Reproducible concurrency for NPTL based applications

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Master's Project defense

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Presentation Outline

- Introduction
- Background
- Recording
- Replay
- Evaluation
- Conclusion
- Future work

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Introduction

- Debugging single-threaded programs
  - Program is repeatedly traced - GDB
  - Focus on specific parts of the program where the bug is
  - Generally known as “cyclic debugging”
  - Assumption – repeated executions are identical
- Debugging multi-threaded programs
  - Available features more suitable for cyclic debugging
  - Main problem – repeated executions not identical
  - Affected by several non-deterministic factors
  - Need faulty execution reproduction to identify bugs

Introduction

- Objectives
  - Identify execution path and reproduce faulty execution
  - Make program execution deterministic
    - cyclic debugging techniques can then be applied
- Focus on POSIX threads on uni-processor Linux systems
- Proposed Solution – Two phases
  - Recording
    - Log necessary data during experimental run
  - Replay
    - Reproduce execution within GDB
      - Use recorded data to set appropriate replay breakpoints

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Background

- POSIX thread Library
  - 1:1 thread library model
    - Each thread is mapped to a kernel process
    - Kernel takes care of scheduling
  - LinuxThreads – old implementation
  - NPTL
    - Latest implementation
    - Requires 2.6 kernel series
    - Faster Thread Creation/Destruction
    - Futexes

Background

- Pthreads
  - Individual PID, user and kernel mode stacks
  - Shared address space
  - Scheduled by kernel scheduler
- Threads created using clone system call
- TGID – Thread Group ID
  - TGID = Parent’s PID for Pthreads
  - TGID = PID for “real” processes
- TGID List
  - List of all threads created by a process
  - Used for group stop and exit

Background

- DataStreams Kernel Interface
  - Framework to collect status and performance related data from kernel
- Instrumentation points
  - Hierarchy
    - Family
    - Events, Counters and Histograms
- Device driver interface
  - Select subset of events, counters or histograms to be logged

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Recording

- Execution path – set of all instructions executed
- Factors affecting execution path
  - Scheduling decisions – non-deterministic
  - Signals – non-deterministic
  - Inputs (network, system and user) – variable

Recording

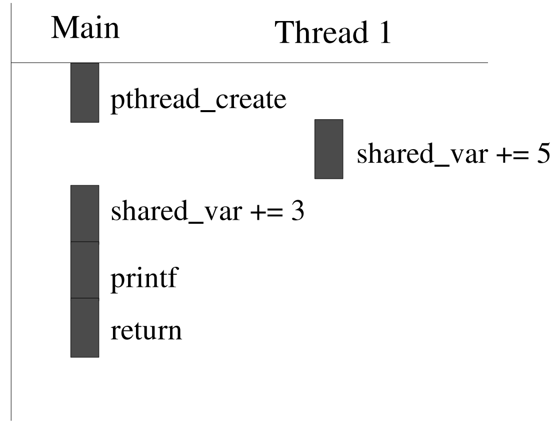
- Sample multi-threaded program – two threads

Program 3.1 A simple program to illustrate the importance of recording interleaving information.

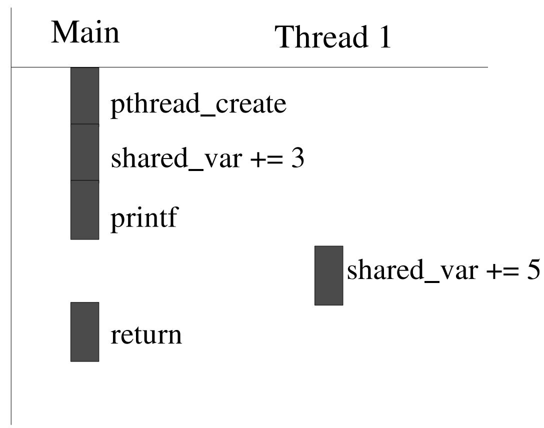
```
#include <stdio.h>
#include <pthread.h>

int shared_var = 0;

int thread_func(void) {
 shared_var += 5;
}

int main() {

 pthread_t t1;

 pthread_create(t1, NULL, thread_func, null);

 shared_var += 3;

 printf("In main: shared_var is %d", shared_var);

 return 0;
}
```

