemented with a zmq_proxy forwarding messages:**

```
zmq::context_t context(1);

//  Socket facing ventilators
zmq::socket_t frontend(context, ZMQ_PULL);
frontend.bind("tcp://*:5556");

//  Socket facing workers
zmq::socket_t backend(context, ZMQ_PUSH);
backend.bind("tcp://*:5557");

// Pass messages from ventilators to workers
zmq_proxy(frontend, backend, NULL);
```

ØMQ – Broker

- **Now you only have to change one line in the ventilator:**

```
socket.bind("tcp://*:5559"); → socket.connect("tcp://broker:5559");
```

- **And connect the worker to the broker instead of the ventilators**

```
ventilator.connect("tcp://ventilator1:5557");
ventilator.connect("tcp://ventilator2:5557"); …
Turns to:
ventilator.connect("tcp://broker:5557");
```

- **And again you can start ventilators, workers, broker and sink in whatever order you like:**

Messages are queued as close to the receiver as possible

ØMQ – IPC

- **So far we used: socket.bind("tcp://*:5555");**
- **To run the same programs locally one should use:**
  - socket.bind("**ipc**:///tmp/helloWorld"); // For processes
  - socket.bind("**inproc**:///helloWorld"); // For threads
- **Start developing your software with many modules communicating with IPC**
- **Then outsource heavy loaded services to external boxes just by changing**
- **inproc/ipc://... → tcp://...**

ØMQ – Multithreading

- **ØMQ sockets are not thread safe!**
- **But they are extremely lightweight**
    - Create one (or more) sockets per thread
    - Use these ØMQ sockets to exchange messages between the threads
    - **Use a proxy to distribute work among the threads**

ØMQ – Multithreaded Worker

```
void workerThread(zmq::context_t& context) {
	zmq::socket_t ventilatorProxy(context, ZMQ_PULL);
	ventilatorProxy.connect("inproc://workers");

	zmq::socket_t sink(context, ZMQ_PUSH);
	sink.connect("tcp://sink:5558");

	while (1) {
		zmq::message_t task;
		ventilatorProxy.recv(&task);

		zmq::message_t result = doSomeWork(task);
		sink.send(result);
	}
}
```

ØMQ – Multithreaded Worker

```
int main() {
    zmq::context_t context(1);
    zmq::socket_t ventilatorProxy(context, ZMQ_PULL);
    ventilatorProxy.connect("tcp://broker:5557");
    zmq::socket_t workers(context, ZMQ_PUSH);
    workers.bind("inproc://workers");

    std::vector < std::thread > threadPool;
    for (std::size_t i = 0; i < std::thread::hardware_concurrency(); ++i) {
        threadPool.push_back(std::thread([&]() {
            workerThread(context); // will connect with inproc://workers
        }));
    }

    zmq::proxy(ventilatorProxy, workers, NULL);
}
```

ØMQ – Notes

- With ØMQ messages still need to be translated to procedure executions
- Object serialization has to be implemented on top of ØMQ

- There's much more functionality in ØMQ!
- Read the great guide: http://zguide.zeromq.org
- The examples in this lecture are based on the examples from the zguide

