uThreads

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Chapter 1

uThreads: Concurrent User Threads in C++(and C)

What are uThreads?

uThreads is a concurrent library based on cooperative scheduling of user-level threads(fibers) implemented in C++. User-level threads are lightweight threads that execute on top of kernel threads to provide concurrency as well as parallelism. Kernel threads are necessary to utilize processors, but they come with the following drawbacks:

- Each suspend/resume operation involves a kernel context switch
- Thread preemption causes additional overhead
- Thread priorities and advanced scheduling causes additional overhead

Cooperative user-level threads, on the other hand, provide light weight context switches and omit the additional overhead of preemption and kernel scheduling. Most Operating Systems only support a 1:1 thread mapping (1 user-level thread to 1 kernel-level thread), where multiple kernel threads execute at the same time to utilize multiple cores and provide parallelism. e.g., Linux supports only 1:1 thread mapping. There is also N:1 thread mapping, where multiple user-level threads can be mapped to a single kernel-level thread. The kernel thread is not aware of the user-level threads existence. For example, `Facebook's folly::fiber`, `libmill`, and `libtask` use N:1 mapping. Having N:1 mapping means if the application blocks at the kernel level, all user-level threads are blocked and application cannot move forward. One way to address this is to only block on user level, hence, blocking user-level threads. This setting works very well with IO bound applications, however, if a user thread requires using a CPU for a while, it can block other user threads and the task is better to be executed asynchronously on another core to prevent this from happening. In order to avoid this problem, user threads can be mapped to multiple kernel-level threads. Thus, creating the third scenario with M:N or hybrid mapping. e.g., `go` and `uC++` use M:N mapping.

uThreads supports M:N mapping of *uThreads* (user-level threads) over *kThreads* (kernel-level threads) with cooperative scheduling. kThreads can be grouped together by *Clusters*, and uThreads can migrate among Clusters. Figure 1 shows the structure of an application implemented using uThreads using a single ReadyQueue Scheduler. You can find the documentation here `http://samanbarghi.github.io/uThreads`

Webserver throughput results

Here are a comparsion of a simple webserver throughput with `fasthttp`, `cppsp`, and nodejs. Experiments are executed on my laptop (i7 quad core). Note that not much optimization is applied to any of the applications, thus there might me some space to squeeze more throughput out of these applications. You can check the source code of the sample webserver under the test directory. All servers return a "hello world" response, and the client (in this case wrk) throws a huge number of concurrent and pipelined requests at each server. This experiment shows the overhead of each framework since the response is kept very small (similar to `TechEmpower "plaintext" benchmark"`).

Dependencies

Currently uThreads only supports Linux on x86_64 platforms. It also depends on the following:

- gcc $>$ 4.8
- linux kernel $>=$ 2.9

Building and installation

To build and install the library issue the following commands:

```
1 make
2 make install
```

Currently, everything is installed under /usr/local/lib and /usr/local/include/uThreads. To change this you need to edit the Makefile and change the DEST_DIR.

Usage

- Include "uThreads/uThreads.h" in your source file.
- Link your program with uThreads library (-luThreads) at compile time.

There are sample applications under *test* directory, to compile them issue `make test`, and you can find the binaries under *bin* directory. Refer to the `documentation` for more information.

uThreads structure

This section explains the internals of uThreads.

Basics

Clusters are used to group kThreads together. Each Cluster can contain one or more kThreads, but each kThread only belongs to a single Cluster. Each Cluster includes a *Scheduler* which is used to schedule uThreads over kThreads in that Cluster. Application programmer decides how many kThreads belong to a *Cluster* by assigning them upon creation. *Clusters* can be used to execute different tasks over separate kThreads and if pinned properly, over separate cores. For exampl,e they can be used to provide better CPU cache locality for different set of tasks, by executing them on specific cores.

kThreads are kernel-level threads (std::thread), that are the main vehicle to utilize cores and execute the program. Each kThread can interact with the local scheduler in the *Cluster* and execute the *uThreads* provided by the local *Scheduler*, but it can move uThreads to another Cluster in the application. The former can happen when uThreads *yield* or *block* at user level, and the latter happens when uThreads *migrate* to another Cluster. Migration let the uThread continue execution on a different set of kThreads based on the requirements of the code.

uThreads are the main building blocks of the library. They are either sitting in a readyQueue or runQueue waiting to be picked by a kThread, running by a kThread, or blocked and waiting for an event to occur. uThreads are being

scheduled cooperatively over Clusters, they can either yield, migrate or block on an event to let other uThreads utilized the same kThread they are being executed over.

Each application has at least one Cluster, one kThread and one uThread. Each C++ application has at least one thread of execution (kernel thread) which runs the *main()* function. A C++ application that is linked with uThreads library, upon execution, creates a *defaultCluster*, a wrapper around the main execution thread and call it *defaultk↩ Thread*, and also a uThread called *mainUT* to take over the defaultkThread stack and run the *main* function.

In addition, there is a single *Poller kThread* which is responsible for polling the network devices, and multiplexing network events over the Cluster. uThreads provides a user-level blocking on network events, where network calls are non-blocking at the kernel-level but uThreads block on network events if the device is not ready. The poller thread is thus responsible for unblocking the uThreads upon receiving the related network event. The poller thread is using *edge triggered epoll* in Linux, and which is similar to how `Golang` supports multiplexing of network events.

Currently, uThreads only supports **fixed** stack sizes for performance purposes. uThread's stack is cached after finishing execution to avoid the extra overhead of memory allocation.

Scheduler

As Explained earlier, each *Cluster* has a local *Scheduler* which is responsible for distributing *uThreads* among the *kThreads* whithin that *Cluster*. Currently, there are 4 different schedulers, which will be explained below. These schedulers do not support any work sharing or work stealing at the moment and based on the type of the Scheduler either uThreads are assigned in a round robin manner, or kThreads ask the Scheduler for more uThreads when they run out of work. The type of the scheduler is determined at compile time by defining **SCHEDULERNO** and pass the related scheduler number. The default scheduler is Scheduler #2, with local instrusive Multiple-Producer-Single-Consumer Queues per kThread (since it provides better performance and scalability).

- **Global ReadyQueue per *Cluster***: The first scheduler is implemented using an unbounded intrusive Ready↩ Queue per Cluster, and C++ synchronization primitievs (std::mutex and std::condition_variable) are used to orchestrate kThreads to access the ReadyQueue. To avoid the high overhead of mutex and condition_variable (in linux: pthread_mutex and pthread_cond) under contention, a local queue is added to each kThread, so everytime a kThread runs out of work, it simply removes many uThreads, based on the size of the Ready↩ Queue and the number of kThreads in that Cluster, instead of one. The local queue is only accessed by a single kThread and thus does not require mutual exclusion. The following shows the design: To measure the performance of different schedulers, the follwing experiment is designed:
- The experiment starts with 2 Clusters.
- Thre are *k* kThreads per Cluster, and the number of kThreads are changed (x-axis of the following graphs shows the number of kThreads).
- There are $1,000,000 \times k$ uThreads created when the experiment starts.
- Each uThread migrates back and forth between Clusters.
- uThread exits after 10 migrations.
- We measure the number of migrations/second and plot it on y-axis, thus higher is better.

Figure 3 shows result for the first Scheduler:

Based on the results, this approach is not very scalable past 4 kThreads per Cluster.

- **Local RunQueue per kThread using mutex and cv**: To provide better scalability, we can remove the global ReadyQueue to avoid the contention for mutex. Thus, the next scheduler (#3, numbering does not follow the story line here), provides local unbounded intrusive queue per kThread and removes the global ReadyQueue. The scheduler assign the uThreads to kThreads in a round-robin manner. Each queue is protected with a std::mutex and std::condition_variable, and the following figure shows the design: and here are the results: Removing the bottleneck and getting rid of the central lock seems to provide better scalability, but can we do better?

