Design and Implementation of a User Level Thread Library for Testing and Reproducing Concurrency Scenarios

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Outline of Presentation

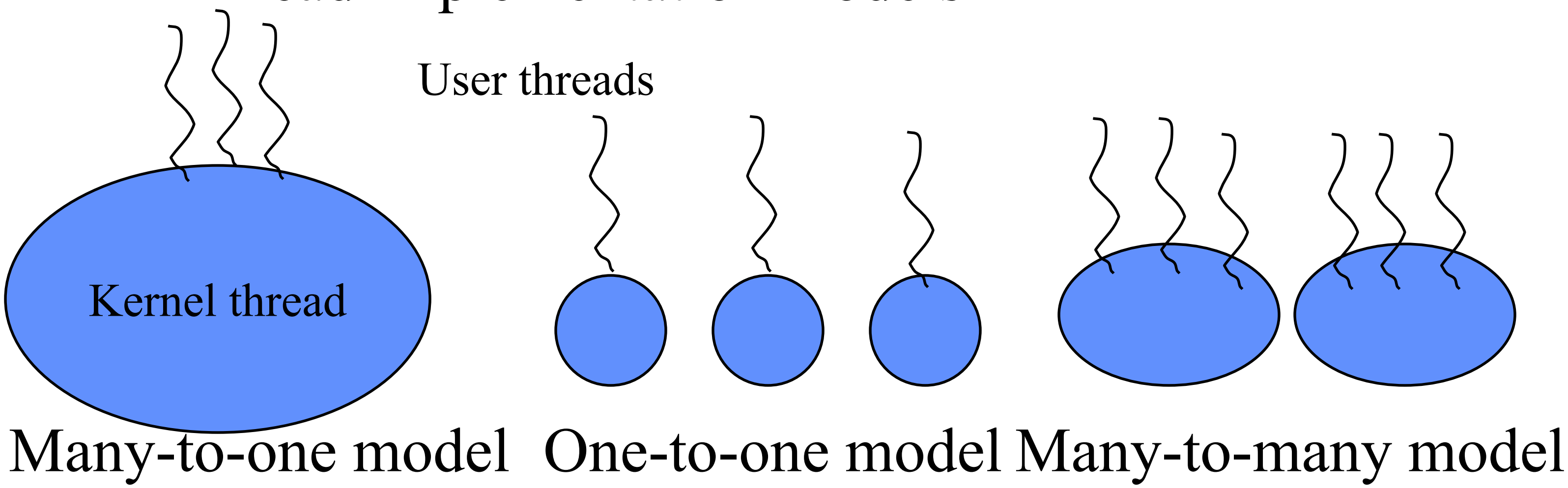
- Introduction
- Motivation
- Solution
- BERT
- Design and Implementation of BThreads
- Debugging features of BThreads
- Testing and Results
- Conclusions
- Future work

Introduction

- High performance computing (HPC) one of the key requirements for scientific, web based and military applications — parallel computing one solution
- An example: web server and web browser
- Web server and web browser benefit from parallelism
- Web browser displaying and fetching HTML can be done in parallel
- Web servers need parallelism to attain maximum throughput: number of client requests processed/unit time
- Multithreading is a popular parallel model

Introduction

- Thread implementation models



Many threads per process (M:1)	One thread per one kernel level thread (1:1)	Many threads many kernel level threads (M:N)
Easiest to debug	Hardest to debug	Intermediate in difficulty
I/O blocks all threads	I/O blocks one thread	I/O blocks some threads

Motivation

- Debugging multi-threaded programs is difficult
- The execution of program can differ from one run to another
- Multi-threaded programs don't execute deterministically (race conditions, deadlocks)
- Sources of nondeterminism: Context switching, completion of I/O, signals, scheduler decisions
- Execution model and the debugging model are mismatched; insufficient debugging control

Solution

- Without kernel modifications, don’t have sufficient control with the one-to-one and many-to-many models
- With the many-to-one model, we have potential for sufficient control, but current libraries don’t provide it
- With an event-driven framework, we can provide this control
- Such an event-driven framework has been developed at ITTC: BERT

BERT

- BERT interface is built using REACTOR, which provides an event-demultiplexing framework
- An event is associated with a handler that has non-blocking methods that are called upon detection of event
- An event can be: I/O completion, timer expiration, signal
- All these events are captured at REACTOR
- Hence REACTOR is a single point of control

BERT

- Capture all the asynchronous events at deterministic points in REACTOR
- The information can be recorded here and later used for replay
- With many-to-one model, as scheduler runs in user level, it is possible to test different concurrency scenarios by forcing context switches from debugger
- BThreads library is based on many-to-one model, built on top of BERT interface

Design and Implementation of BThreads

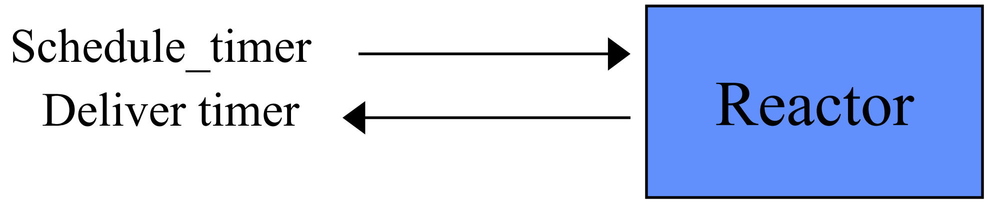
- Thread creation and termination
- Thread scheduling
- Thread synchronization
- I/O
- Signals
- Thread Safety
- Pushing function call onto thread stack
- Other features implemented
- Limitations Of BThreads