Recording

- Execution Path 1
  - Output printed: 8



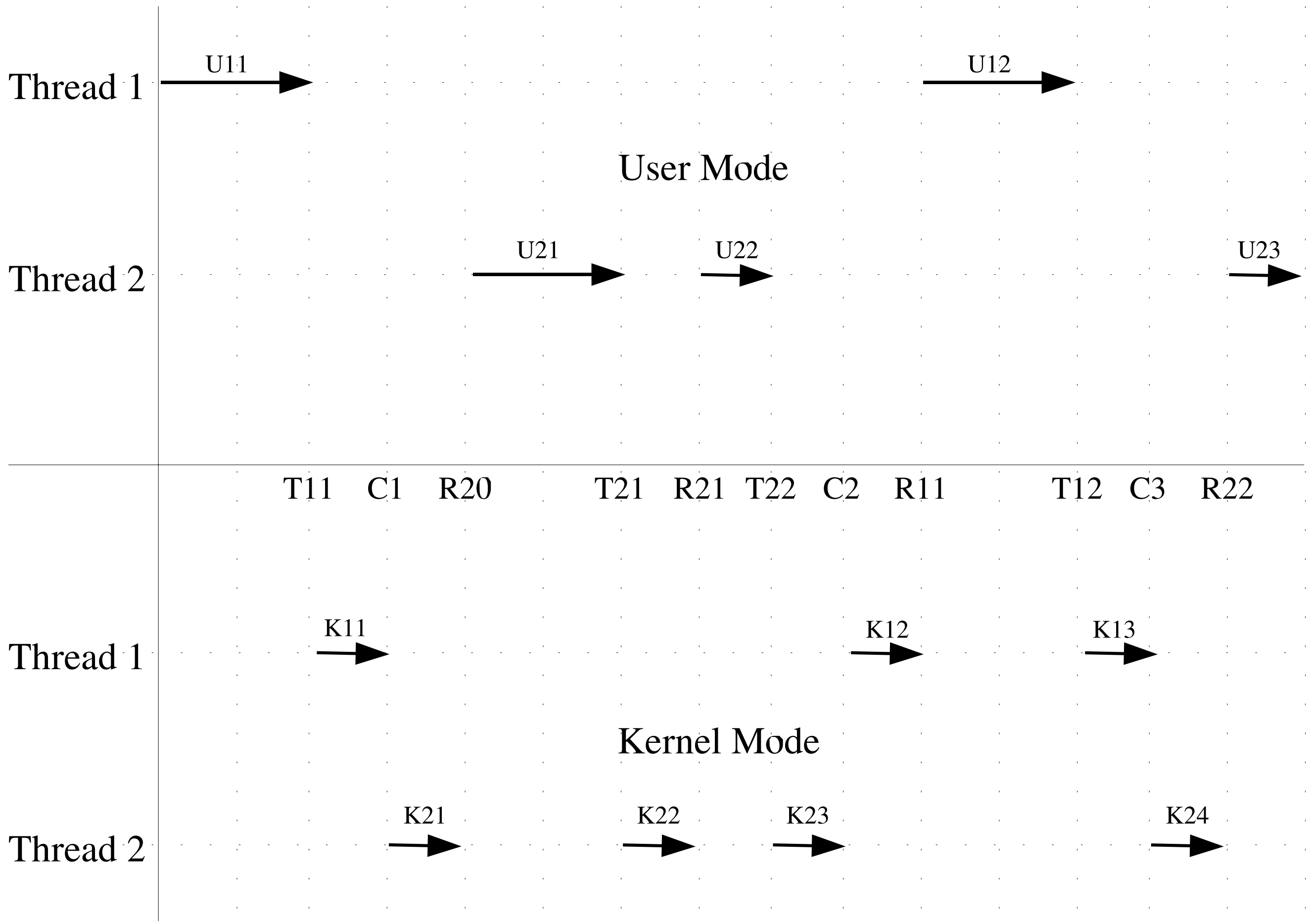
- Execution Path 2
  - Output printed: 3



Recording

- Thread schedule
  - (thread identifier, stop address) pair
  - Example: (main thread, 14)
    - Main resumed execution and stopped after line 14 in a schedule
- Schedule Order (SO) – an ordered set of thread schedules
  - Ordered by time
  - Example: { (main thread, 18), (thread 1, exit), (main thread, exit) }
- SO uniquely identifies an execution path
  - If inputs supplied to the program are the same
  - If the effects due to signals are reproduced
    - Addressed by Ram's project

Recording



Thread 1
U11
U12
User Mode
Thread 2
U21
U22
U23
T11
C1
R20
T21
R21
T22
C2
R11
T12
C3
R22
Thread 1
K11
K12
K13
Kernel Mode
Thread 2
K21
K22
K23
K24