- **Local RunQueue per kThread using lock-free non-intrusive Multiple-Producer-Single-Consumer Queue**: Since the only consumer for each local queue, is a single kThread, to reduce the synchronization overhead it is better to use a lock-free Multiple-Producer-Single-Consumer queue. The queue that is being used is a non-intrusive queue (you can find an implementation in the source code or here). With this queue, there is no contention on the consumer side and producers rarely block the consumer, and to push to the queue producers using an atomic exchange. Here is the result for using Scheduler #4:

- **Local RunQueue per kThread using lock-free intrusive Multiple-Producer-Single-Consumer Queue**: To avoid managing an extra state, the above queue is modified to be intrusive, and here are the results for using the intrusive queue:

For lower number of threads the global queue seems to do better, but as the number increases the intrusive lock-free MPSC Queue is a better Choice. The default scheduler for uThreads is Scheduler #2 (intrusive MPSCQ), which can be changed at compile time by defining **SCHEDULERNO** and set it to the appropriate scheduler.

You can add your own scheduler by looking at the source code under *src/runtime/schedulers*, and provide a scheduler number and a Scheduler class in its own header. Documentation for adding a new scheduler will be added as soon as the code base reaches a stable state.

Migration and Joinable uThreads

uThreads can be joinable, which means upon creation the creator uThread can block until they finish execution. There are three ways to execute a piece of code on another Cluster (These can be used to execute tasks asynchronously on current Cluster or a remote one):

- **Migration:** uThread can migrate to another Cluster to execute a piece of code and it can either migrate back to the previous Cluster or continue the execution on the same Cluster or migrate to a different Cluster. The state is saved in the stack and when migrated the state is resumed from the uThread's stack. The following code demonstrates a simple scenario of migrating to a different cluster and back, assuming uThread is executing on the *defaultCluster*:

```
Cluster *cluster1;

void func(){
    // some code
    migrate(*cluster1);
    // code to run on cluster1
    migrate(Cluster::getDefaultCluster());
 // some more code
}


int main(){

    cluster1 = new Cluster();
    kThread kt(*cluster1);
    uThread *ut = uThread::create();
    ut->start(Cluster::getDefaultCluster(), func);
.
.
.
}
```

- **Non-joinable uThread:** Create a non-joinable uThread on the remote Cluster and wait for it to finish execution. While waiting, the creator uThread continues execution and does not care about when the new uThread finishes the job.

```
Cluster *cluster1;

void run(){
    //code to run on cluster1
}
void func(){
    // some code
    uThread *ut2 = uThread::create(false); //create a non-joinable thread
    ut2->start(cluster1, run);
    //continue executing
 // some more code
}


int main(){

    cluster1 = new Cluster();
    kThread kt(*cluster1);
    uThread *ut = uThread::create();
    ut->start(Cluster::getDefaultCluster(), func);
.
.
.
}
```

- **Joinable uThread:** Create a joinable thread on the remote Cluster and wait for it to finish execution. While waiting, the uThread is blocked at user-level and will be unblocked when the new uThread finishes its job. Currently, only the creator can wait on the new uThread, waiting on the uThread from other uThreads leads to undefined behaviour. This will be fixed in the near future.

```
Cluster *cluster1;

void run(){
    //code to run on cluster1
}
void func(){
    // some code
    uThread *ut2 = uThread::create(true); //create a joinable thread
    ut2->start(cluster1, run);
    ut2->join(); //wait for ut2 to finish execution and join
 // some more code
}


int main(){

    cluster1 = new Cluster();
    kThread kt(*cluster1);
    uThread *ut = uThread::create();
    ut->start(Cluster::getDefaultCluster(), func);
.
.
.
}
```

User-level Blocking Synchronization Primitives

uThreads also provides user-level blocking synchronization and mutex primitives. It has basic Mutex, Condition Variable and Semaphore. You can find examples of their usage under *test* directory.

Examples

You can find various examples under the test directory in the `github repo`. There is an `EchoClient` and `EchoServer` implemented using uThreads.

There is also a simple `webserver` to test uThreads functionality.

For performance comparisons, memached code has been updated to use uThreads instead of event loops (except the thread that accepts connections), where tasks are assigned to uThreads instead of using the underlying event library. The code can be found `here`.

Acknowledgement

This work made possible through invaluable helps and advices I received from `Martin Karsten`.

Chapter 2

Hierarchical Index

2.1 Class Hierarchy

This inheritance list is sorted roughly, but not completely, alphabetically:

BlockingQueue 13
Cluster 16
ConditionVariable 18
Connection 19
IOPoller 26
Link
    kThread 26
    uThread 34
Mutex 29
    OwnerLock 31
Semaphore 33
uThreadCache 39

Chapter 3

Class Index

3.1 Class List

Here are the classes, structs, unions and interfaces with brief descriptions:

BlockingQueue
: A queue used to keep track of blocked uThreads . . . 13

Cluster
: Scheduler and Cluster of kThreads . . . 16

ConditionVariable
: A user level condition variable . . . 18

Connection
: Represents a network connection . . . 19

IOPoller . . . 26

kThread
: Object to represent kernel threads . . . 26

Mutex
: A user-level Mutex . . . 29

OwnerLock
: Owner Mutex where owner can recursively acquire the Mutex . . . 31

Semaphore
: A user-level Semaphore . . . 33

uThread
: User-level threads (fiber) . . . 34

uThreadCache
: Data structure to cache uThreads . . . 39

Chapter 4

File Index

4.1 File List

Here is a list of all documented files with brief descriptions:

/home/saman/Programming/Research/uThreads/src/cwrapper.h
C Wrapper for uThreads 41
/home/saman/Programming/Research/uThreads/src/io/**EpollIOHandler.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/io/**IOHandler.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/io/**Network.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/runtime/**BlockingSync.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/runtime/**Cluster.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/runtime/**kThread.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/runtime/**Stack.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/runtime/**uThread.h** . . . . . **??**
/home/saman/Programming/Research/uThreads/src/runtime/**uThreadCache.h** . . . . . **??**

Chapter 5

Class Documentation

5.1 BlockingQueue Class Reference

A queue used to keep track of blocked uThreads.

`#include <BlockingSync.h>`

Public Member Functions

- BlockingQueue (const BlockingQueue &)=delete
  BlockingQueue cannot be copied or assigned.
- const BlockingQueue & operator= (const BlockingQueue &)=delete
  BlockingQueue cannot be copied or assigned.
- bool empty () const
  Whether the queue is empty or not.
- bool suspend (std::mutex &lock)
  Suspends the uThread and add it to the queue.
- bool suspend (Mutex &)
  Suspends the uThread and add it to the queue.
- bool signal (std::mutex &lock, uThread *&owner)
  Unblock one blocked uThread, used for OwnerLock.
- bool signal (std::mutex &lock)
  unblock one blocked, used for Mutex
- bool signal (Mutex &)
  unblock one blocked uThread, used for ConditionVariable
- void signalAll (Mutex &)
  unblock all blocked uThreads, used for Condition Variable

Static Public Member Functions

- template<typename T >
  static void **postSwitchFunc** (void *ut, void *args)

Friends

- class **uThread**
- class **Mutex**
- class **OwnerLock**
- class **ConditionVariable**
- class **Semaphore**

5.1.1 Detailed Description

A queue used to keep track of blocked uThreads.

This queue is a FIFO queue used to hold blocked uThreads on Mutex, Semaphore, or Condition Variable.

5.1.2 Member Function Documentation

5.1.2.1 bool BlockingQueue::signal (std::mutex & *lock,* uThread ∗& *owner*)

Unblock one blocked uThread, used for OwnerLock.

Parameters

lock	mutex to be released after signal is done
owner	passed to support atomic setting of Mutex::owner

Returns

true if a uThread was unblocked, and false otherwise

5.1.2.2 bool BlockingQueue::signal (std::mutex & *lock*) [inline]

unblock one blocked, used for Mutex

Parameters

lock	mutex to be released after signal is done

Returns

true if a uThread was unblocked, and false otherwise

5.1.2.3 bool BlockingQueue::signal (Mutex & *mutex*)

unblock one blocked uThread, used for ConditionVariable

Parameters

Mutex	that is released after signal is done

Returns

true if a uThread was unblocked, and false otherwise

5.1.2.4 void BlockingQueue::signalAll (Mutex & *mutex*)

unblock all blocked uThreads, used for Condition Variable

Parameters

Mutex	to be released after signallAll is done

5.1.2.5 bool BlockingQueue::suspend (std::mutex & *lock*)

Suspends the uThread and add it to the queue.