Thread Creation and Termination

- Two interfaces are available for creation of user space threads:
  - Ucontext API
  - JMPBUF based functions
- Ucontext API is used in the BThreads library
- Thread creation and termination have been implemented in BThreads according to POSIX requirement
- Termination Queue holds terminated threads in detached state
  - Memory resources of threads in this queue are deallocated (reaping)

Thread Scheduling

- Default scheduling in BThreads is Round Robin
- Timers are registered with Reactor and Reactor dispatches timer to BThreads library when it expires



- FIFO scheduling can be realized by turning off timers

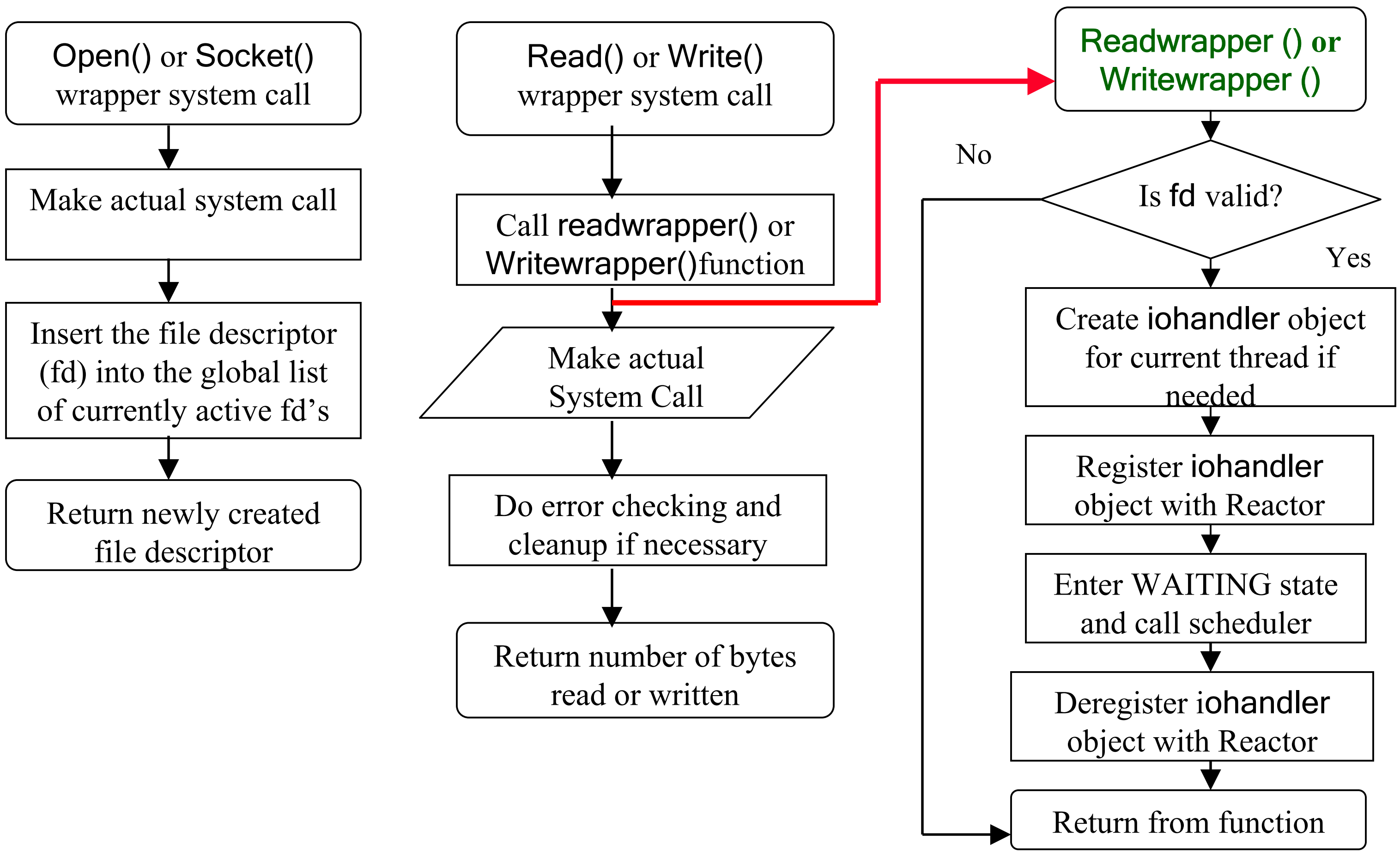
Thread synchronization

- If a thread blocks on a synchronization variable, process as a whole may block
- Following synchronization primitives required in a POSIX compliant thread library have been provided:
  - Mutexes
  - Condition Variables
- In addition, waitlocks and spinlocks were implemented
- Used wait locks for protecting critical sections of mutex and condition variable functions

