Easier Debugging of Multithreaded Software

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Easier Debugging of Multithreaded Software

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by

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The Undersigned Project Committee Approves the Project Titled

Easier Debugging of Multithreaded Software

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ABSTRACT

Easier debugging of multithreaded software

By

Sampada Kathare

Software activation is a technique designed to avoid illegal use of a licensed software. This is achieved by having a legitimate user enter a software activation key to validate the purchase of the software. Generally, a software is a single-threaded program. From an attacker's perspective, who does not wish to pay for this software, it is not hard to reverse engineer such a single threaded program and trace its path of execution. With tools such as OllyDbg, the attacker can look into the disassembled code of this software and find out where the verification logic is being performed and then patch it to skip the verification altogether.

In order to make the attacker's task difficult, a multi-threaded approach towards software development was proposed [1]. According to this approach, you should break the verification logic into several pieces, each of which should run in a separate thread. Any debugger, such as OllyDbg, is capable of single-stepping through only one thread at a time, although it is aware of the existence of other threads. This makes it difficult for an attacker to trace the verification logic. Not just for an attacker, it is also difficult for any ethical developer to debug a multithreaded program.

The motivation behind this project is to develop the prototype of a debugger that will make it easer to trace the execution path of a multi-threaded program. The intended debugger has to be able to single-step through all of the threads in lockstep.

1. Introduction

A lot of commercial softwares in the market, today, usually come with a trial version that has limited functionality. In order to take advantage of the full set of promised features, users are required to buy the software. After making the purchase, typically, a software activation key is provided to the user for activating his copy of the software, thereby enabling its full functionality.

Reverse engineering is the art of backtracking a program with the intent of tracing its flow of execution. It is also the skill of refuting the assumptions made by the developer of the program with respect to its security and privacy. In this world of reverse engineering, it is a common area of interest to be able to overcome the limitations of such a trial version without having to actually buy the software. There are a number of debuggers/disassemblers available, viz: OllyDbg, that provide a disassembled view of the software. With just the executable or the binary image in hand and the help of such a tool, it then takes the knowledge and expertise of the user to figure out the patch of code that needs to be changed to disable the check that performs the validation of activation key entered by the user.

There are a number of techniques that can be employed by the software developer to make it tougher to reverse engineer his software. Such techniques include detection of debugger, injecting junk code just to confuse the attacker, putting in lot of jumps in the code to damage the sense of locality etc. Multithreading or splitting the logic in different threads is one such technique. In case of a single-threaded program, it is easy for the debugger tool to trace the execution path of the single thread that also includes all the validation logic. However, if the software is multithreaded, the task gets tougher, with the difficulty of debugging lying in the core principle of multithreading itself. My project deals with reducing this level of difficulty and making it one step easier to debug a multithreaded software. My intention here is not to encourage hacking of softwares, but just to solve an intellectual challenge raised by multithreaded programming.

1.1 Problem statement & motivation

The difficulty of debugging such a multi-threaded software lies in the basic principle that multithreading was designed for – concurrent and, if possible, parallel execution of a program. *Concurrent programming* is an illusion given to the user that multiple tasks are being executed simultaneously. In reality, the threads of execution are being swapped in and out of the processor, completely utilizing the processor time. The processor *idle time* is effectively reduced and hence this is faster than a normal execution of tasks.

Parallel programming, on the other hand, is literal parallel execution of threads on multiple cores. On a multi-core system, the resources available for executing threads are also multiple. Hence, the threads can literally execute in parallel, one on each of the cores, at a particular instance of time. In case of a single processor system, this is nothing but concurrent execution. The task of scheduling threads to execute in the CPU entirely lies in the hands of the scheduler of the operating system. Depending upon the scheduling algorithm applied (such as round robin, first-in-first-out, shortest remaining time etc.), there can be a wide range of possible paths of execution for the same application. Also, depending upon whether the application is running on a single core or multiple cores, it may run *concurrently* or *parallelly*, as explained previously. A lot of the debuggers available today, however, are not able to single-step through multiple threads in lockstep i.e. while you are single-stepping through one thread, you might end up executing multiple instructions in the other threads before returning to your thread. This led to the idea of my project – to be able to visibly trace the execution path of a multithreaded program.

The prototype that has been designed as part of this project will serve as a basic debugger that outputs the code of whichever thread is running in the CPU at that instance of time.

2. Research topics

2.1 Multithreading fundamentals

2.1.1 Parallel versus concurrent programming

A thread is the smallest unit of execution that can run within the execution engine of a system. There can be multiple threads running within the context of a process, sharing the address space of the parent process. Shown below is the relationship between the processors, processes and threads.

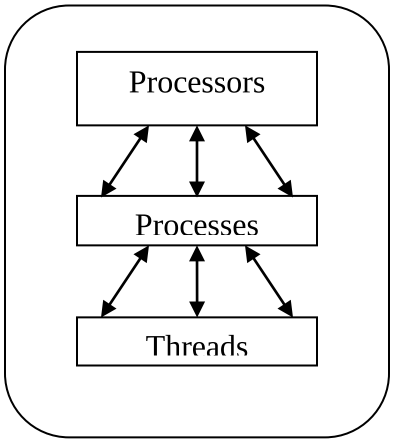


Figure 1. Relationship between processors, processes and threads

With different threads performing different tasks each, task level parallelism is achieved. This parallelism can be in terms of reducing the latency of execution of a task or true parallelism with simultaneous execution of tasks. When the multiple threads are running on a single core, they achieve *concurrency*. Whenever a thread that has access to the CPU and its resources goes in a wait state, it is swapped out of the execution and some other thread that is ready to actually utilize the resources is put into the execution engine. Thus, the CPU cycles are avoided from getting wasted, thereby reducing the latency of execution.

When these threads run on a multi-core system, however, they do run simultaneously, owing to the multiple sets of resources available.