Parameters

lock	a mutex to be released after blocking

Returns

whether the suspension was successful or not

Suspends the uThread and adds it to the BlockingQueue.

5.1.2.6 bool BlockingQueue::suspend (Mutex & *mutex*)

Suspends the uThread and add it to the queue.

Parameters

lock	a mutex to be released after blocking

Returns

whether the suspension was successful or not

Suspends the uThread and adds it to the BlockingQueue.

The documentation for this class was generated from the following files:

- /home/saman/Programming/Research/uThreads/src/runtime/BlockingSync.h
- /home/saman/Programming/Research/uThreads/src/runtime/BlockingSync.cpp

5.2 Cluster Class Reference

Scheduler and Cluster of kThreads.

`#include <Cluster.h>`

Public Member Functions

- Cluster ()
- Cluster (const Cluster &)=delete
- const Cluster & operator= (const Cluster &)=delete
- uint64_t getID () const

  Get the ID of Cluster.
- size_t getNumberOfkThreads () const

  Total number of kThreads belonging to this cluster.

Static Public Member Functions

- static Cluster & getDefaultCluster ()

Friends

- class **kThread**
- class **uThread**
- class **Connection**
- class **IOHandler**
- class **Scheduler**

5.2.1 Detailed Description

Scheduler and Cluster of kThreads.

Cluster is an entity that contains multiple kernel threads (kThread). Each cluster is responsible for maintaining a ready queue and performing basic scheduling tasks. Programs can have as many Clusters as is necessary. The Cluster's ReadyQueue is a multiple-producer multiple-consumer queue where consumers are only kThreads belonging to that Cluster, and producers can be any running kThread. kThreads constantly push and pull uThreads to/from the ReadyQueue. Cluster is an interface between kThreads and the ReadyQueue, and also provides the means to group kThreads together.

Each Cluster has its own IOHandler. IOHandler is responsible for providing asynchronous nonblocking access to IO devices. For now each instance of an IOHandler has its own dedicated poller thread, which means each cluster has a dedicated IO poller thread when it is created. This might change in the future. Each uThread that requires access to IO uses the IOHandler to avoid blocking the kThread, if the device is ready for read or write, the uThread continues otherwise it blocks until it is ready, and the kThread execute another uThread from the ReadyQueue.

When the program starts a defaultCluster is created for the kernel thread that runs the *main* function. defaultCluster can be used like any other clusters.

5.2.2 Constructor & Destructor Documentation

5.2.2.1 Cluster::Cluster ( )

Create a new Cluster

5.2.2.2 Cluster::Cluster (const Cluster &) [delete]

Cluster cannot be copied or assigned.

5.2.3 Member Function Documentation

5.2.3.1 static Cluster& Cluster::getDefaultCluster ( ) [inline], [static]

Returns

defaultCluster

5.2.3.2 uint64_t Cluster::getID ( ) const [inline]

Get the ID of Cluster.

Returns

The ID of the cluster

5.2.3.3 size_t Cluster::getNumberOfkThreads ( ) const [inline]

Total number of kThreads belonging to this cluster.

Returns

Total number of kThreads belonging to this cluster

5.2.3.4 const Cluster& Cluster::operator= (const Cluster &) [delete]

Cluster cannot be copied or assigned.

The documentation for this class was generated from the following files:

- /home/saman/Programming/Research/uThreads/src/runtime/Cluster.h
- /home/saman/Programming/Research/uThreads/src/runtime/Cluster.cpp
- /home/saman/Programming/Research/uThreads/src/runtime/uThread.cpp

5.3 ConditionVariable Class Reference

A user level condition variable.

`#include <BlockingSync.h>`

Public Member Functions

- void wait (Mutex &mutex)

  Block uThread on the condition variable using the provided mutex.
- void signal (Mutex &mutex)

  Unblock one uThread waiting on the condition variable.
- void signalAll (Mutex &mutex)

  unblock all uThreads waiting on the condition variable
- bool empty ()

  Whether the waiting list is empty or not.

5.3.1 Detailed Description

A user level condition variable.

User-level Condition Variable blocks only in user-level by suspending the uThreads instead of blocking the kernel threads.

5.3.2 Member Function Documentation

5.3.2.1 bool ConditionVariable::empty ( ) [inline]

Whether the waiting list is empty or not.

Returns

Whether the waiting list is empty or not

5.3.2.2 void ConditionVariable::signal (Mutex & *mutex*) [inline]

Unblock one uThread waiting on the condition variable.

Parameters

mutex	The mutex to be released after unblocking is done

5.3.2.3 void ConditionVariable::signalAll (Mutex & *mutex*) [inline]

unblock all uThreads waiting on the condition variable

Parameters

mutex	The mutex to be released after unblocking is done

5.3.2.4 void ConditionVariable::wait (Mutex & *mutex*) [inline]

Block uThread on the condition variable using the provided mutex.

Parameters

mutex	used to synchronize access to the condition

The documentation for this class was generated from the following file:

- /home/saman/Programming/Research/uThreads/src/runtime/BlockingSync.h

5.4 Connection Class Reference

Represents a network connection.

`#include <Network.h>`

Public Member Functions

- Connection ()
  Create a Connection that does not have.
- Connection (int fd)
  Create a connection object with the provided fd.
- Connection (int domain, int type, int protocol) throw (std::system_error)
  Same as socket syscall adds | SOCK_NONBLOCK to type.
- int accept (Connection *conn, struct sockaddr *addr, socklen_t *addrlen)
  nonblocking accept syscall and updating the passed Connection object
- Connection * accept (struct sockaddr *addr, socklen_t *addrlen) throw (std::system_error)
  Accepts a connection and returns a connection object.
- int socket (int domain, int type, int protocol)
  Same as socket syscall, set the fd for current connection.
- int listen (int backlog)
  Same as listen syscall on current fd.
- int bind (const struct sockaddr *addr, socklen_t addrlen)
  Same as bind syscall.
- int connect (const struct sockaddr *addr, socklen_t addrlen)
  Same as connect syscall.
- ssize_t recv (void *buf, size_t len, int flags)
  Call the underlying system call on Connection's file descriptor.
- ssize_t recvfrom (void *buf, size_t len, int flags, struct sockaddr *src_addr, socklen_t *addrlen)
  Call the underlying system call on Connection's file descriptor.

- ssize_t recvmsg (int sockfd, struct msghdr *msg, int flags)

  Call the underlying system call on Connection's file descriptor.
- int recvmmsg (int sockfd, struct mmsghdr *msgvec, unsigned int vlen, unsigned int flags, struct timespec *timeout)

  Call the underlying system call on Connection's file descriptor.
- ssize_t send (const void *buf, size_t len, int flags)

  Call the underlying system call on Connection's file descriptor.
- ssize_t sendto (int sockfd, const void *buf, size_t len, int flags, const struct sockaddr *dest_addr, socklen_t addrlen)

  Call the underlying system call on Connection's file descriptor.
- ssize_t sendmsg (const struct msghdr *msg, int flags)

  Call the underlying system call on Connection's file descriptor.
- int sendmmsg (int sockfd, struct mmsghdr *msgvec, unsigned int vlen, unsigned int flags)

  Call the underlying system call on Connection's file descriptor.
- ssize_t read (void *buf, size_t count)

  Call the underlying system call on Connection's file descriptor.
- ssize_t write (const void *buf, size_t count)

  Call the underlying system call on Connection's file descriptor.
- void blockOnRead ()

  Block uThread, waiting for fd to become ready for read.
- void blockOnWrite ()

  Block uThread, waiting for fd to become ready for write.
- int close ()

  closes the socket
- int getFd () const

  return the Connection's file descriptor

5.4.1 Detailed Description

Represents a network connection.

Connection class is a wrapper around socket and provides the ability to do nonblocking read/write on sockets, and nonblocking accept. It first tries to read/write/accept and if the fd is not ready uses the underlying polling structure to wait for the fd to be ready. Thus, the uThread that is calling these functions is blocked if the fd is not ready, and kThread never blocks.