I/O

- I/O blocking is a major issue in many-to-one thread library
- If a thread blocks, process as a whole blocks
- Before entering WAITING state, register the event handler object with the reactor
- EventHandler object :Handle_input, Handle_output methods
- Event handler methods invoked upon detection of events
  - For I/O this means that thread will be put in READY state when I/O can be done without blocking
- When to invoke Reactor to check for I/O completion?
  - Whenever scheduler is invoked

Wrapper Functions in Library(I/O)



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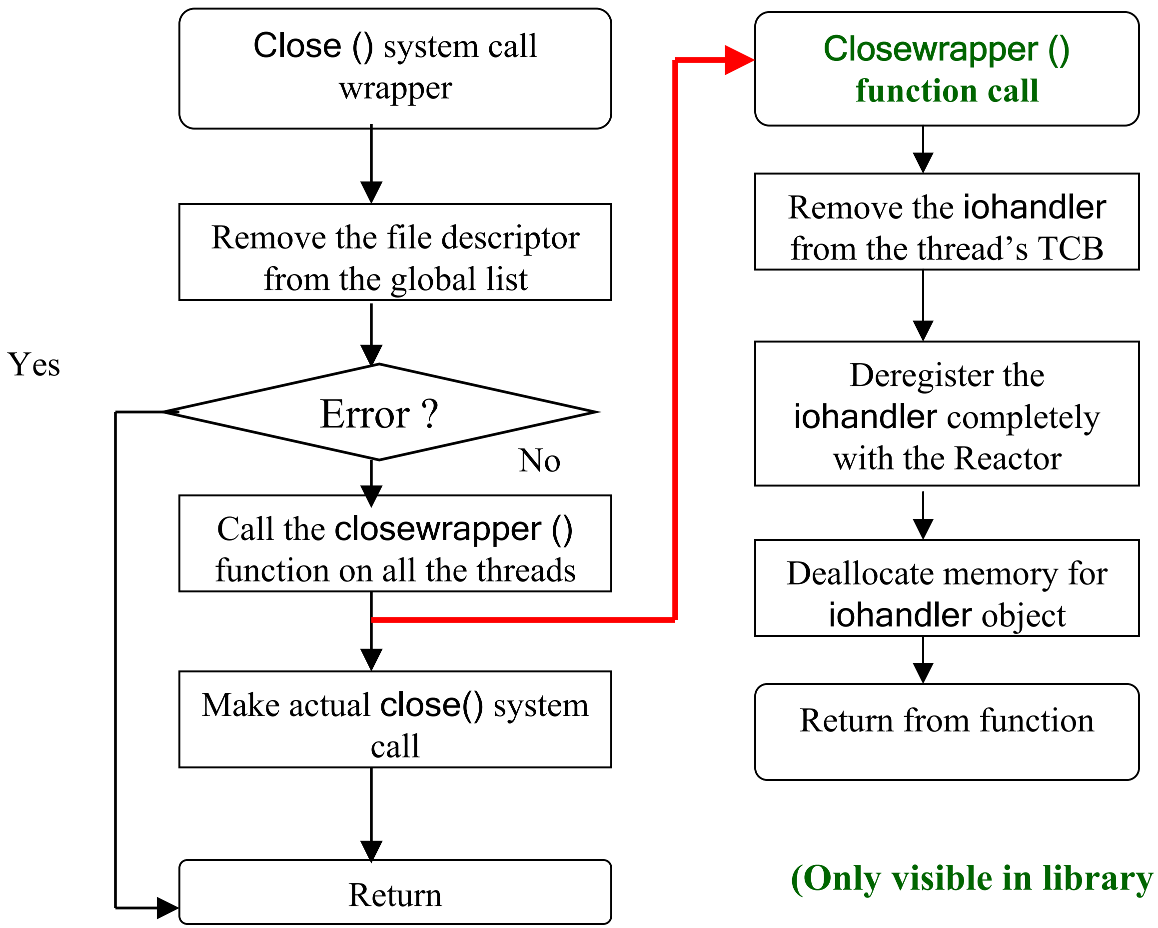
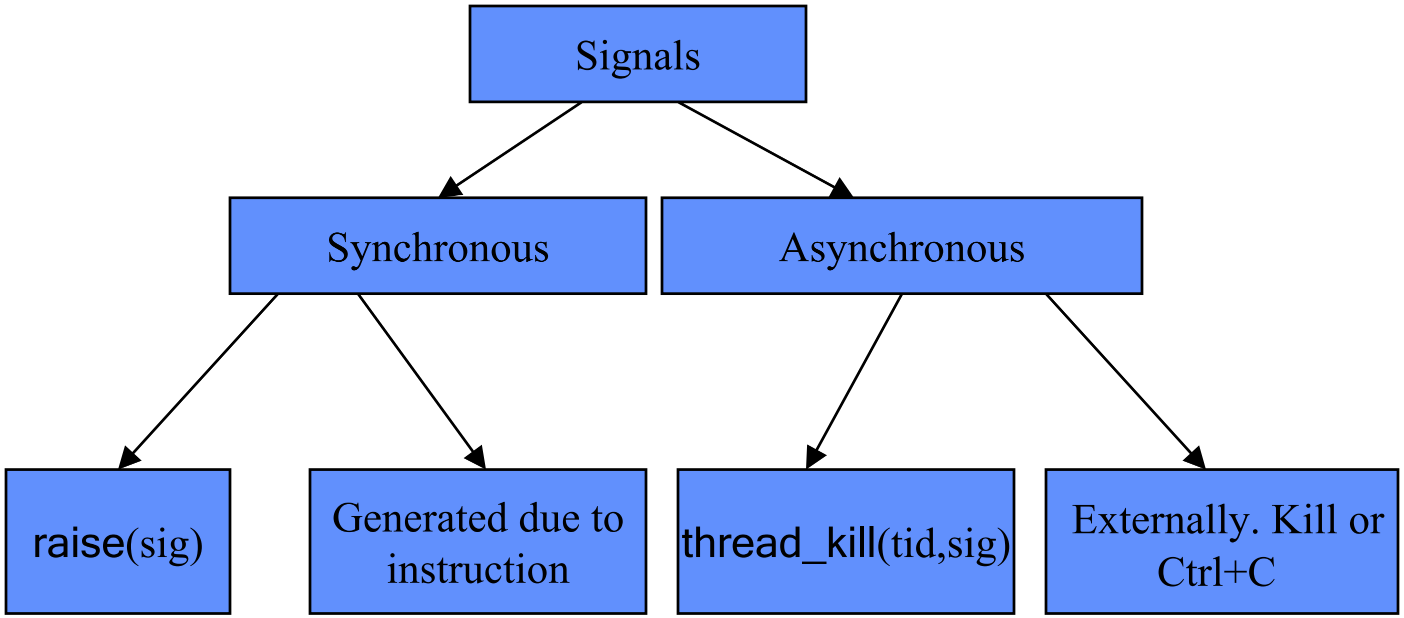
Wrapper Functions in Library(I/O)