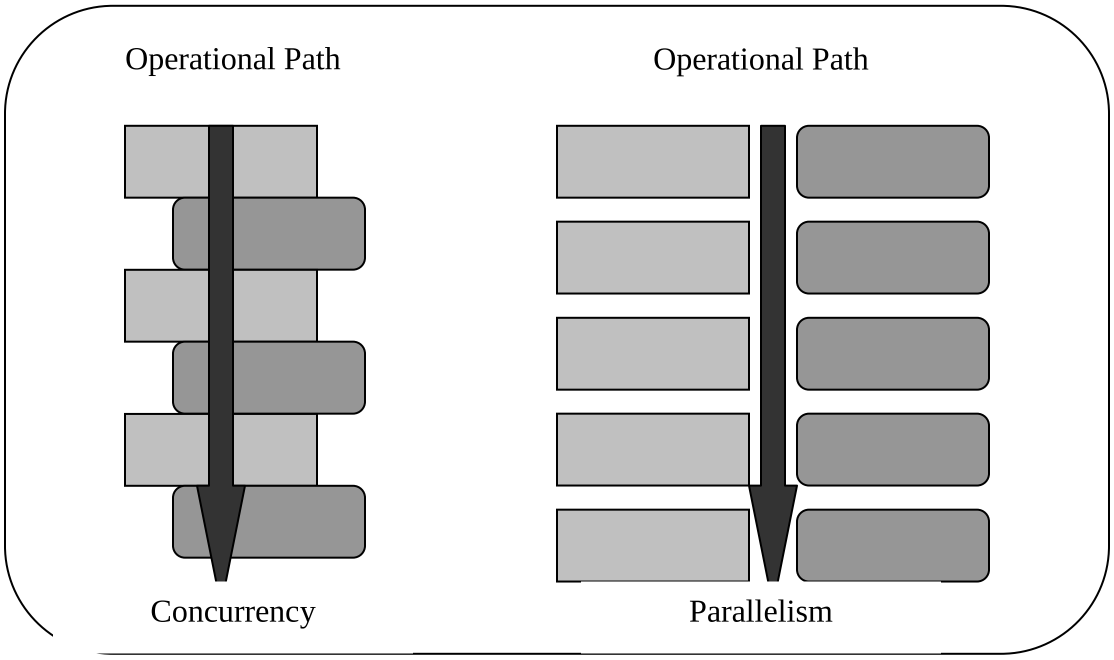


Figure 2. Concurrency versus parallelism

2.1.2 Thread synchronization primitives

Since all the threads run within the address space of a single process, there is bound to be access to some shared memory. To impose an order of execution of threads and control the order in which these threads access the shared memory, there is a need of synchronization mechanisms. These mechanisms come in the form of *mutex, semaphore, monitors, condition variables &* so on. The section of code that accesses shared memory is termed as a *critical section* of the code. It is required to use one of these synchronization mechanisms before and after accessing this critical section.

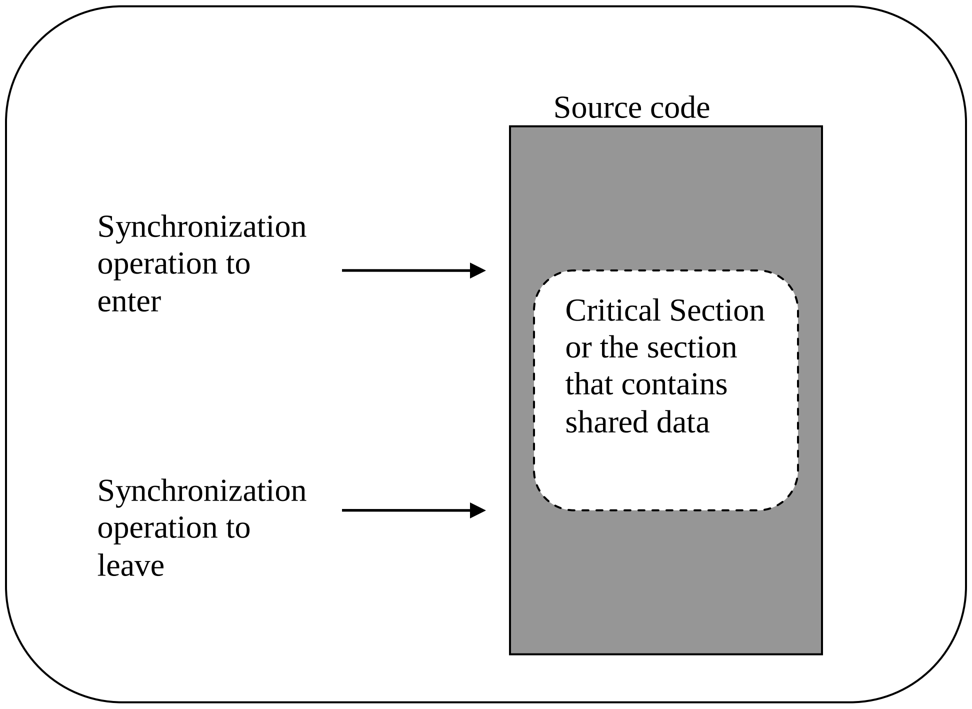

Source code
Synchronization operation to enter
Critical Section or the section that contains shared data
Synchronization operation to leave

Figure 3. Critical Section and synchronization primitives

Multithreading leads to certain peculiar and intermittent bugs, that may or may not occur during runtime. Mentioned ahead are the most notorious of such bugs – deadlocks and race conditions.

2.1.3 Deadlocks

Deadlock occurs when a thread is blocked on a resource held by another thread. This is usually not a consequence of a programming error. However, it can be avoided programmatically by various techniques.

2.1.4 Race Conditions

If no synchronization mechanism is used in the code, there is a race amongst the threads to gain access to the shared memory. Depending upon who gets the access first, the sequence in which this shared memory is read and modified by the threads can lead to a different output in every run. This is known as a *race condition.*

2.2 Multi-threading and multi-core

The notion of multiple threads running in a process has been around for decades. As a recap, a thread is the smallest unit of execution, that runs within the address space of the process. All threads of a process share its memory. Hence, context switching between threads is easier and cheaper than context-switching between processes.

Two threads running on a single core is different from multiple threads running on multiple cores. On a single core, with Hyper-threading technology, most of the processor resources are duplicated and each thread gets its own set of resources. The actual execution engine, however, is not duplicated. The instructions of both threads are interleaved in such a fashion that the processor is kept busy all the time, without wasting any cycles. This achieves performance gains through latency hiding.

With two threads running on two cores, however, each thread gets its own execution engine. This means the threads can run in a truly parallel manner, as shown below.

This difference of single-core and multi-core had to be kept in mind while developing the debugger and also while analyzing it’s output.

2.3 How scheduling works

The task of executing a thread of instructions is done in the CPU. The task of scheduling which thread gets access to the CPU and its resources belongs to the scheduler. The scheduler is concerned with keeping all the processors busy without wasting any CPU cycles. As mentioned previously, the lifetime of a thread consists of various states as *ready, running, wait etc.*:

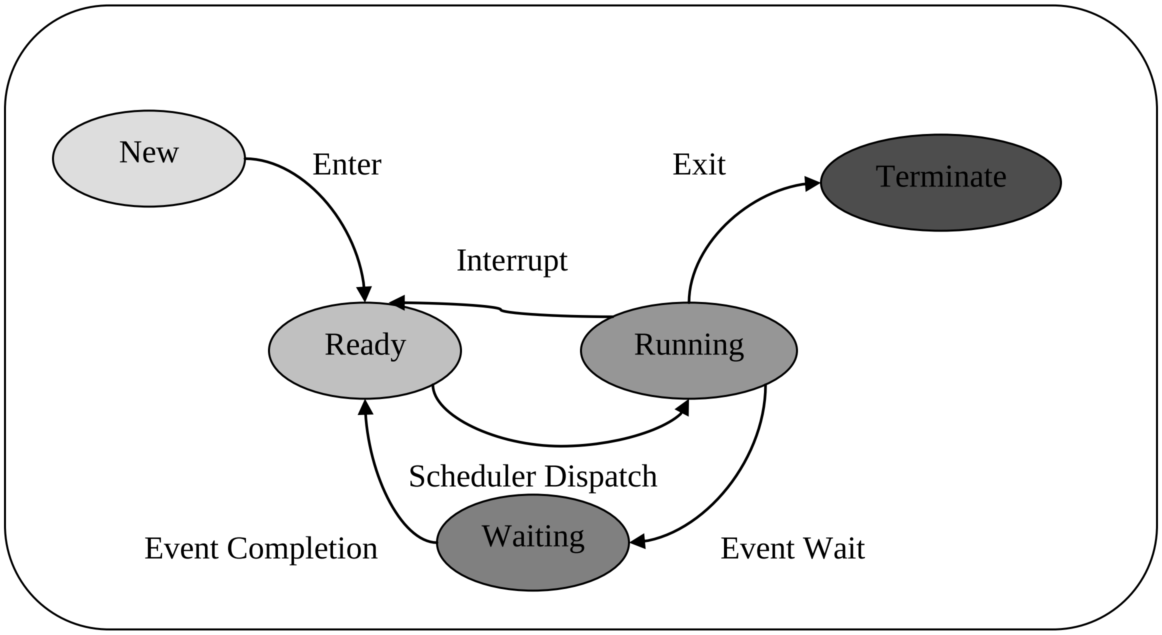


Figure 4. Lifecycle of a thread

When a thread is not running, or is “waiting” for I/O or waiting on an event, it is not utilizing the CPU cycle. Instead of keeping it in the execution engine, the scheduler decides to swap it out and put another thread that is in “ready” into the execution engine. This is what is called *context switching.* In this fashion, each thread gets access to the execution resources during any particular CPU cycle.