5.4.2 Constructor & Destructor Documentation

5.4.2.1 Connection::Connection ( ) [inline]

Create a Connection that does not have.

This is useful for accept or socket functions that require a Connection object without fd being set

5.4.2.2 Connection::Connection (int *fd*) [inline]

Create a connection object with the provided fd.

Parameters

fd	If the connection is already established by other means, set the fd and add it to the polling structure

5.4.2.3 Connection::Connection (int *domain,* int *type,* int *protocol*) throw std::system_error)

Same as socket syscall adds | SOCK_NONBLOCK to type.

Returns

same as socket syscall

Throws a std::system_error exception. Do not call from C code. The unerlying socket is always nonbelocking. This is achieved by adding a (| SOCK_NONBLOCK) to type, thus requires linux kernels $>$ 2.6.27

5.4.3 Member Function Documentation

5.4.3.1 int Connection::accept (Connection * *conn,* struct sockaddr * *addr,* socklen_t * *addrlen*)

nonblocking accept syscall and updating the passed Connection object

Parameters

conn	Pointer to a Connection object that is not initialized

Returns

same as accept system call

This format is used for compatibility with C

5.4.3.2 Connection * Connection::accept (struct sockaddr * *addr,* socklen_t * *addrlen*) throw std::system_error)

Accepts a connection and returns a connection object.

Returns

Newly created connection

Throws a std::system_error exception on error. Never call from C.

5.4.3.3 int Connection::bind (const struct sockaddr * *addr,* socklen_t *addrlen*)

Same as bind syscall.

Returns

Same as bind syscall

5.4.3.4 int Connection::close ( )

closes the socket

Returns

the same as close system call

5.4.3.5 int Connection::connect (const struct sockaddr * *addr*, socklen_t *addrlen*)

Same as connect syscall.

Returns

Same as connect syscall

5.4.3.6 int Connection::getFd ( ) const [inline]

return the Connection's file descriptor

Returns

file descriptor

5.4.3.7 int Connection::listen (int *backlog*)

Same as listen syscall on current fd.

Returns

Same as listen syscall

5.4.3.8 ssize_t Connection::read (void * *buf*, size_t *count*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.9 ssize_t Connection::recv (void * *buf*, size_t *len*, int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.10 ssize_t Connection::recvfrom (void * *buf*, size_t *len*, int *flags*, struct sockaddr * *src_addr*, socklen_t * *addrlen*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.11 int Connection::recvmmsg (int *sockfd*, struct mmsghdr * *msgvec*, unsigned int *vlen*, unsigned int *flags*, struct timespec * *timeout*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.12 ssize_t Connection::recvmsg (int *sockfd,* struct msghdr * *msg,* int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.13 ssize_t Connection::send (const void * *buf,* size_t *len,* int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.14 int Connection::sendmmsg (int *sockfd,* struct mmsghdr * *msgvec,* unsigned int *vlen,* unsigned int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.15 ssize_t Connection::sendmsg (const struct msghdr * *msg*, int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.16 ssize_t Connection::sendto (int *sockfd*, const void * *buf*, size_t *len*, int *flags*, const struct sockaddr * *dest_addr*, socklen_t *addrlen*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

5.4.3.17 int Connection::socket (int *domain*, int *type*, int *protocol*)

Same as socket syscall, set the fd for current connection.

Returns

same as socket syscall The unerlying socket is always nonbelocking. This is achieved by adding a (| SOC↩ K_NONBLOCK) to type, thus requires linux kernels > 2.6.27

5.4.3.18 ssize_t Connection::write (const void * *buf*, size_t *count*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

The documentation for this class was generated from the following files:

- /home/saman/Programming/Research/uThreads/src/io/Network.h
- /home/saman/Programming/Research/uThreads/src/io/Network.cpp

5.5 IOPoller Class Reference

Protected Member Functions

- **IOPoller** (IOHandler &)

The documentation for this class was generated from the following files:

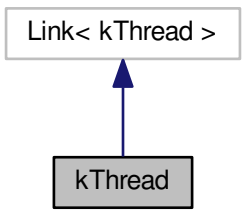
- /home/saman/Programming/Research/uThreads/src/io/EpollIOHandler.h
- /home/saman/Programming/Research/uThreads/src/io/EpollIOHandler.cpp

5.6 kThread Class Reference

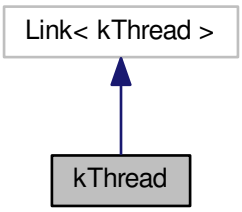
Object to represent kernel threads.

`#include <kThread.h>`

Inheritance diagram for kThread:



Collaboration diagram for kThread:



Public Member Functions

- kThread (Cluster &)

  Create a kThread on the passed cluster.
- kThread (const kThread &)=delete

  kThread cannot be copied or assigned.
- const kThread & operator= (const kThread &)=delete

  kThread cannot be copied or assigned.
- std::thread::native_handle_type getThreadNativeHandle ()

  return the native hanlde for the kernel thread
- std::thread::id getID ()

  returns the kernel thread ID

Static Public Member Functions

- static kThread * currentkThread ()

  Get the pointer to the current kThread.
- static uint getTotalNumberOfkThreads ()

Friends

- class **uThread**
- class **Cluster**
- class **IOHandler**
- class **Scheduler**

5.6.1 Detailed Description

Object to represent kernel threads.

kThread is an interface for underlying kernel threads. kThreads are pulling and pushing uThreads from Ready↩ Queue provided by the Cluster and context switch to them and execute them. Each kThread belongs to only and only one Cluster and it can only pull uThreads from the ReadyQueue of that Cluster. However, kThreads can push uThreads to the ReadyQueue of any cluster.

defaultKT is the first kernel thread that executes and is responsible for running the main() function. defaultKT is created when the program starts.

Each kThread has a mainUT which is a uThread used when the ReadyQueue is empty. mainUT is used to switch out the previous uThread and either pull uThreads from the ReadyQueue if it's not empty, or block on a condition variable waiting for uThreads to be pushed to the queue.

kThreads can be created by passing a Cluster to the constructor of the kThread.

5.6.2 Constructor & Destructor Documentation

5.6.2.1 kThread::kThread (Cluster & *cluster*)

Create a kThread on the passed cluster.

Parameters

The	Cluster this kThread belongs to.

5.6.3 Member Function Documentation

5.6.3.1 static kThread* kThread::currentkThread ( ) [inline], [static]

Get the pointer to the current kThread.

Returns

current kThread

This is necessary when a uThread wants to find which kThread it is being executed over.

5.6.3.2 std::thread::id kThread::getID ( )

returns the kernel thread ID

Returns

the kThread ID

The returned type depends on the platform.

5.6.3.3 std::thread::native_handle_type kThread::getThreadNativeHandle ( )

return the native hanlde for the kernel thread

Returns

native handle for the kThread

In linux this is pthread_t representation of the thread.

5.6.3.4 static uint kThread::getTotalNumberOfkThreads ( ) [inline], [static]

Returns

total number of kThreads running under the program.

5.6.3.5 const kThread& kThread::operator= (const kThread &) [delete]

kThread cannot be copied or assigned.

The documentation for this class was generated from the following files:

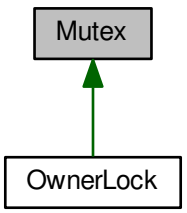
- /home/saman/Programming/Research/uThreads/src/runtime/kThread.h
- /home/saman/Programming/Research/uThreads/src/runtime/kThread.cpp
- /home/saman/Programming/Research/uThreads/src/runtime/uThread.cpp

5.7 Mutex Class Reference

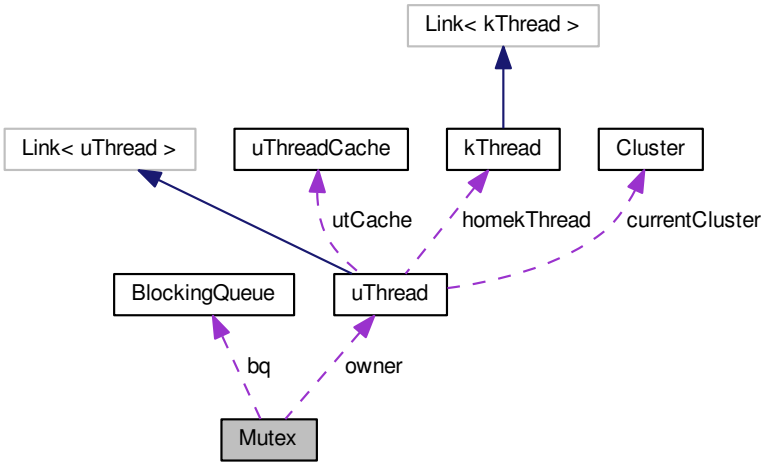
A user-level Mutex.