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- **Apache Thrift**

Apache Thrift

- **Remote Procedure Calls (RPCs):**

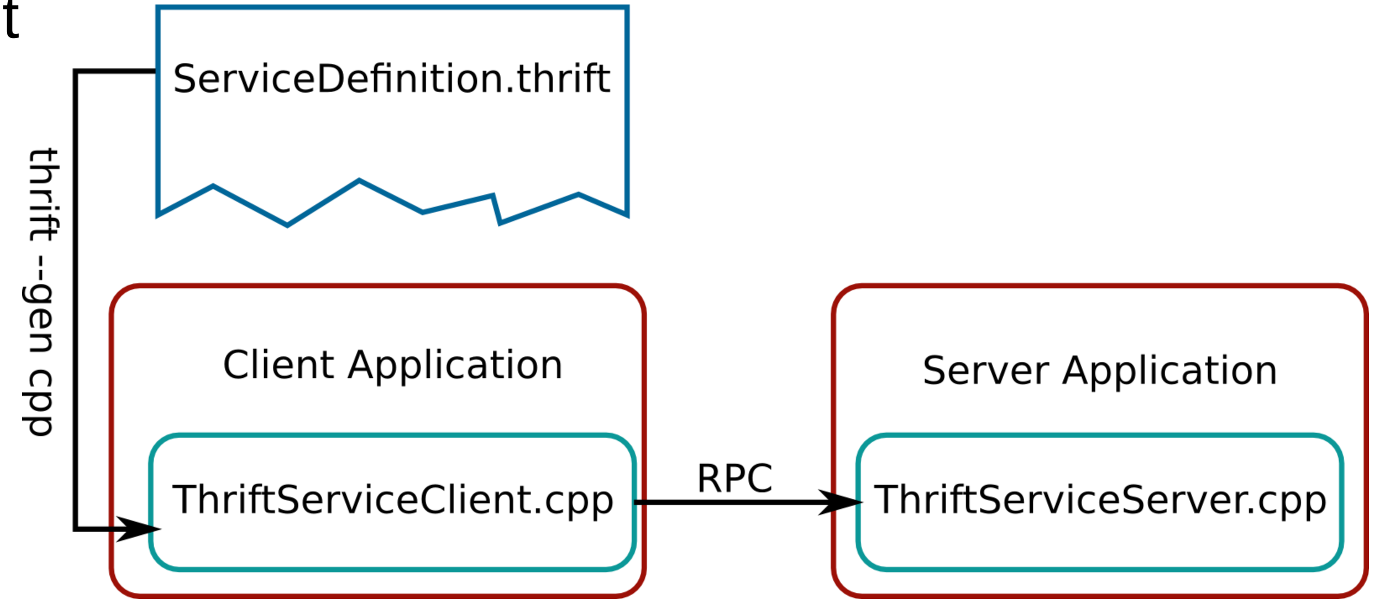
  Executing subroutines (functions, methods) on a program running remotely

- **Thrift is a scalable cross-language RPC framework developed by Facebook**
  - It implements the missing object serialization
- **It's an open source project in the Apache Software Foundation**

Apache Thrift

- **The developer defines services in an Interface Definition Language (IDL) file**

- **Thrift generates code (Interfaces) to be used to call these services remotely**
  - E.g. calling a Java Method from a PHP script running on a remote host



Thrift – Interface Definition

- **Interface Definition Language (.thrift) files**
  - Define namespace, data structures, types, methods, services
  - Similar to C syntax
  - Basic types are bool, byte, i16/32/64, double, string, map<t1,t2>, list<t1>, set<t1>

```
namespace cpp ch.cern.icsc14

enum Operation {
  ADD = 1,
  SUBTRACT = 2,
  MULTIPLY = 3,
  DIVIDE = 4
}
```

```
struct Work {
  1: i32 num1,
  2: i32 num2,
  3: Operation op
}
service Calculator {
  i32 calculate(1:Work w)
}
```

Thrift – Compiling Thrift Files

- **Thrift compiles the IDL files to server (and client) source code**
- **It generates thousands of lines of code with placeholders**
- **Calculator_server.skeleton.cpp:**

```
using namespace  ::ch::cern::icsc14;
class CalculatorHandler : virtual public CalculatorIf {
 public:
  CalculatorHandler() {
    // Your initialization goes here
  }

  int32_t calculate(const Work& w) {
    // Your implementation goes here
  }
};
```

Thrift – Documentation

- **There is only very little documentation online**
- **Useful links:**
    - http://wiki.apache.org/thrift/ThriftUsage
    - http://thrift-tutorial.readthedocs.org/
    - http://www.slideshare.net/dvirsky/introduction-to-thrift
    - http://diwakergupta.github.io/thrift-missing-guide

Good Luck!

Summary

- **There is no native C++ library for network programming**
- **There are many different libraries for different purposes**
  - Boost.Asio for easy **asynchronous** and **multithreaded** socket programming
  - ØMQ additionally provides **message passing** and helpful **patterns**
  - Apache Thrift provides an efficient **RPC framework**
- **All these libraries are cross-platform capable**
- **ØMQ and Thrift provide interfaces for many languages**

Visit https://github.com/JonasKunze for code snippets and these slides