(Only visible in library level)

Signals

- Delivery and masking of signals must be thread-specific
- Signal handlers are shared among all the threads
- Classification (depending on how signals are generated):



Signals

- POSIX requirements for delivery of signals:
  - Synchronous signal - thread that generated the signal
  - Asynchronous fatal signals - all the threads running in the process must be terminated (Default behavior with BThreads)
  - Asynchronous non-fatal signals
    - If generated due to thread_kill - only a specific thread
    - If generated due to kill/TTY- Any one thread that doesn't block the signal

Signals

- Signal delivered in BThreads when
  - Signal mask of thread is changed thread_sigmask
  - When a new thread is scheduled in the scheduler and it starts running
- How asynchronous signals are delivered
  - Signals due to thread_kill generated by inserting raise_threads
  - Signals that are generated externally will be delivered automatically

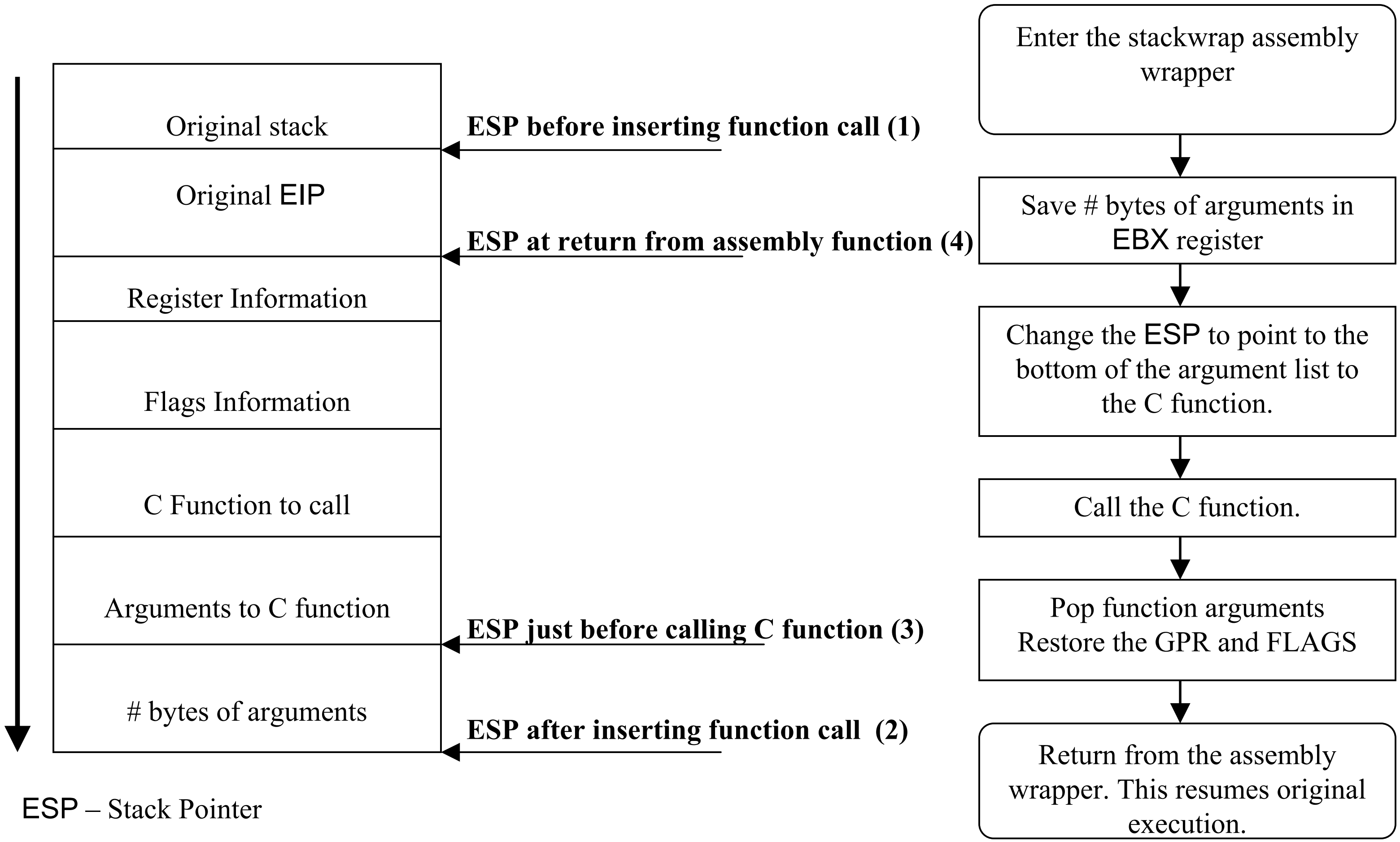
Thread Safety

- Thread safe : Multiple threads can call methods simultaneously - An issue in *preemptive library*
- User-Level data consistency: Mutexes, Condition variables.
- How to ensure Library-Level data Consistency?
- Solution: Two ways to ensure consistency
  - Consistency using atomicity (Disable and re-enable signals)
    - Ready Queue (Accessed in thread_create, scheduler)
    - Reactor Queue (Accessed in Reactor and scheduler)
  - Consistency using mutual exclusion (Using waitlocks)
    - Termination Queue (Queue having all the terminated threads), Thread Control Block

Pushing function call onto thread stack

- This mechanism is used when
  - Delivering signals due to thread_kill
  - Calling scheduler due to generation of SIGPROF