`#include <BlockingSync.h>`

Inheritance diagram for Mutex:



Collaboration diagram for Mutex:



Public Member Functions

- template<bool OL = false>
  bool acquire ()

  acquire the mutex
- void release ()

  release the Mutex
- void **unlock** ()

Protected Member Functions

- template<bool OL>
  bool **internalAcquire** (mword timeout)
- void **internalRelease** ()

Protected Attributes

- std::mutex **lock**
- BlockingQueue **bq**
- uThread * **owner**

Friends

- class **ConditionVariable**
- class **Semaphore**
- class **BlockingQueue**

5.7.1 Detailed Description

A user-level Mutex.

5.7.2 Member Function Documentation

5.7.2.1 template<bool OL = false> bool Mutex::acquire ( ) [inline]

acquire the mutex

Returns

true if it was acquired, false otherwise

The return value is only for when timeouts are implemented

The documentation for this class was generated from the following file:

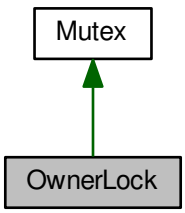
- /home/saman/Programming/Research/uThreads/src/runtime/BlockingSync.h

5.8 OwnerLock Class Reference

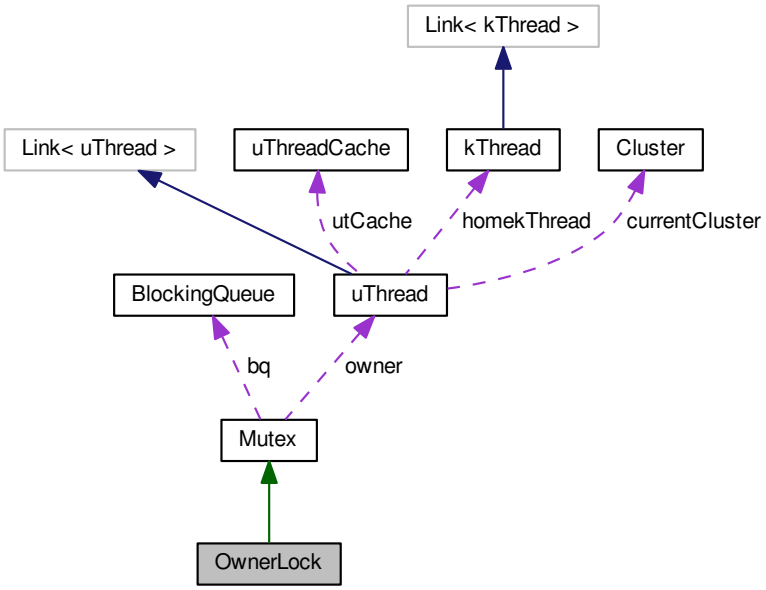
an Owner Mutex where owner can recursively acquire the Mutex

`#include <BlockingSync.h>`

Inheritance diagram for OwnerLock:



Collaboration diagram for OwnerLock:



Public Member Functions

- OwnerLock ()
  Create a new OwnerLock.
- mword acquire ()
  Acquire the OwnerLock.
- mword release ()
  Release the OwnerLock once.

Additional Inherited Members

5.8.1 Detailed Description

an Owner Mutex where owner can recursively acquire the Mutex

5.8.2 Member Function Documentation

5.8.2.1 mword OwnerLock::acquire ( ) [inline]

Acquire the OwnerLock.

Returns

The number of times current owner acquired the lock

5.8.2.2 mword OwnerLock::release ( ) [inline]

Release the OwnerLock once.

Returns

The number of times current owner acquired the lock, if lock is released completely the result is 0

The documentation for this class was generated from the following file:

- /home/saman/Programming/Research/uThreads/src/runtime/BlockingSync.h

5.9 Semaphore Class Reference

A user-level Semaphore.

`#include <BlockingSync.h>`

Public Member Functions

- Semaphore (mword c=0)
  Create a new Semaphore.
- bool P ()
  Decrement the value of the Semaphore.
- void V ()
  increment the value of the Semaphore

5.9.1 Detailed Description

A user-level Semaphore.

blocks in user levle by blocking uThreads and does not cause kernel threads to block.

5.9.2 Constructor & Destructor Documentation

5.9.2.1 Semaphore::Semaphore (mword *c* = 0) [inline], [explicit]

Create a new Semaphore.

Parameters

c	Initial value of the Semaphore

5.9.3 Member Function Documentation

5.9.3.1 bool Semaphore::P ( ) [inline]

Decrement the value of the Semaphore.

Returns

Whether it was successful or not

The documentation for this class was generated from the following file:

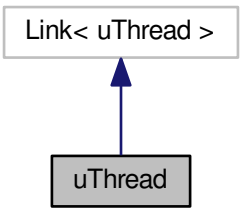
- /home/saman/Programming/Research/uThreads/src/runtime/BlockingSync.h

5.10 uThread Class Reference

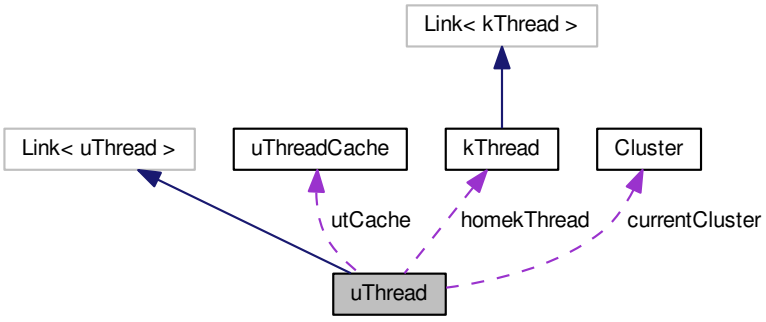
user-level threads (fiber)

`#include <uThread.h>`

Inheritance diagram for uThread:



Collaboration diagram for uThread:



Public Member Functions

- uThread (const uThread &)=delete

  uThread cannot be copied or assigned
- const uThread & operator= (const uThread &)=delete
- void start (const Cluster &cluster, ptr_t func, ptr_t arg1=nullptr, ptr_t arg2=nullptr, ptr_t arg3=nullptr)

  start the uThread by calling the function passed to it
- void resume ()

  Resumes the uThread. If uThread is blocked or is waiting on IO it will be placed back on the ReadyQueue.
- bool join ()

  Wait for uThread to finish execution and exit.
- void detach ()

  Detach a joinable thread.
- Cluster & getCurrentCluster () const

  return the current Cluster uThread is executed on
- uint64_t getID () const

  get the ID of this uThread

Static Public Member Functions

- static uThread * create (size_t ss, bool joinable=false)

  Create a uThread with a given stack size.
- static uThread * create (bool joinable=false)

  Create a uThread with default stack size.
- static void yield ()

  Causes uThread to yield.
- static void terminate ()

  Terminates the uThread.
- static void migrate (Cluster *)

  Move the uThread to the provided cluster.
- static uint64_t getTotalNumberofUTs ()
- static uThread * currentUThread ()

  Get a pointer to the current running uThread.