2.4 Reverse engineering techniques

Given only the binary of an application, there are few techniques that can be applied to figure out what might be going on within the program. Mentioned below are some of these techniques.

2.4.1 Black box analysis

This is a standard reverse engineering methodology that does not require any access to the source code of the binary. The analysis involves testing the running program for all sorts of inputs, and analyzes the corresponding behavior of the program. With the knowledge of how the output varies with input, a guess can be made about the internals of the system.

2.4.2 Code coverage tools

Code coverage is finding out what execution path has been taken by each run of the program. A lot of code coverage tools available today do not require the source code of the program to be available. It is human, while trying to reverse engineer, to skip certain portions of code, thinking that it is not significant. Such tools can give a report of how much of such code is yet to be analyzed.

2.4.3 Decompiling and disassembling

Decompiling is recovering the high-level source code from the binary executable of a program. Disassembling is recovering the assembly language code of the binary. There are a few such decompilers/disassemblers available in the market today, IdeaPro and OllyDbg to name a few. These tools give the best possible estimate of the source code using which, the vulnerabilities of the program can be explored.

2.5 How debuggers work

A *debugger* is nothing but a process that debugs another process. Typically, the debugger can either create the process to be debugged or simply attach to a running process. Any basic debugger needs to be able to do the following in order to debug a process :

- Set breakpoints in the process
- Single-step through the code
- Display the lines of source code

2.5.1 Setting breakpoints

Placing breakpoint is equivalent to deliberately introducing a trap or a software-invoked interrupt to occur. When such an interrupt occurs, irrespective of the source code, control is transferred to corresponding interrupt service routine. This gives the debugger an opportunity to decide on the further course of action to be followed. Usually, the *int 3* instruction (0xcc) is used by a debugger to set a breakpoint. The instruction where breakpoint is desired is replaced with the *int 3* instruction, the instruction pointer is decremented and the program is resumed. This causes the *int 3* instruction to be executed, thereby generating a trap, and pausing the process.

2.5.2 Single-stepping

Single-stepping is a feature of the x86 chipset that is used to trace the execution of a program. There is a special flag in the processor that, if set, will cause only a single instruction to be executed followed by an interrupt [1]. For tracing the execution path, this flag needs to be reset again and again, for every instruction.

2.5.3 Enumerating source code

Any executable is a binary image of the source code. However, to enumerate the lines of source code from this binary, certain other information is required for the debugger. This information comes in various formats, one of them being PDB file.

3 Design

The developed prototype has been developed with the following functionality:

- The debugger is notified for various events that occur in the application being debugged. These events primarily include
    - Thread creation
    - Process creation
    - Thread completion (indicated by the exit status of the thread)
    - Process completion
    - Exceptions such as breakpoint, single-step, array out-of-bounds etc.
- When an event is notified to the debugger, all the threads/processes in the debugged application are paused, until some action is taken by the debugger.
- Every new thread that is created in the application is put in a single-step mode.
- For every thread that is scheduled by the scheduler, it is displayed in the output window with a unique color.

- Whenever the thread is swapped out and another thread is scheduled to run, the corresponding color changes too. This makes it easier to track the thread execution.
- The disassembled view of each thread is displayed as and when the thread is scheduled to run.

3.1 Justification

My intention while starting this project was to develop some prototype tool that will assist a user to debug a multithreaded program in some way. With the above stated design, the user gets to look at whatever thread is running on the system. The prototype is able to single-step through all the threads. With some expertise in assembly language, the output of the debugger can be used to understand the code of a multithreaded exe. Whenever a context switch between threads occurs, the user can clearly identify it on the output screen as each thread is represented with a different color. If a user is only interested in a particular thread, he can choose to trace only that color of code throughout the output.

The debugger is not affected by multithreading bugs like deadlocks and race conditions within the program being debugged. If a thread is stuck on deadlock, the scheduler might swap it out of execution engine during some CPU cycle. When that happens, the debugger will display corresponding code on the output screen.

3.2 Platform

The debugger has been implemented using Microsoft's Visual Studio – Express edition. Primarily, windows APIs have been used and the development language has been C.

To disassemble the line of code being executed, *beangine* library has been used. Beaengine is a multi-platform disassembler for Intel and AMD processors.

The system that this prototype has been tested upon is an x64-based PC with an Intel i5 processor that comes with 2 cores and 4 logical processors.

4 Implementation

4.1 Attaching to the debuggee

A debugger is just another process bound to run in the system and so is the debuggee. Hence, in order to debug the application, it is created as a child process from the debugger process. We also specify the creation flags that control the scheduling priorities of the process. By specifying `DEBUG_PROCESS` as the process creation flag, we ask the Windows OS to communicate all the events such as process/thread creation/termination, runtime exceptions etc. of this thread as well all it's child threads and processes.

/*Code Snippet*/

```
STARTUPINFO si;
PROCESS_INFORMATION pi;
ZeroMemory( &si, sizeof(si) );
si.cb = sizeof(si);
EXCEPTION_DEBUG_INFO exception;
ZeroMemory( &pi, sizeof(pi) );
CreateProcess(NULL, argv[1], NULL, NULL, FALSE,
                DEBUG_PROCESS, NULL,NULL, &si, &pi )
```

4.2 Main Debugger loop

This is the main area of the debugger. It is a while loop that keeps waiting for debugging events from the debuggee, processes each event, and then continues waiting again. This is achieved through the windows APIs *WaitForDebugEvent* and *ContinueDebugEvent.* When an event is notified to the debugger, all the processes and threads of the debuggee are paused. Only after

ContinueDebugEvent is executed with DBG_CONTINUE as the last parameter, the debuggee process is resumed.