Recording

- Transition due to interrupt
  - Instruction at transition address was already executed
  - Breakpoint should be set at resumption address
- Transition due to system call
  - Instruction at transition address is a system call
    - transition should not be allowed for most system calls (especially sys_futex)
    - breakpoint should be placed at transition address
  - Exceptions: *clone*, *exit*
    - effects should actually take place
    - breakpoint should be placed at resumption address

Recording

- Record both during context switch
- Sample SO

  CS <Thread 1, T11, R11>

  CS <Thread 2, T22, R22>

  CS <Thread 1, T12, R12>
- Resumption address
  - User-space return address - found in kernel stack
- Transition address
  - Address of the previous instruction – but length can vary
  - Manual lookup required
- Record only return addresses

Recording

- Resumption point – not determined by return address alone
  - (address, count) pair
- Basic blocks – set of instructions with single point of entry and exit with no branches in between
  - GCC's block profiling feature can be used
- Final SO
  - CS <thread 1, (R11, basic block count)>
  - CS <thread 2, (R22, basic block count)>
  - CS <thread 1, (R12, basic block count)>

Recording

- Need to identify pthread processes in kernel
  - Log context switch events of pthread processes alone
- New variable *pthread_flag* in *task_struct*
- Set *pthread_flag* during clone
  - New *clone* flag in both GLIBC and kernel
- Set *pthread_flag* for main thread when it creates first thread

Recording

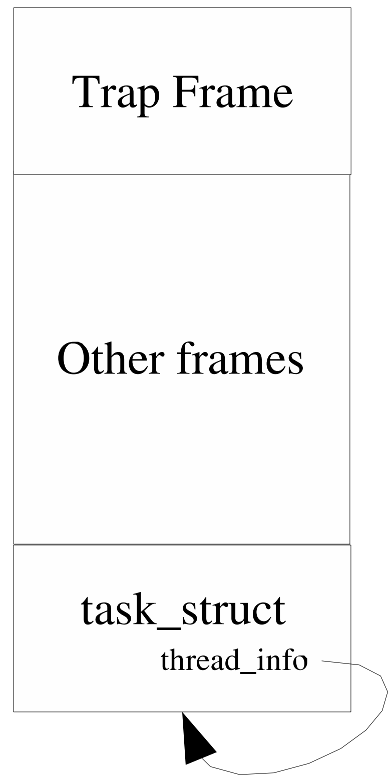
- Maintaining basic block count
  - Function *__bb_trace_func* called for every basic block entry
  - New function *__bb_new_trace_func* increments basic block count
  - Work done by Satya at ITTC
- Modifications
  - New variable *bb_count* in *pthread_struct*
  - New functions: *pthread_incr_bb_count* and *pthread_get_bb_count*
  - *__bb_new_trace_func* now calls *pthread_incr_bb_count*
- Accessing basic block count during context switch
  - New variable *bb_count_addr* in *task_struct*
  - Update *bb_count_addr* during *set_thread_area* for main thread
  - Update *bb_count_addr* during *clone* for other threads

Recording

- Return address
  - Stored in trap frame
  - Trap frame stored in kernel stack
- Kernel stack
  - *THREAD_SIZE*: stack size
  - Stored from higher to lower addresses
  - *task_struct* stored in bottom
- Trap frame can be obtained using

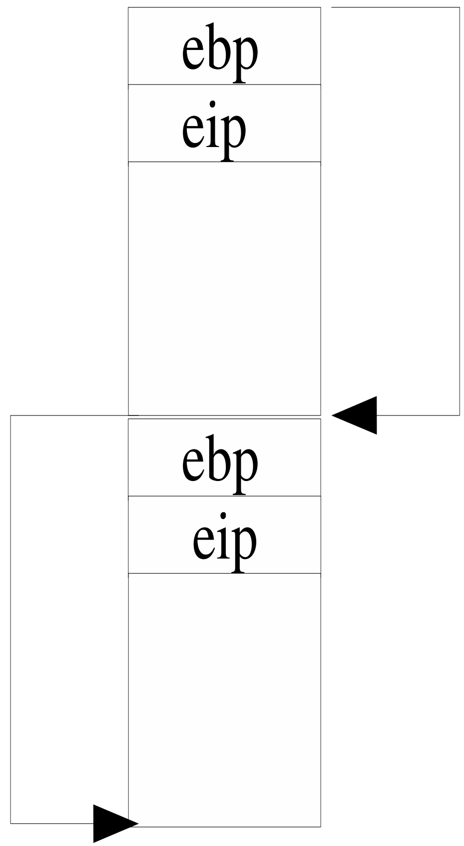
  (*THREAD_SIZE* +

  current → thread_info) - 1



Recording

- Virtual system calls
  - Added to 2.6.x kernels for performance improvement
  - Kernel page *vsyscall* mapped to all user processes
- Problem: return address in trap frame points to *SYSENTER_RETURN* in *vsyscall*
  - Breakpoint cannot be set
- Solution: user stack
  - Follow frame pointer address in trap frame