Protected Types

- enum **State** : std::uint8_t {
  INITIALIZED, **READY**, **RUNNING**, **YIELD**,
  MIGRATE, **WAITING**, **TERMINATED** }
- enum **JState** : std::uint8_t { **DETACHED**, **JOINABLE**, **JOINING** }

Protected Member Functions

- uThread (vaddr sb, size_t ss)
- virtual void **destory** (bool)
- void **reset** ()
- void **suspend** (funcvoid2_t, void *)

Static Protected Member Functions

- static vaddr **createStack** (size_t)
- static void **invoke** (funcvoid3_t, ptr_t, ptr_t, ptr_t) __noreturn

Protected Attributes

- Cluster * **currentCluster**
- kThread * **homekThread**
- vaddr **stackPointer**
- vaddr **stackBottom**
- size_t **stackSize**
- UTVar * **utvar**
- uint64_t **uThreadID**
- enum uThread::State **state**
- enum uThread::JState **jState**

Static Protected Attributes

- static uThreadCache **utCache**
- static std::atomic_ulong **totalNumberofUTs**
- static std::atomic_ulong **uThreadMasterID**

Friends

- class **uThreadCache**
- class **kThread**
- class **Cluster**
- class **BlockingQueue**
- class **IOHandler**
- class **Scheduler**

5.10.1 Detailed Description

user-level threads (fiber)

uThreads are building blocks of this library. They are lightweight threads and do not have the same context switch overhead as kernel threads. Each uThread is an execution unit provided to run small tasks. uThreads are being managed cooperatively and there is no preemption involved. uThreads either yield, migrate, or blocked and giving way to other uThreads to get a chance to run.

Due to the cooperative nature of uThreads, it is recommended that uThreads do not block the underlying kernel thread for a long time. However, since there can be multiple kernel threads (kThread) in the program, if one or more uThreads block underlying kThreads for small amount of time the execution of the program does not stop and other kThreads keep executing.

Another pitfall can be when all uThreads are blocked and each waiting for an event to occurs which can cause deadlocks. It is programmer's responsibility to make sure this never happens. Although it never happens unless a uThread is blocked without a reason (not waiting on a lock or IO), otherwise there is always an event (another uThread or polling structure) that unblock the uThread.

Each uThread has its own stack which is very smaller than kernel thread's stack. This stack is allocated when uThread is created.

5.10.2 Constructor & Destructor Documentation

5.10.2.1 uThread::uThread (vaddr *sb,* size_t *ss*) [inline],[protected]

The main and only constructor for uThread. uThreads are not supposed to be created by using the constructor. The memory used to save the uThread object is allocated at the beginning of its own stack. Thus, by freeing the stack memory uThread object is being destroyed as well. Therefore, the implicit destructor is not necessary.

5.10.3 Member Function Documentation

5.10.3.1 uThread * uThread::create (size_t *ss,* bool *joinable* = false) [static]

Create a uThread with a given stack size.

Parameters

ss	stack size
joinable	Whether this thread is joinable or detached

Returns

a pointer to a new uThread

This function relies on a uThreadCache structure and does not always allocate the stack.

5.10.3.2 static uThread* uThread::create (bool *joinable* = false) [inline],[static]

Create a uThread with default stack size.

Parameters

joinable	Whether this thread is joinable or detached

Returns

a pointer to a new uThread

5.10.3.3 uThread * uThread::currentUThread ( ) [static]

Get a pointer to the current running uThread.

Returns

pointer to the current uThread

5.10.3.4 Cluster& uThread::getCurrentCluster ( ) const [inline]

return the current Cluster uThread is executed on

Returns

the current Cluster uThread is executed on

5.10.3.5 uint64_t uThread::getID ( ) const [inline]

get the ID of this uThread

Returns

ID of the uThread

5.10.3.6 static uint64_t uThread::getTotalNumberofUTs ( ) [inline], [static]

Returns

Total number of uThreads in the program

This number does not include mainUT or IOUTs

5.10.3.7 bool uThread::join ( )

Wait for uThread to finish execution and exit.

Returns

Whether join was successful or failed

5.10.3.8 void uThread::migrate (Cluster * *cluster*) [static]

Move the uThread to the provided cluster.

Parameters

cluster	This function is used to migrate the uThread to another Cluster. Migration is useful specially if clusters form a pipeline of execution.

5.10.3.9 const uThread& uThread::operator= (const uThread &) [delete]

5.10.3.10 void uThread::start (const Cluster & *cluster*, ptr_t *func*, ptr_t *arg1* = `nullptr`, ptr_t *arg2* = `nullptr`, ptr_t *arg3* = `nullptr`)

start the uThread by calling the function passed to it

Parameters

cluster	The cluster that function belongs to.
func	a pointer to a function that should be executed by the uThread.
arg1	first argument of the function (can be nullptr)
arg2	second argument of the function (can be nullptr)
arg3	third argument of the function (can be nullptr)

After creating the uThread and allocating the stack, the start() function should be called to get the uThread going.

5.10.3.11 void uThread::terminate ( ) [static]

Terminates the uThread.

By calling this function uThread is being terminated and uThread object is either destroyed or put back into the cache.

5.10.3.12 void uThread::yield ( ) [static]

Causes uThread to yield.

uThread give up the execution context and place itself back on the ReadyQueue of the Cluster. If there is no other uThreads available to switch to, the current uThread continues execution.

The documentation for this class was generated from the following files:

- /home/saman/Programming/Research/uThreads/src/runtime/uThread.h
- /home/saman/Programming/Research/uThreads/src/runtime/uThread.cpp

5.11 uThreadCache Class Reference

Data structure to cache uThreads.

`#include <uThreadCache.h>`

Public Member Functions

- **uThreadCache** (size_t size=defaultuThreadCacheSize)
- ssize_t push (uThread *ut)

  adds a uThread to the cache
- uThread * pop ()

  pop a uThread from the list in FIFO order and return it

5.11.1 Detailed Description

Data structure to cache uThreads.

uThreadCache is a linked list of uThreads using and intrusive container to cache all terminated uThreads. Instead of destroying the memory allocated for the stack, simply reset the stack pointer and push it to the cache.

5.11.2 Member Function Documentation

5.11.2.1 uThread* uThreadCache::pop ( ) [inline]

pop a uThread from the list in FIFO order and return it

Returns

nullptr on failure, or a pointer to a uThread on success

5.11.2.2 ssize_t uThreadCache::push (uThread * *ut*) [inline]

adds a uThread to the cache

Parameters

ut	pointer to a uThread

Returns

size of the cache if push was successful or -1 if not

This function tries to push a uThread into the cache structure. If the cache is full or the mutex cannot be acquired immediately the operation has failed and the function returns -1. Otherwise, it adds the uThread to the list and return the size of the cache.

The documentation for this class was generated from the following file:

- /home/saman/Programming/Research/uThreads/src/runtime/uThreadCache.h

Chapter 6

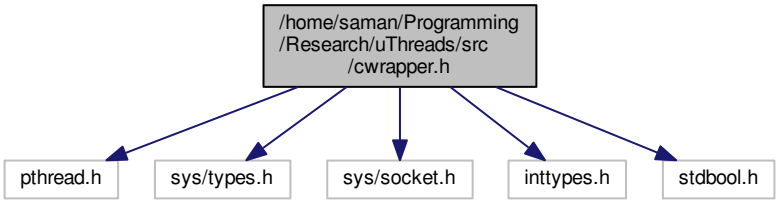
File Documentation

6.1 /home/saman/Programming/Research/uThreads/src/cwrapper.h File Reference

C Wrapper for uThreads.

```
#include <pthread.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <inttypes.h>
#include <stdbool.h>
```

Include dependency graph for cwrapper.h:



Cluster

C interface for class Cluster.

- typedef struct WCluster **WCluster**
- WCluster * cluster_create ()
- void cluster_destroy (WCluster *cluster)
- WCluster * cluster_get_default ()
- WCluster * cluster_get_current ()
- uint64_t cluster_get_id (WCluster *cluster)

  Get the ID of Cluster.
- size_t cluster_get_number_of_kThreads (WCluster *cluster)

  Total number of kThreads belonging to this cluster.

kThread

C interface for class kThread.

- typedef struct WkThread **WkThread**
- WkThread * kThread_create (WCluster *cluster)
- void kThread_destroy (WkThread *kt)
- uint64_t kThread_get_total_number_of_kThreads ()
- WkThread * kThread_get_current ()

  Get the pointer to the current kThread.
- pthread_t kThread_get_current_pthread_id ()

  return the native hanlde for the kernel thread
- pthread_t kThread_get_pthread_id (WkThread *kt)

  return the native hanlde for the kernel thread

uThread

C interface for class uThread.