/*Code snippet*/

```
while(ContinueDebugging)
{

     if (!WaitForDebugEvent(&debug_event, INFINITE))
        return 0;
     Sleep(500);
     switch(debug_event.dwDebugEventCode)
     {
          //Handle the debug events
          ContinueDebugging = true;
     }

     ContinueDebugEvent(debug_event.dwProcessId,
          debug_event.dwThreadId,
                      DBG_CONTINUE);
}
```

4.3 *Handling Debugging events*

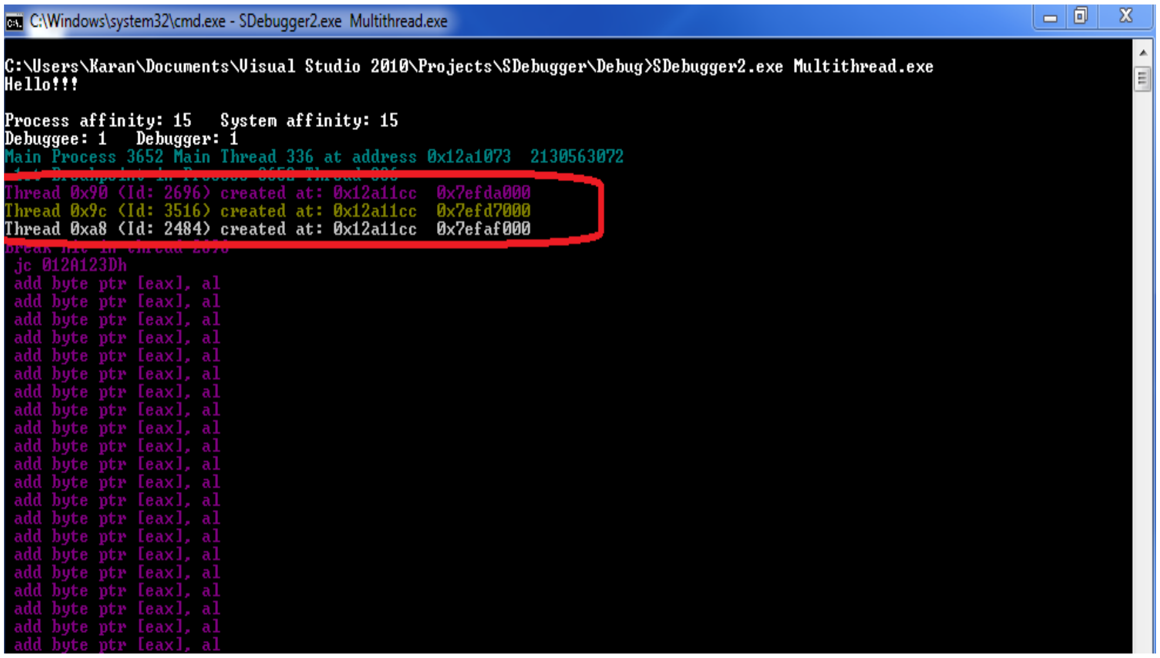
Certain steps of execution are treated as "events" in every running process. For every event occurring in the debuggee, the debugger is notified. At the same time, all the threads and processes running in the debuggee are paused. Listed below are some of the relevant events that have been handled in order to implement the intended prototype.

4.3.1 CreateThread event

Every time a new thread is created in the debuggee, it is treated as a new event and the debugger is notified about it. Upon receiving such an event, the debugger prints it out to the output screen with a unique color that it assigns to this thread. Going further, every time this thread is running, the corresponding prints will be in this particular color to identify the thread.

In order to debug the thread, a breakpoint needs to be added at the starting point of the thread. Hence, the thread context is retrieved and the very first instruction is replaced with a breakpoint instruction 0xcc. Note that this is not the only breakpoint instruction that can be used. The instruction pointer will have already moved ahead by one instruction by this time. But since we want the breakpoint instruction to be executed, we decrement the instruction pointer of this thread and then continue. This leads to the very next event to be an exception event caused by this thread, with the exception type being a breakpoint exception.

```
/*Code Snippet*/
// Read the first instruction
ReadProcessMemory(main_process,(void*)debug_event.u.CreateThread.lpStartAddress,
&(threads[i].OriginalInstruction), 1, &dwReadBytes);
// Replace it with Breakpoint
cInstruction = 0xCC;
WriteProcessMemory(main_process,(void*)debug_event.u.CreateThread.lpStartAddress,
&cInstruction, 1, &dwReadBytes);
FlushInstructionCache(main_process,(void*)debug_event.u.CreateThread.lpStartAddress,1);
```



```
C:\Windows\system32\cmd.exe - SDebugger2.exe  Multithread.exe

C:\Users\Karan\Documents\Visual Studio 2010\Projects\SDebugger\Debug>SDebugger2.exe Multithread.exe
Hello!!!

Process affinity: 15   System affinity: 15
Debuggee: 1   Debugger: 1
Main Process 3652 Main Thread 336 at address 0x12a1073  2130563072
1st Breakpoint in Process 3652 Thread 336
Thread 0x90 (Id: 2696) created at: 0x12a11cc  0x7efda000
Thread 0x9c (Id: 3516) created at: 0x12a11cc  0x7efd7000
Thread 0xa8 (Id: 2484) created at: 0x12a11cc  0x7efaf000
Break hit in thread 2696
 jc 012A123Dh
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
```

Figure 5. Handling Create Thread event

4.3.2 Exception event

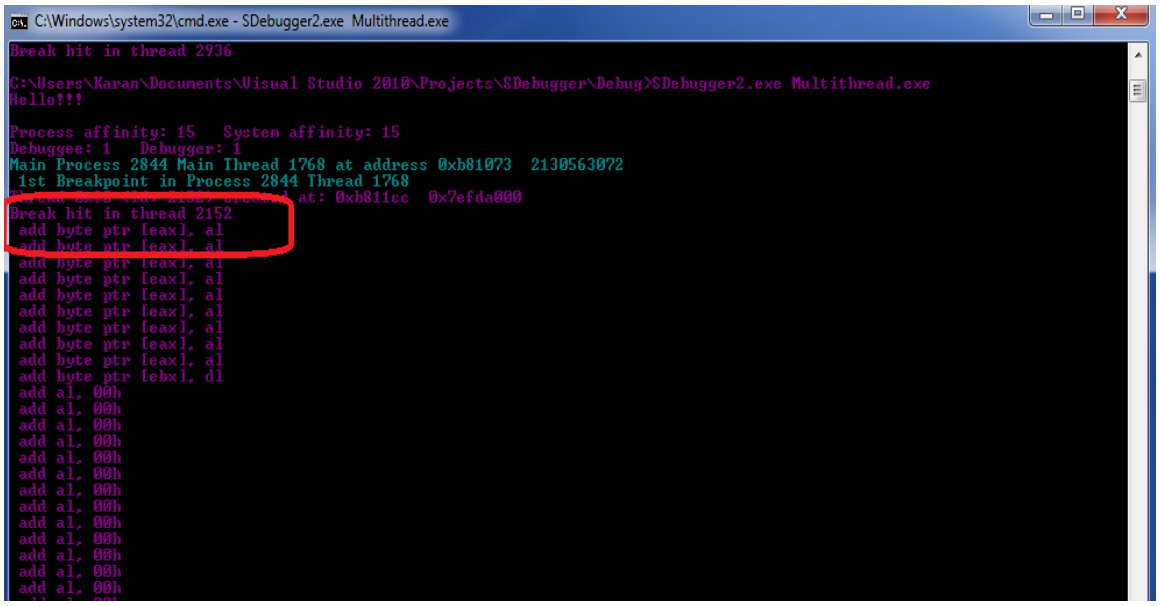
Exceptions are abnormal behaviors of a process, such divide-by-zero, stack overflow, access violation etc. Listed below are couple of important exceptions that are intentionally planted into the debuggee as part of the debugging process.

4.3.2.1 Breakpoint exception

Since this was the breakpoint that we implanted by replacing the first instruction, we need to place the original instruction in it's place. Before doing that, we set the single-step bit in the thread context. This will cause the thread to go into a single-stepping mode and raise single-step exception when it is about to execute the next instruction. After setting the bit, we replace the breakpoint instruction with the original instruction, decrement the instruction pointer again, and continue.