Recording

Sample SO


```
<ENTITY number="1" tag="2540" ... time_std="0" type="EVENT">
<EVENT name="PTHREAD_SWITCH_FROM" family="SCHEDULER" id="66">
<EXTRA_DATA  format="base64">
TIALQNDq/7846/+/AwAAAA==
</EXTRA_DATA>
<EXTRA_DATA format="custom">
from_eip(hex)=400b804c
bb_count=3
</EXTRA_DATA></EVENT>
</ENTITY>
<ENTITY number="2" tag="2541" ... time_std="0" type="EVENT">
<EVENT name="PTHREAD_SWITCH_FROM" family="SCHEDULER" id="66">
<EXTRA_DATA  format="base64">
GEcRQMQakkAcG5JAzQAAAA==
</EXTRA_DATA>
<EXTRA_DATA format="custom">
from_eip(hex)=40114718
bb_count=205
</EXTRA_DATA></EVENT>
</ENTITY>
```

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Replay

- Thread debugging support in GDB
  - Builds thread list internally
  - Thread create and death events: *threadnum*
- Thread debugging commands
  - Thread specific breakpoints
    - break *address* thread *threadnum*
    - All threads are stopped when any thread hits breakpoint
  - Switch context to desired thread
    - thread *threadnum*
  - Scheduler locking
    - set schedlock on
    - *continue* command resumes only current thread (thread that has context)

Replay

- PIDs in SO are invalid – needs mapping
  - Post-processing filter in DataStreams
  - Map PIDs in thread creation order: similar to *threadnum*
- Transition addresses have to be found
  - Only for some system calls
  - Manual lookup in *objdump* output
  - Can be input to GDB using *syscall_address_file* command
- Clever Insight
  - Nested breakpoints
  - Ability to attach TCL scripts to breakpoint

Replay

- Run *inferior* in scheduler locked mode
  - Only one thread runs at a time
  - Context can be switched using “thread *threadnum*” command
- Use SO to insert replay breakpoints
  - at return addresses: SO
  - transition addresses: mapping file

Replay

Program 4.1 Pseudo code for Automatic Breakpoint insertion

```
 1: Set breakpoint at main and start the inferior
 2: Wait for the inferior to report an event
 3: If Event = Thread Exit
 4:     Add threadnum to exited thread list
 5:     Goto 10
 6: Else If Event = Replay Breakpoint
 7:     Goto 10
 8: EndIf
 9: Continue Inferior

10: Read next schedule event from schedule order file
11: If threadnum is in exited thread list
12:     Goto 10
13: EndIf
14: Switch to threadnum
15: If breakpoint return address has a corresponding transition address
16:     Set Next Replay Breakpoint at Transition address
17: Else
18:     Set Next Replay Breakpoint at Return address
19: EndIf
20: Goto 9
```

Replay

- Sample command group executed when a replay breakpoint is hit

Program 4.2 A sample command group that is executed upon hitting a replay breakpoint

```
info threads
thread 1
break *1074174393 thread 1 if pthread_get_bb_count() == 68
commands
disable_last_breakpoint_hit
set_next_replay_breakpoint
end
continue
```

Replay

- GDB features can still be used
- Experimental interleaving
  - Automatic breakpoint insertion can be controlled
  - Control returns to user after a replay breakpoint is hit
  - New interleaving can be created

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Evaluation

- Recording framework
  - Testing basic blocks
  - Testing return addresses
- Replay framework
  - Tested with programs that had data races: different results for different executions
  - Save experimental execution result
  - Replay in GDB produced experimental execution result

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Conclusion

- A framework to record execution path of NPTL based applications
  - GCC and GLIBC sources modified to support basic block count
  - GLIBC and kernel sources modified
    - to identify *pthreads* in kernel
    - to retrieve basic block count during context switch
- A replay framework to reproduce user-mode execution path of a program
  - Automatic breakpoint insertion feature in GDB

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Future Work

- Finding transition addresses automatically
  - Transition address required only for some system calls - Wrap them to generate a SYSCALL event
- Using *Progenitor* to separate events of multiple NPTL applications executing at same time
- Modify basic block maintenance using edge profiler
  - Newer versions of GCC use edge profiler
  - Use new GIMPLE intermediate language of GCC 4.0 to do tree walking/modification

Thank you

Questions?