- typedef struct WuThread **WuThread**
- WuThread * uThread_create (bool joinable)

  Create a uThread with a given stack size.
- void uThread_start (WuThread *ut, WCluster *cluster, void *func, void *arg1, void *arg2, void *arg3)

  start the uThread by calling the function passed to it
- void uThread_migrate (WCluster *cluster)

  Move the uThread to the provided cluster.
- void uThread_terminate (WuThread *ut)

  Terminates the uThread.
- void uThread_yield ()

  Causes uThread to yield.
- bool uThread_join (WuThread *ut)

  Wait for uThread to finish execution and exit.
- void uThread_detach (WuThread *ut)

  Detach a joinable thread.
- uint64_t uThread_get_id (WuThread *ut)

  get the ID of this uThread
- WuThread * uThread_get_current ()

  Get a pointer to the current running uThread.
- uint64_t uThread_get_total_number_of_uThreads ()

Connection

C interface for class Connection.

- typedef struct WConnection **WConnection**
- WConnection * connection_create ()

  Create a Connection that does not have.
- WConnection * connection_create_with_fd (int fd)

  Create a connection object with the provided fd.
- WConnection * connection_create_socket (int domain, int type, int protocol)

  Same as socket syscall adds | SOCK_NONBLOCK to type.
- void connection_destroy (WConnection *c)
- int connection_accept (WConnection *acceptor, WConnection *conn, struct sockaddr *addr, socklen_t *addrlen)

  nonblocking accept syscall and updating the passed Connection object
- WConnection * connection_accept_connenction (WConnection *acceptor, struct sockaddr *addr, socklen_t *addrlen)

  Accepts a connection and returns a connection object.
- int connection_socket (WConnection *conn, int domain, int type, int protocol)

  Same as socket syscall, set the fd for current connection.
- int connection_listen (WConnection *conn, int backlog)

  Same as listen syscall on current fd.
- int connection_bind (WConnection *conn, const struct sockaddr *addr, socklen_t addrlen)

  Same as bind syscall.
- int connection_connect (WConnection *conn, const struct sockaddr *addr, socklen_t addrlen)

  Same as connect syscall.
- int connection_close (WConnection *conn)

  closes the socket
- ssize_t connection_recv (WConnection *conn, void *buf, size_t len, int flags)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_recvfrom (WConnection *conn, void *buf, size_t len, int flags, struct sockaddr *src_addr, socklen_t *addrlen)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_recvmsg (WConnection *conn, int sockfd, struct msghdr *msg, int flags)

  Call the underlying system call on Connection's file descriptor.
- int connection_recvmmsg (WConnection *conn, int sockfd, struct mmsghdr *msgvec, unsigned int vlen, unsigned int flags, struct timespec *timeout)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_send (WConnection *conn, const void *buf, size_t len, int flags)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_sendto (WConnection *conn, int sockfd, const void *buf, size_t len, int flags, const struct sockaddr *dest_addr, socklen_t addrlen)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_sendmsg (WConnection *conn, const struct msghdr *msg, int flags)

  Call the underlying system call on Connection's file descriptor.
- int connection_sendmmsg (WConnection *conn, int sockfd, struct mmsghdr *msgvec, unsigned int vlen, unsigned int flags)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_read (WConnection *conn, void *buf, size_t count)

  Call the underlying system call on Connection's file descriptor.
- ssize_t connection_write (WConnection *conn, const void *buf, size_t count)

Call the underlying system call on Connection's file descriptor.

- void connection_block_on_read (WConnection *conn)

  Block uThread, waiting for fd to become ready for read.
- void connection_block_on_write (WConnection *conn)

  Block uThread, waiting for fd to become ready for write.
- int connection_get_fd (WConnection *conn)

Mutex

C interface for class Mutex.

- typedef struct WMutex **WMutex**
- WMutex * mutex_create ()
- void mutex_destroy (WMutex *mutex)
- bool mutex_acquire (WMutex *mutex)

  acquire the mutex
- void mutex_release (WMutex *mutex)

  release the Mutex

OwnerLock

C interface for class OwnerLock.

- typedef struct WOwnerLock **WOwnerLock**
- WOwnerLock * ownerlock_create ()
- void ownerlock_destroy (WOwnerLock *olock)
- uint64_t ownerlock_acquire (WOwnerLock *olock)
- void ownerlock_release (WOwnerLock *olock)

ConditionVariable

C interface for class ConditionVariable.

- typedef struct WConditionVariable **WConditionVariable**
- WConditionVariable * condition_variable_create ()
- void condition_variable_destroy (WConditionVariable *cv)
- void condition_variable_wait (WConditionVariable *cv, WMutex *mutex)

  Block uThread on the condition variable using the provided mutex.
- void condition_variable_signal (WConditionVariable *cv, WMutex *mutex)

  Unblock one uThread waiting on the condition variable.
- void condition_variable_signall_all (WConditionVariable *cv, WMutex *mutex)

  unblock all uThreads waiting on the condition variable
- bool condition_variable_empty (WConditionVariable *cv)

  Whether the waiting list is empty or not.

Semaphore

C interface for class Semaphore.

- typedef struct WSemaphore **WSemaphore**
- WSemaphore * semaphore_create ()

  Create a new Semaphore.
- void semaphore_destroy (WSemaphore *sem)
- bool semaphore_p (WSemaphore *sem)

  Decrement the value of the Semaphore.
- void semaphore_v (WSemaphore *sem)

  increment the value of the Semaphore

uThreadPool

C interface for class uThreadPool.

- typedef struct WuThreadPool **WuThreadPool**
- WuThreadPool * **uthreadpool_create** ()
- void **uthreadpool_destory** (WuThreadPool *utp)
- void **uthreadpool_execute** (WuThreadPool *utp, WCluster *cluster, void *(*start_routine)(void *), void *arg)

6.1.1 Detailed Description

C Wrapper for uThreads.

Author

Saman Barghi

6.1.2 Function Documentation

6.1.2.1 WCluster* cluster_create ( )

Create a new Cluster

6.1.2.2 void cluster_destroy (WCluster * *cluster*)

6.1.2.3 WCluster* cluster_get_current ( )

6.1.2.4 WCluster* cluster_get_default ( )

Returns

defaultCluster

6.1.2.5 uint64_t cluster_get_id (WCluster * *cluster*)

Get the ID of Cluster.

Returns

The ID of the cluster

6.1.2.6 size_t cluster_get_number_of_kThreads (WCluster * *cluster*)

Total number of kThreads belonging to this cluster.

Returns

Total number of kThreads belonging to this cluster

6.1.2.7 WConditionVariable* condition_variable_create ( )

6.1.2.8 void condition_variable_destroy (WConditionVariable * *cv*)

6.1.2.9 bool condition_variable_empty (WConditionVariable * *cv*)

Whether the waiting list is empty or not.

Returns

Whether the waiting list is empty or not

6.1.2.10 void condition_variable_signal (WConditionVariable * *cv*, WMutex * *mutex*)

Unblock one uThread waiting on the condition variable.

Parameters

mutex	The mutex to be released after unblocking is done

6.1.2.11 void condition_variable_signall_all (WConditionVariable * *cv*, WMutex * *mutex*)

unblock all uThreads waiting on the condition variable

Parameters

mutex	The mutex to be released after unblocking is done

6.1.2.12 void condition_variable_wait (WConditionVariable * *cv,* WMutex * *mutex*)

Block uThread on the condition variable using the provided mutex.

Parameters

mutex	used to synchronize access to the condition

6.1.2.13 int connection_accept (WConnection * *acceptor,* WConnection * *conn,* struct sockaddr * *addr,* socklen_t * *addrlen*)

nonblocking accept syscall and updating the passed Connection object

Parameters

conn	Pointer to a Connection object that is not initialized

Returns

same as accept system call

This format is used for compatibility with C

6.1.2.14 WConnection* connection_accept_connenction (WConnection * *acceptor,* struct sockaddr * *addr,* socklen_t * *addrlen*)

Accepts a connection and returns a connection object.