/*Code snippet*/

```
//Fetch the context of the thread

GetThreadContext(threads[j].child_handle,
&(threads[j].lcContext));

//Replace the breakpoint instruction with the original

instruction

WriteProcessMemory(main_process,

exception.ExceptionRecord.ExceptionAddress,

&(threads[j].OriginalInstruction), 1,&dwWriteSize);

// Set trap flag, which raises "single-step" exception

threads[j].lcContext.EFlags |= 0x100;

// Decrement the instruction pointer

 threads[j].lcContext.Eip--;
```



```
C:\Windows\system32\cmd.exe - SDebugger2.exe  Multithread.exe
Break hit in thread 2936

C:\Users\Karan\Documents\Visual Studio 2010\Projects\SDebugger\Debug>SDebugger2.exe Multithread.exe
Hello!!!

Process affinity: 15   System affinity: 15
Debuggee: 1   Debugger: 1
Main Process 2844 Main Thread 1768 at address 0xb81073  2130563072
 1st Breakpoint in Process 2844 Thread 1768
Thread 0x78 (Id: 2152) created at: 0xb811cc  0x7efda000
Break hit in thread 2152
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [ebx], dl
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
```

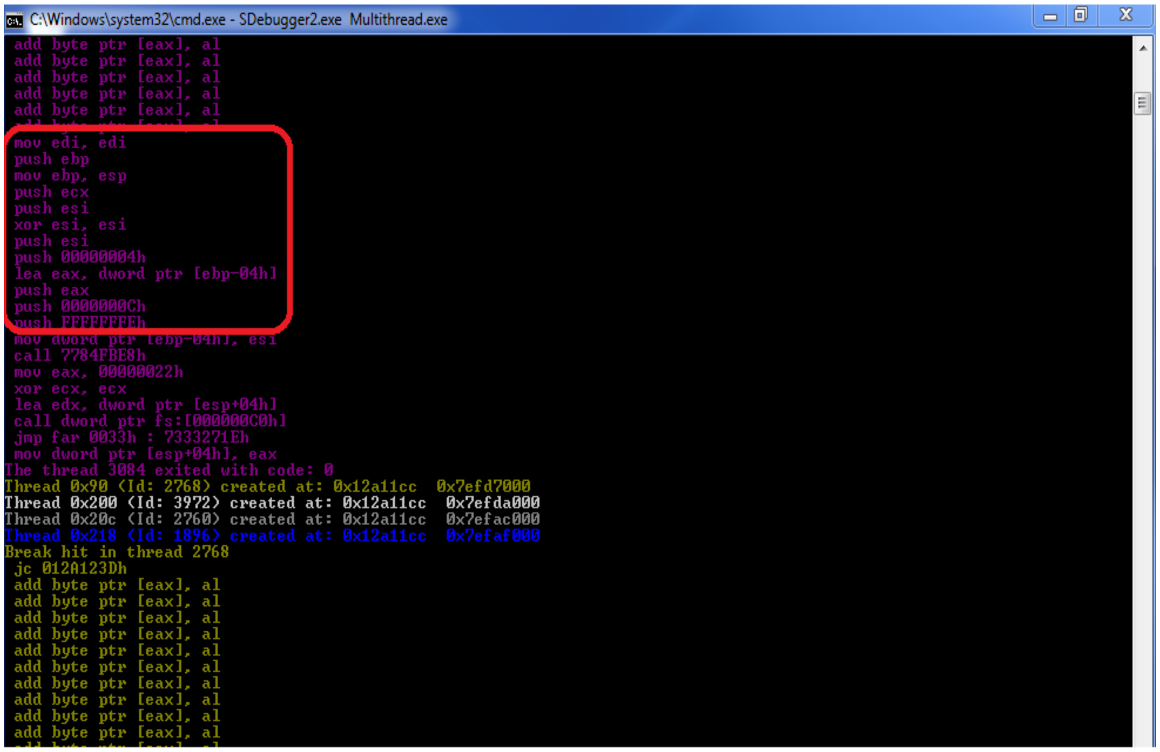
Figure 6. Handling breakpoint exception event

4.3.2.2 Single-step exception

As a result of the processing done during breakpoint exception handling, the very next exception raised by a thread, if it is scheduled to run, is the single-step exception. This exception is raised for the next line of instruction that the thread is about to execute. It is at this point, that we take the address of this next instruction, pointed by the instruction pointer, and give it to the disassembler routine, thereby getting the corresponding assembly language instruction.
We also need to again set the bit for single-step , to keep stepping through the code of this thread.

/*Code snippet*/

```
//  Fetch the context of the thread
GetThreadContext(threads[j].child_handle,
&(threads[j].lcContext));
// Take the instruction address
threads[j].MyDisasm.EIP = threads[j].lcContext.Eip;
//Give it to the disassembler routine
len = Disasm(&threads[j].MyDisasm);
//Print the disassembled instruction
printf(" %s \n",&threads[j].MyDisasm.CompleteInstr);
//Set the single-step flag again
threads[j].lcContext.EFlags |= 0x100;
```

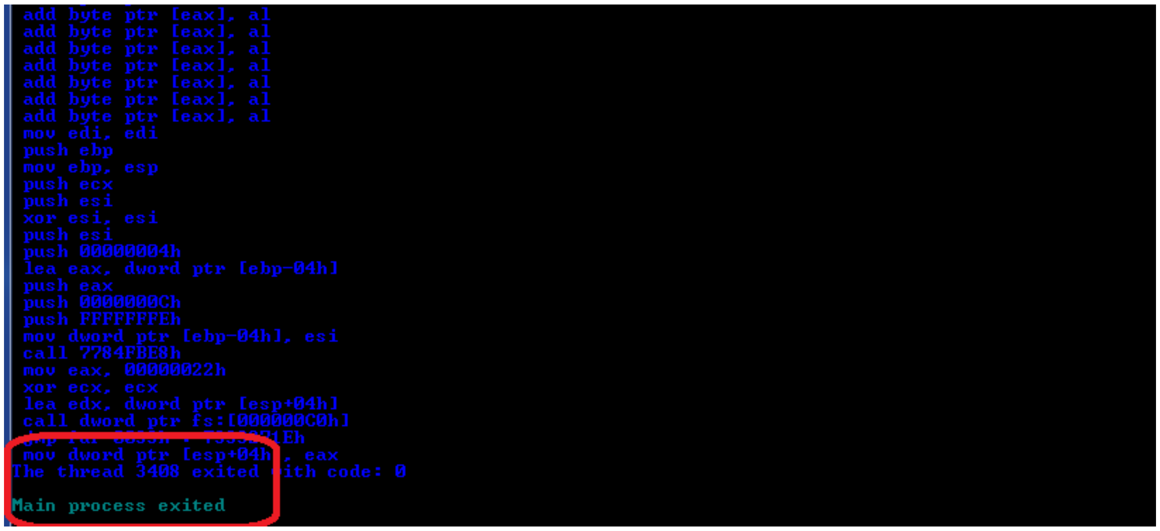


```
C:\Windows\system32\cmd.exe - SDebugger2.exe  Multithread.exe
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 mov edi, edi
 push ebp
 mov ebp, esp
 push ecx
 push esi
 xor esi, esi
 push esi
 push 00000004h
 lea eax, dword ptr [ebp-04h]
 push eax
 push 0000000Ch
 push FFFFFFFEh
 mov dword ptr [ebp-04h], esi
 call 7784FBE8h
 mov eax, 00000022h
 xor ecx, ecx
 lea edx, dword ptr [esp+04h]
 call dword ptr fs:[000000C0h]
 jmp far 0033h : 7333271Eh
 mov dword ptr [esp+04h], eax
The thread 3084 exited with code: 0
Thread 0x90 (Id: 2768) created at: 0x12a11cc  0x7efd7000
Thread 0x200 (Id: 3972) created at: 0x12a11cc  0x7efda000
Thread 0x20c (Id: 2760) created at: 0x12a11cc  0x7efac000
Thread 0x218 (Id: 1896) created at: 0x12a11cc  0x7efaf000
Break hit in thread 2768
 jc 012A123Dh
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
```