  - Implementing asynchronous cancellation
- To allow insertion of an arbitrary function on an execution stack, esp, eip registers need to be modified
- Current implementation is for x86 architecture
- To support insertion of C function with arbitrary signature, an assembly wrapper function is needed

Pushing function call onto thread stack



Other Features Implemented

- Functions implemented according to standard POSIX requirements:
- Thread cancellation
- Cleanup handling
- Thread specific data
- Thread once functions

Limitations of BThreads

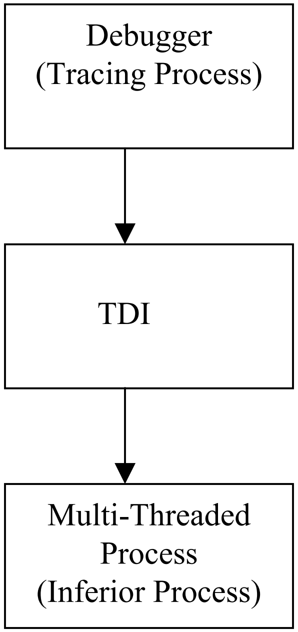
- Priority based scheduling
- Timed variants of condition variables and mutexes
  - thread_cond_timedwait
  - thread_mutex_timedlock (not required by POSIX).
  - These return ETIMEDOUT when timeout occurs
- Thread barrier functions (not required by POSIX)
- Thread Read/Write (R/W) locks
- Process shared or process private mutexes, R/W locks, condition variables
- Concurrency level (Only for many-to-many thread models)

Debugging features of BThreads

- Thread Debug Interface
- Testing concurrency scenarios
- Recording concurrency scenarios

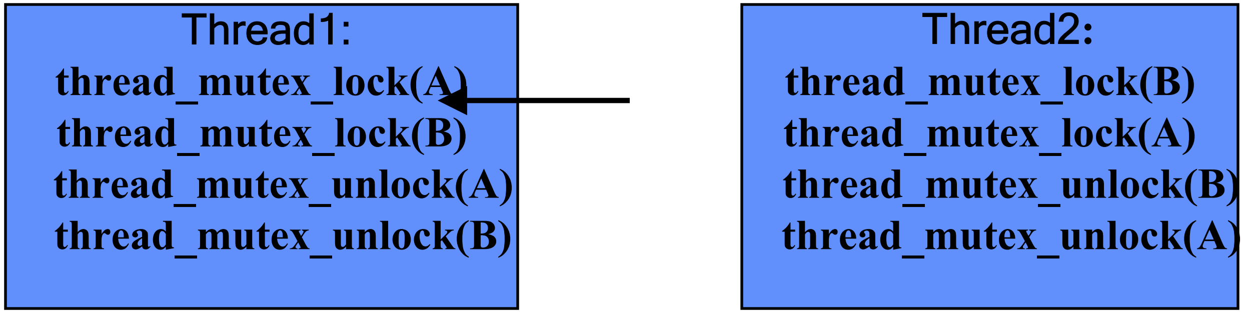
Thread Debug Interface (TDI)

- GDB uses TDI to get information about thread library
- TDI provides ability to access and modify data structures in the inferior process
- Event enabling and reporting
- Examining thread related information
- Invoke call back functions over a set of threads that meet some criterion
- List of mutexes and condition variables
- Get and set register information



Testing Concurrency Scenarios

- User can form his/her own concurrency scenarios
- BThreads library provides ability to an arbitrary thread using switch_to_thread function
- This can be used by GDB debugger to switch to any thread