Returns

Newly created connection

Throws a std::system_error exception on error. Never call from C.

6.1.2.15 int connection_bind (WConnection * *conn,* const struct sockaddr * *addr,* socklen_t *addrlen*)

Same as bind syscall.

Returns

Same as bind syscall

6.1.2.16 void connection_block_on_read (WConnection * *conn*)

Block uThread, waiting for fd to become ready for read.

6.1.2.17 void connection_block_on_write (WConnection * *conn*)

Block uThread, waiting for fd to become ready for write.

6.1.2.18 int connection_close (WConnection * *conn*)

closes the socket

Returns

the same as close system call

6.1.2.19 int connection_connect (WConnection * *conn*, const struct sockaddr * *addr*, socklen_t *addrlen*)

Same as connect syscall.

Returns

Same as connect syscall

6.1.2.20 WConnection* connection_create ( )

Create a Connection that does not have.

This is useful for accept or socket functions that require a Connection object without fd being set

6.1.2.21 WConnection* connection_create_socket (int *domain*, int *type*, int *protocol*)

Same as socket syscall adds | SOCK_NONBLOCK to type.

Returns

same as socket syscall

Throws a std::system_error exception. Do not call from C code. The unerlying socket is always nonbelocking. This is achieved by adding a (| SOCK_NONBLOCK) to type, thus requires linux kernels > 2.6.27

6.1.2.22 WConnection* connection_create_with_fd (int *fd*)

Create a connection object with the provided fd.

Parameters

fd	If the connection is already established by other means, set the fd and add it to the polling structure

6.1.2.23 void connection_destroy (WConnection * *c*)

6.1.2.24 int connection_get_fd (WConnection * *conn*)

6.1.2.25 int connection_listen (WConnection * *conn,* int *backlog*)

Same as listen syscall on current fd.

Returns

Same as listen syscall

6.1.2.26 ssize_t connection_read (WConnection * *conn,* void * *buf,* size_t *count*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.27 ssize_t connection_recv (WConnection * *conn,* void * *buf,* size_t *len,* int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.28 ssize_t connection_recvfrom (WConnection * *conn*, void * *buf*, size_t *len*, int *flags*, struct sockaddr * *src_addr*, socklen_t * *addrlen*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.29 int connection_recvmmsg (WConnection * *conn*, int *sockfd*, struct mmsghdr * *msgvec*, unsigned int *vlen*, unsigned int *flags*, struct timespec * *timeout*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.30 ssize_t connection_recvmsg (WConnection * *conn*, int *sockfd*, struct msghdr * *msg*, int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.31 ssize_t connection_send (WConnection * *conn*, const void * *buf*, size_t *len*, int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.32 int connection_sendmmsg (WConnection * *conn*, int *sockfd*, struct mmsghdr * *msgvec*, unsigned int *vlen*, unsigned int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.33 ssize_t connection_sendmsg (WConnection * *conn*, const struct msghdr * *msg*, int *flags*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.34 ssize_t connection_sendto (WConnection * *conn*, int *sockfd*, const void * *buf*, size_t *len*, int *flags*, const struct sockaddr * *dest_addr*, socklen_t *addrlen*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.35 int connection_socket (WConnection * *conn*, int *domain*, int *type*, int *protocol*)

Same as socket syscall, set the fd for current connection.

Returns

same as socket syscall The unerlying socket is always nonbelocking. This is achieved by adding a (| SOC↩ K_NONBLOCK) to type, thus requires linux kernels > 2.6.27

6.1.2.36 ssize_t connection_write (WConnection * *conn*, const void * *buf*, size_t *count*)

Call the underlying system call on Connection's file descriptor.

Returns

Same as what the related systemcall returns

This function calls the system call with the same name. If the socket is ready for the required function it returns immediately, otherwise it blocks in the user-level (blocks uThread not kThread), and polls the file descriptor until it becomes ready.

The return results is the same as the underlying system call except that the following condition is never true when the function returns: (res == -1) && (errno == EAGAIN || errno == EWOULDBLOCK)

which means the Connection object does the polling and only returns when an error occurs or the socket is ready.

6.1.2.37 WkThread* kThread_create (WCluster * *cluster*)

6.1.2.38 void kThread_destroy (WkThread * *kt*)

6.1.2.39 WkThread* kThread_get_current ( )

Get the pointer to the current kThread.

Returns

current kThread

This is necessary when a uThread wants to find which kThread it is being executed over.

6.1.2.40 pthread_t kThread_get_current_pthread_id ( )

return the native hanlde for the kernel thread

Returns

native handle for the kThread

In linux this is pthread_t representation of the thread.

6.1.2.41 pthread_t kThread_get_pthread_id (WkThread * *kt*)

return the native hanlde for the kernel thread

Returns

native handle for the kThread

In linux this is pthread_t representation of the thread.

6.1.2.42 uint64_t kThread_get_total_number_of_kThreads ( )

Returns

total number of kThreads running under the program.

6.1.2.43 bool mutex_acquire (WMutex * *mutex*)

acquire the mutex

Returns

true if it was acquired, false otherwise

The return value is only for when timeouts are implemented

6.1.2.44 WMutex* mutex_create ( )

6.1.2.45 void mutex_destroy (WMutex * *mutex*)

6.1.2.46 void mutex_release (WMutex * *mutex*)

release the Mutex

6.1.2.47 uint64_t ownerlock_acquire (WOwnerLock * *olock*)

6.1.2.48 WOwnerLock* ownerlock_create ( )

6.1.2.49 void ownerlock_destroy (WOwnerLock * *olock*)

6.1.2.50 void ownerlock_release (WOwnerLock * *olock*)

6.1.2.51 WSemaphore* semaphore_create ( )

Create a new Semaphore.

Parameters

c	Initial value of the Semaphore

6.1.2.52 void semaphore_destroy (WSemaphore * *sem*)

6.1.2.53 bool semaphore_p (WSemaphore * *sem*)

Decrement the value of the Semaphore.

Returns

Whether it was successful or not

6.1.2.54 void semaphore_v (WSemaphore * *sem*)

increment the value of the Semaphore

6.1.2.55 WuThread* uThread_create (bool *joinable*)

Create a uThread with a given stack size.

Parameters

ss	stack size
joinable	Whether this thread is joinable or detached

Returns

a pointer to a new uThread

This function relies on a uThreadCache structure and does not always allocate the stack.

6.1.2.56 void uThread_detach (WuThread * *ut*)

Detach a joinable thread.

6.1.2.57 WuThread* uThread_get_current ( )

Get a pointer to the current running uThread.

Returns

pointer to the current uThread

6.1.2.58 uint64_t uThread_get_id (WuThread * *ut*)

get the ID of this uThread

Returns

ID of the uThread

6.1.2.59 uint64_t uThread_get_total_number_of_uThreads ( )

Returns

Total number of uThreads in the program

This number does not include mainUT or IOUTs

6.1.2.60 bool uThread_join (WuThread * *ut*)

Wait for uThread to finish execution and exit.

Returns

Whether join was successful or failed

6.1.2.61 void uThread_migrate (WCluster * *cluster*)

Move the uThread to the provided cluster.

Parameters

cluster	This function is used to migrate the uThread to another Cluster. Migration is useful specially if clusters form a pipeline of execution.

6.1.2.62 void uThread_start (WuThread * *ut*, WCluster * *cluster*, void * *func*, void * *arg1*, void * *arg2*, void * *arg3*)

start the uThread by calling the function passed to it

Parameters

cluster	The cluster that function belongs to.
func	a pointer to a function that should be executed by the uThread.
arg1	first argument of the function (can be nullptr)
arg2	second argument of the function (can be nullptr)
arg3	third argument of the function (can be nullptr)

After creating the uThread and allocating the stack, the start() function should be called to get the uThread going.

6.1.2.63 void uThread_terminate (WuThread * *ut*)

Terminates the uThread.

By calling this function uThread is being terminated and uThread object is either destroyed or put back into the cache.

6.1.2.64 void uThread_yield ( )

Causes uThread to yield.

uThread give up the execution context and place itself back on the ReadyQueue of the Cluster. If there is no other uThreads available to switch to, the current uThread continues execution.

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