Figure 7. Handling single-step exception event

4.3.2.3 Exit Process event

Once the debuggee completes execution, its main process exits and raises this exception. The debugging is then stopped.



```
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 mov edi, edi
 push ebp
 mov ebp, esp
 push ecx
 push esi
 xor esi, esi
 push esi
 push 00000004h
 lea eax, dword ptr [ebp-04h]
 push eax
 push 0000000Ch
 push FFFFFFFEh
 mov dword ptr [ebp-04h], esi
 call 7784FBE8h
 mov eax, 00000022h
 xor ecx, ecx
 lea edx, dword ptr [esp+04h]
 call dword ptr fs:[000000C0h]
 jmp far 0033h : 7333271Eh
 mov dword ptr [esp+04h], eax
The thread 3408 exited with code: 0

Main process exited
```

Figure 8. Handling exit thread/process event

4.4 Handling multiple cores

During initial runs of the debugger, it was observed that few threads completed execution without giving a chance to single-step. After further analysis, it became clear that it was because of the type of system that I was running it upon. My system has 2 cores and thereby, 4 logical processors. What this implies is that my operating system sees the system as having 4 processors. Hence, it can schedule the threads on any of these processors in parallel. This was the reason that my debugger was not able to single-step through some threads while being able to do so for others.

To overcome this limitation, I had to mask the *processor affinity* of the thread. It is the processor affinity of the thread that determines which processor it will run upon. By default, this is set to all the logical processors i.e. it is eligible to run upon any of the processors. Since my requirement is to be able to look into each thread, I decided to force it to run upon a single logical processor. I also force my debugger process to run upon a single logical processor.

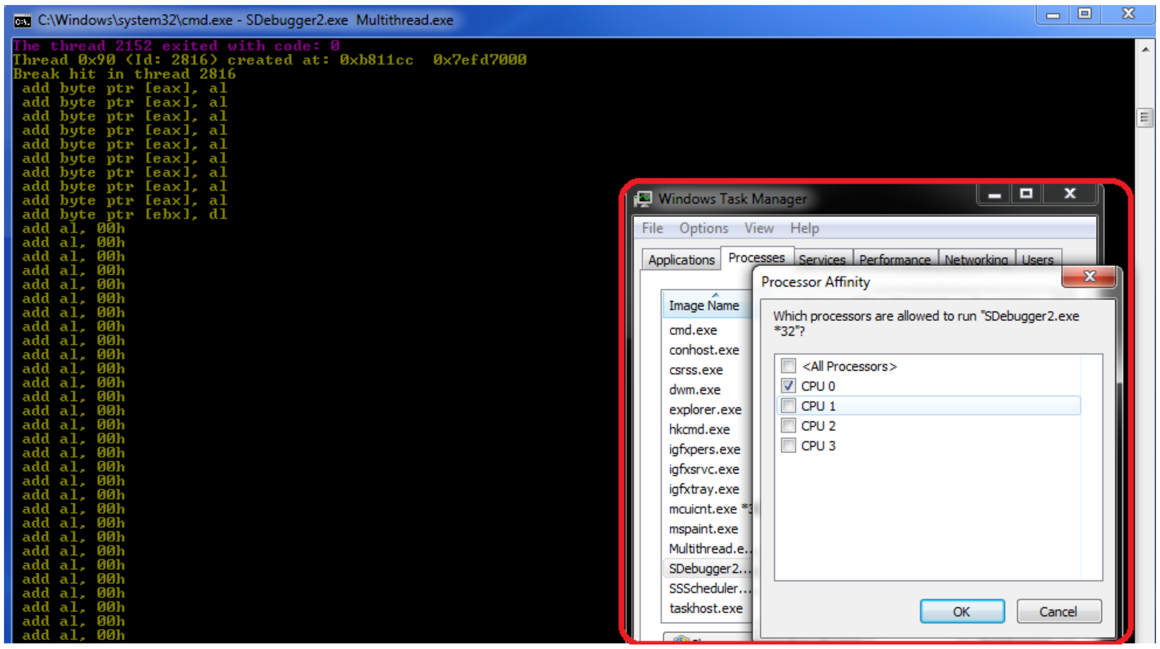
/*Code snippet*/

When the debuggee process is created by the debugger:

```
SetProcessAffinityMask(pi.hProcess, 1); //pi.hProcess is the
handle to the debuggee process
```

For every thread that is created, it is reported by CREATE_THREAD_EVENT :

```
CREATE_THREAD_DEBUG_EVENT:

     SetThreadAffinityMask(OpenThread(THREAD_ALL_ACCESS,FALSE,de
bug_event.dwThreadId),1);
```



```
C:\Windows\system32\cmd.exe - SDebugger2.exe  Multithread.exe
The thread 2152 exited with code: 0
Thread 0x90 (Id: 2816) created at: 0xb811cc  0x7efd7000
Break hit in thread 2816
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [ebx], dl
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
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 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
 add al, 00h
```

Windows Task Manager

File Options View Help

Applications | Processes | Services | Performance | Networking | Users

Image Name
cmd.exe
conhost.exe
csrss.exe
dwm.exe
explorer.exe
hkcmd.exe
igfxpers.exe
igfxsrvc.exe
igfxtray.exe
mcuicnt.exe *
mspaint.exe
Multithread.e...
SDebugger2...
SSScheduler...
taskhost.exe