Recording Concurrency Scenarios

- In normal circumstances, recording is done when program runs without any intervention of debugger
- Record only information, which can disrupt sequential flow
  - Scheduling (due to SIGPROF signal)
  - Signals
  - I/O completion

Testing and Results

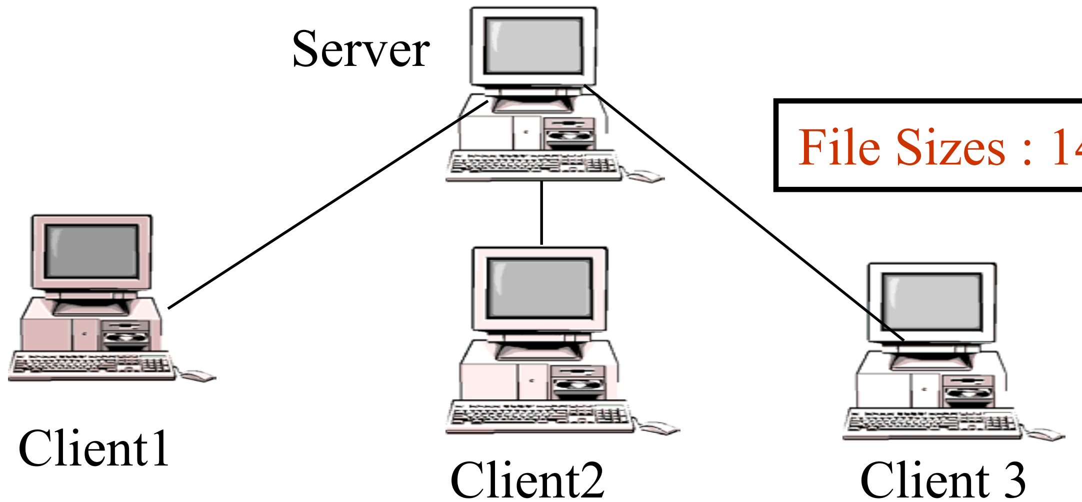
- Correctness Testing
- Performance Testing
- Testing different concurrency scenarios
- Recording and reproducing different concurrency scenarios

Correctness Testing

- White Box Testing for BThreads library
- POSIX Compliance testing (Linux Threads):
  - Basic thread creation and destruction
  - Classic Producer-Consumer problem (Condition variables & mutexes)
  - Multi-thread searching (mutexes, cancellation and cleanup handling)
  - Different threads accumulating their strings concurrently (TSD, thread_once functions)
  - Concurrent multiplication of NxN matrices

Performance Testing

- A multi-threaded FTP server based on Linux Threads was taken
- FTP server based on BThreads was built from it



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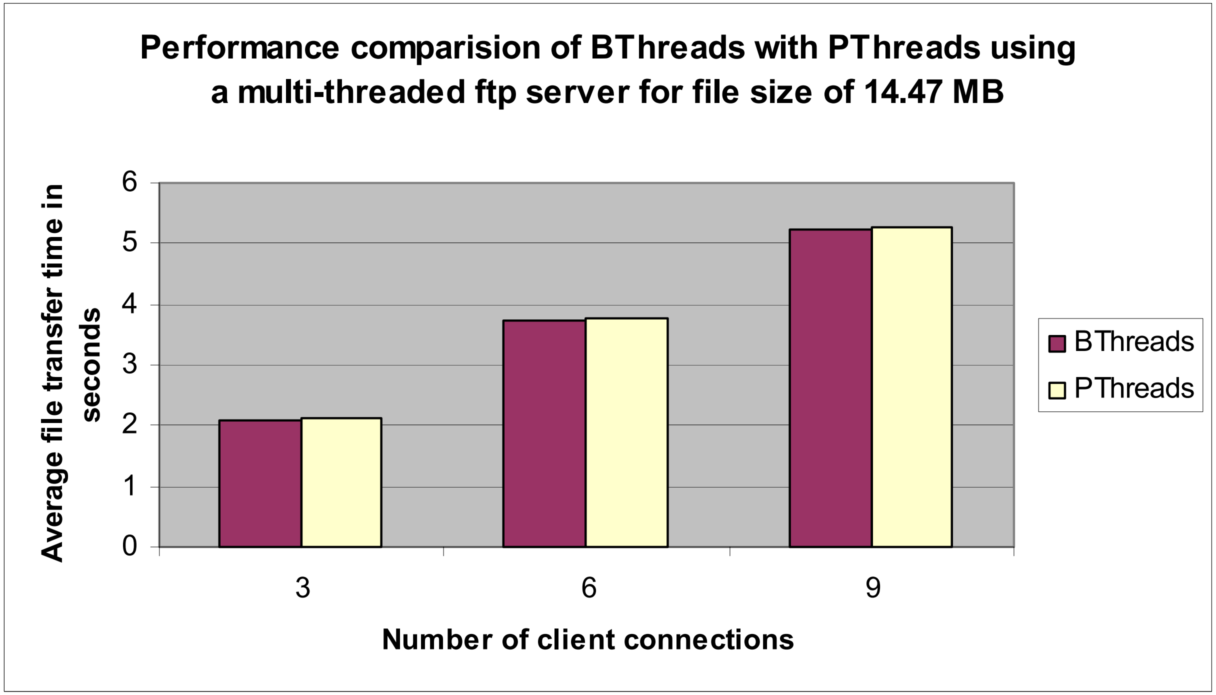
- For 95% confidence , BThreads confidence interval (worst case) 0.40 sec, PThreads 0.5 sec