Processor Affinity

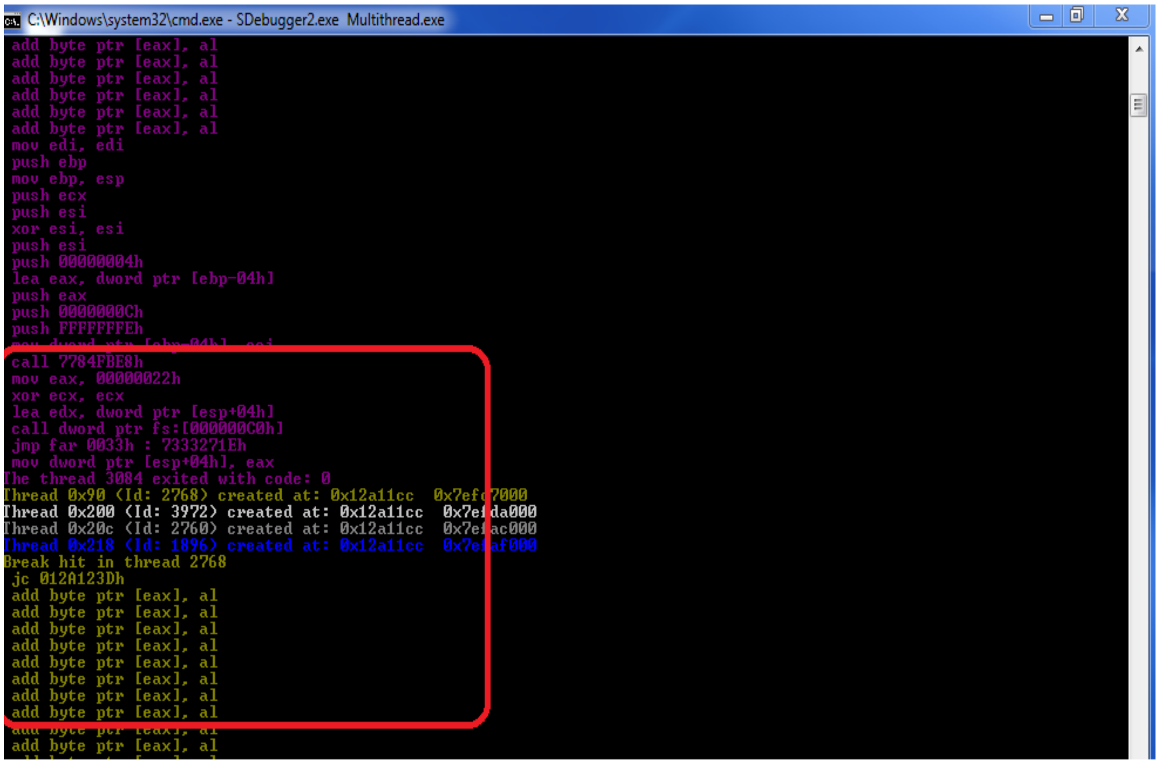
Which processors are allowed to run "SDebugger2.exe *32"?

- [ ] <All Processors>
- [x] CPU 0
- [ ] CPU 1
- [ ] CPU 2
- [ ] CPU 3

Figure 9. Handling multiple cores

4.5 Context switching between threads

The debugger's job is to catch hold of whatever thread is running in the execution engine at that instance of time. Since we put every thread in the single-step mode right when it is created, for every next instruction about to be executed, a notification is sent to the debugger. When such a notification arrives, the debugger checks which thread it has come from and displays the output in a specific color that was assigned to the thread in the beginning. This is to help the user identify that the switch between threads has happened and that there is a new thread running in the CPU.


C:\Windows\system32\cmd.exe - SDebugger2.exe Multithread.exe

```
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 mov edi, edi
 push ebp
 mov ebp, esp
 push ecx
 push esi
 xor esi, esi
 push esi
 push 00000004h
 lea eax, dword ptr [ebp-04h]
 push eax
 push 0000000Ch
 push FFFFFFFEh
 mov dword ptr [ebp-04h], esi
 call 7784FBE8h
 mov eax, 00000022h
 xor ecx, ecx
 lea edx, dword ptr [esp+04h]
 call dword ptr fs:[000000C0h]
 jmp far 0033h : 7333271Eh
 mov dword ptr [esp+04h], eax
The thread 3084 exited with code: 0
Thread 0x90 (Id: 2768) created at: 0x12a11cc  0x7efd7000
Thread 0x200 (Id: 3972) created at: 0x12a11cc  0x7efda000
Thread 0x20c (Id: 2760) created at: 0x12a11cc  0x7efac000
Thread 0x218 (Id: 1896) created at: 0x12a11cc  0x7efaf000
Break hit in thread 2768
 jc 012A123Dh
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
```

Figure 10. Context switching between threads

5 Testing

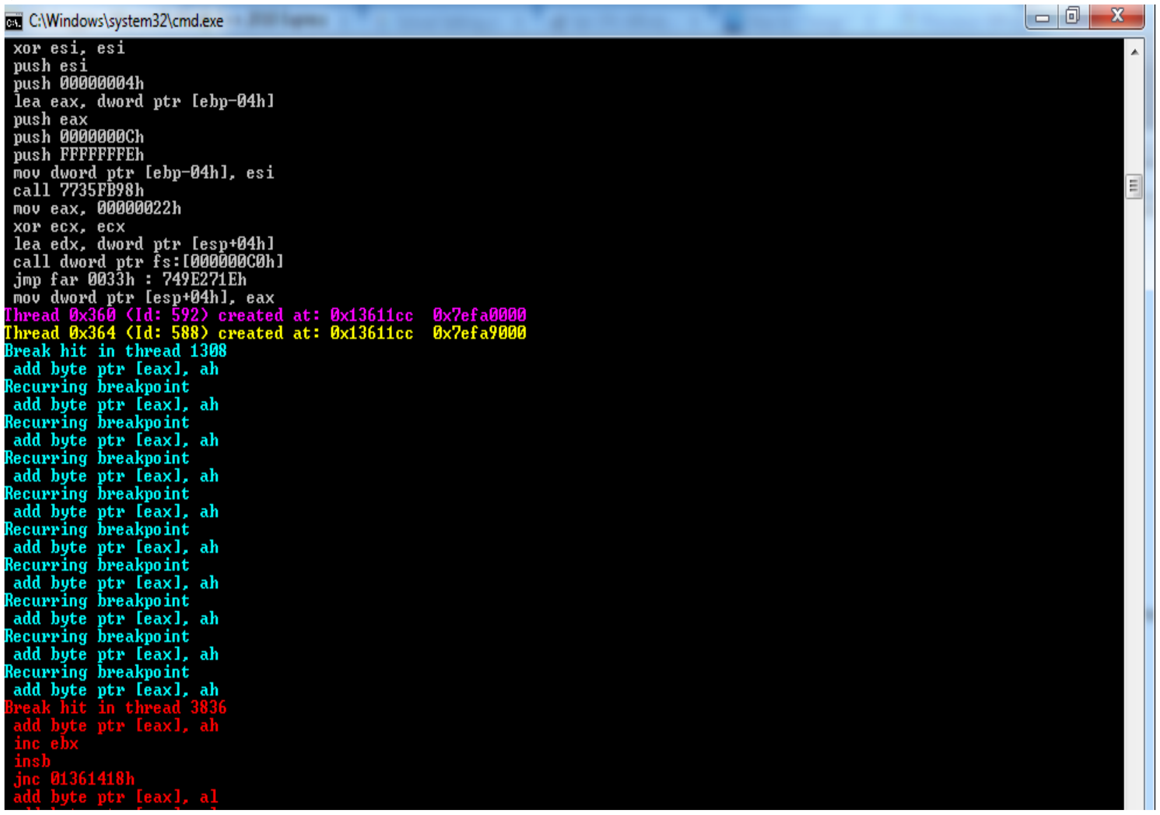
In order to test the debugger, I wrote different versions of multithreaded programs. Each version is intended to test some peculiarity that arises with the multithreading methodology. The nature of multithreading bugs is inherently intermittent. Hence, even though I designed the debuggee with an intention to produce such bugs, they did not occur despite many runs. It was observed that none of these peculiarities really affect the working of my prototype debugger, since it works hand-in-hand with the scheduler of the system.

Following are the test cases:

5.1 **Simple multithreaded debuggee** → 5 Child threads are created by the debuggee, each executing its task independently. There is no communication between the threads, and hence no need of synchronization. There is also no I/O or wait involved in the thread procedure.