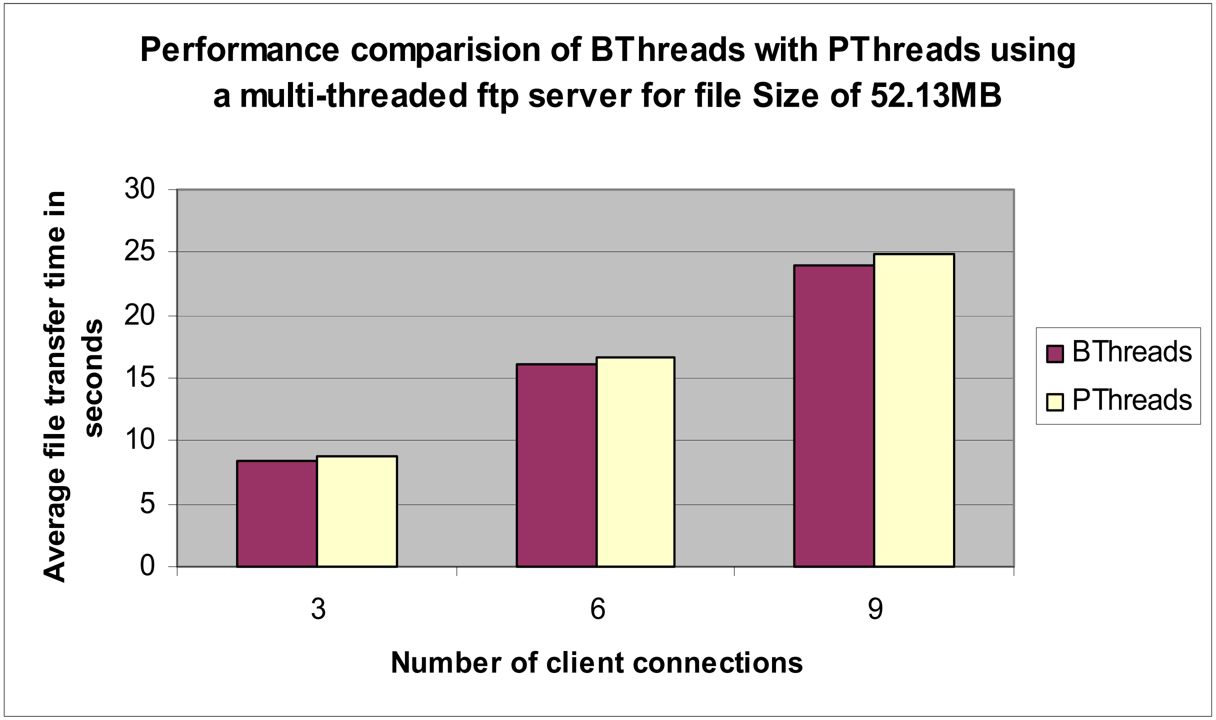
Performance Testing



No of Client Connections	Average FTT	
	BThreads	Pthreads
3	2.07917	2.13417
6	3.71625	3.78375
9	5.24722	5.27722

FTT: File Transfer Time

Performance Testing

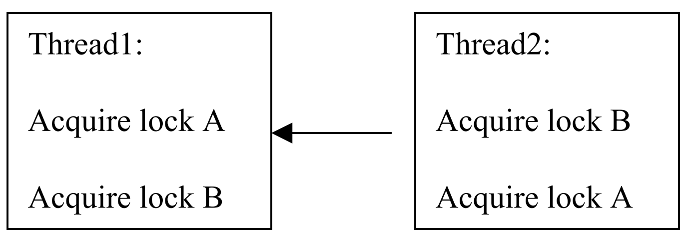


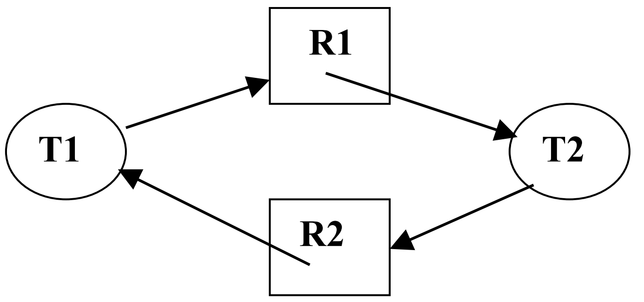
No of Client Connections	Average FTT	
	BThreads	Pthreads
3	8.483	8.704
6	16.079	16.567
9	24.022	24.967

FTT: File Transfer Time

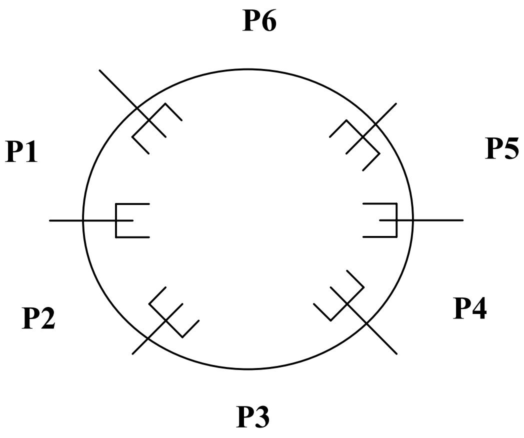
Testing and reproducing concurrency

- Deadlock conditions: Mutual exclusion, Hold & Wait, Circular wait, no preemption
- Two test programs that had possibility of deadlocks were considered:
  - Two threads trying to acquire two locks in different order

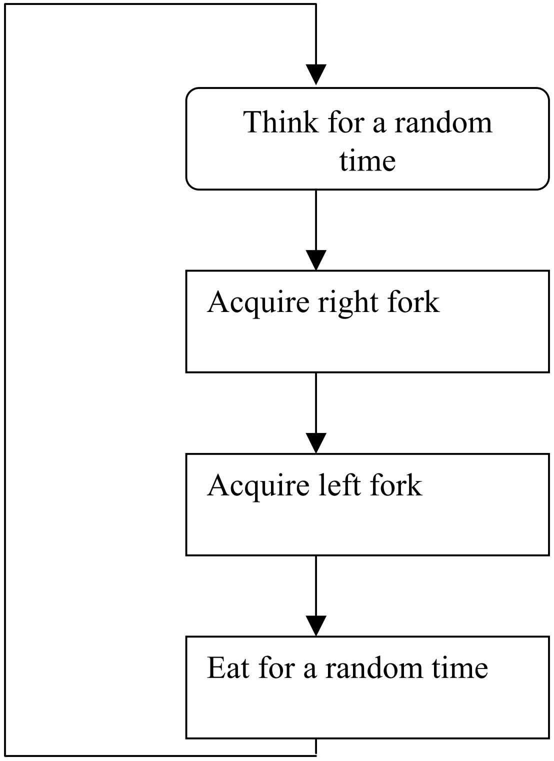




Testing and reproducing concurrency



Dining Philosopher's Problem



Dining Philosopher's algorithm

Conclusions

- Built a thread library that supports most of the features in a POSIX compliant thread library
- Built TDI to support debugging of BThreads programs
- Tested POSIX compliance of the library
- Tested the basic performance
- Provided a *framework* that can be used to improve debugging of multi-threaded programs
    - Tested and verified basic ability to test and reproduce different concurrency scenarios for context switching at arbitrary points

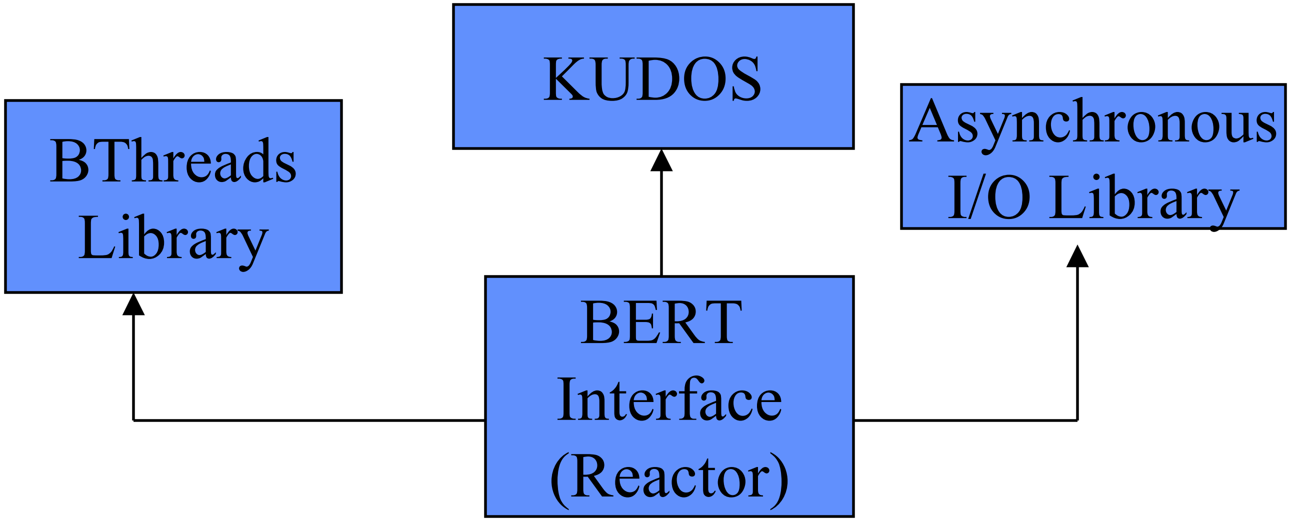
Related Work

- Another student is working for providing debugger support for BThreads and reproducing concurrency scenarios.

Library	**Main goals**
FSU Threads	POSIX compliance. Uses asynchronous I/O
NGPT	Performance, POSIX compliance
Linux Threads	POSIX Compliance (LINUX OS)
ACE Threads. Wrapper thread library	Uniform programming language C++ Portable thread library Minimize subtle synchronization errors

Related Work

- BThreads library is part of the BERT infrastructure



Future Work

- Identify & wrap all system calls that can block
- Make library completely POSIX compliant
- Experiment with scheduling policies
- Port implementation to other architectures: Solaris, Irix
- “Dynamic linker tricks” to debug other thread library programs
- Transition an event-driven application to concurrent application

Questions