/*Code snippet*/

```
void ThreadPRoc(LPVOID param)
{
    int x = 2;
     x++;
   ExitThread(0);
}
```



```
 xor esi, esi
 push esi
 push 00000004h
 lea eax, dword ptr [ebp-04h]
 push eax
 push 0000000Ch
 push FFFFFFFEh
 mov dword ptr [ebp-04h], esi
 call 7735FB98h
 mov eax, 00000022h
 xor ecx, ecx
 lea edx, dword ptr [esp+04h]
 call dword ptr fs:[000000C0h]
 jmp far 0033h : 749E271Eh
 mov dword ptr [esp+04h], eax
Thread 0x360 (Id: 592) created at: 0x13611cc  0x7efa0000
Thread 0x364 (Id: 588) created at: 0x13611cc  0x7efa9000
Break hit in thread 1308
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Recurring breakpoint
 add byte ptr [eax], ah
Break hit in thread 3836
 add byte ptr [eax], ah
 inc ebx
 insb
 jnc 01361418h
 add byte ptr [eax], al
```

Figure 11. Test case 1 – Simple multithreaded debuggee

Observation → The debugger steps through each thread as and when it is scheduled in the CPU.

5.2 **Some sleep time in each thread** → The intention of the sleep state is to check if that affects the way that the threads are swapped in and out of the execution engine. As explained before, when a thread is in a wait or not-running state, not utilizing any of the CPU resources, the scheduler swaps it out of the execution engine and schedules any other thread that is ready to run. It was observed, however, that the sleep induced in the code did not affect the scheduling in a major way. With a heavier thread procedure and more number of threads, the thread swapping might become more visible.

/*Code snippet*/

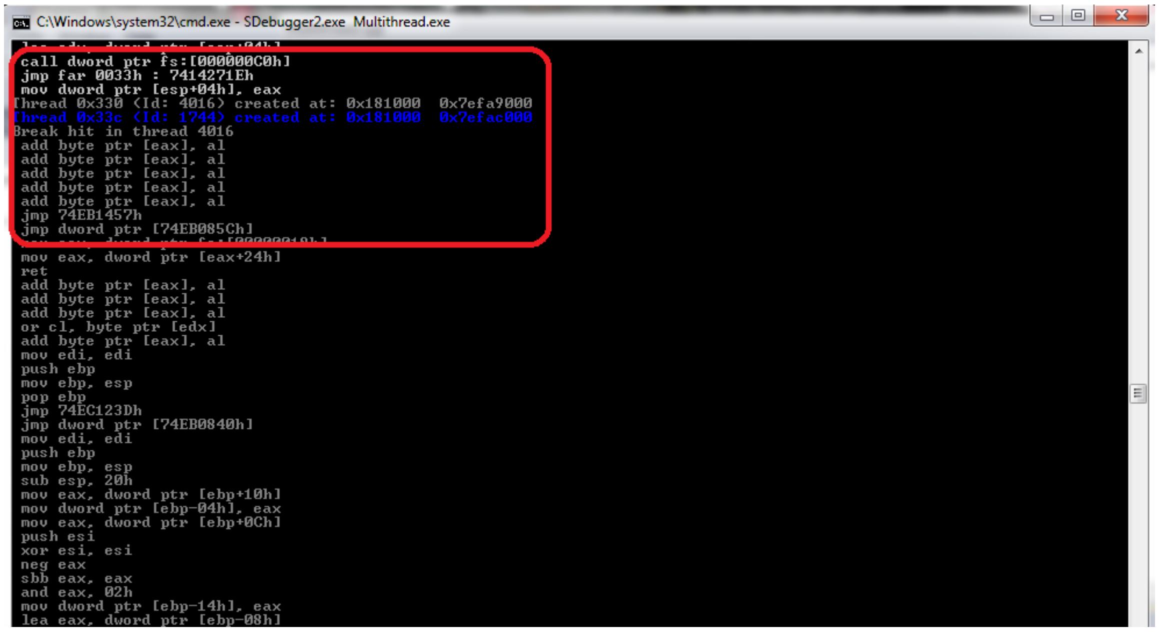
```
void ThreadPRoc(LPVOID param)
{
    int x = 2;
     x++;
     Sleep(1000);
   ExitThread(0);
}
```

5.3 **Thread synchronization →** Here, I induced some basic synchronization between the threads. There is one common variable, *count*, that is shared amongst the threads. Each thread increments the count. Since this is a shared memory, I used a mutex to control the way that the threads gain access to this variable. Each thread has to gain a lock over the mutex before being able to modify the *count* variable.

/*Code snippet*/

```
//Wait to acquire the lock on mutex before modifying shared
memory
if(WaitForSingleObject(hMutex1, INFINITE) == WAIT_OBJECT_0)
{
     printf("Thread %d in critical
     section\n",GetCurrentThreadId());
     while(count>0)
          count--;
     Sleep(10000);
}
else
{
     printf("Thread %d : not allowed to enter critical
     section\n", GetCurrentThreadId());
```

```
        ExitThread(0);
}
```



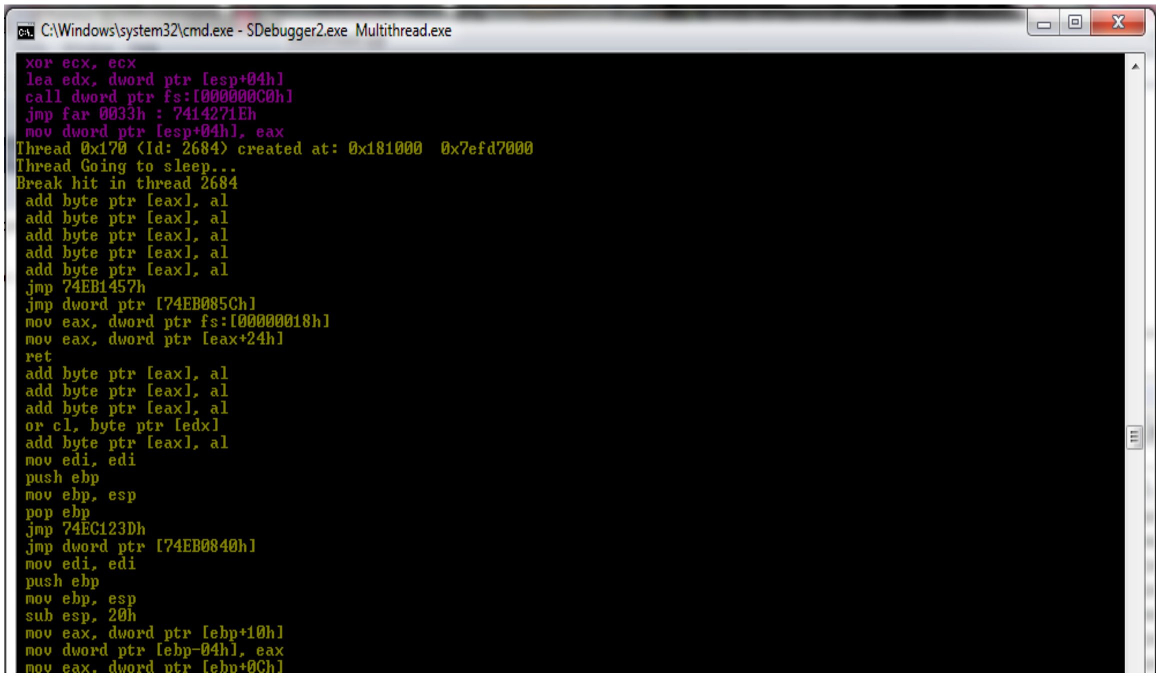
```
C:\Windows\system32\cmd.exe - SDebugger2.exe  Multithread.exe
 call dword ptr fs:[000000C0h]
 jmp far 0033h : 7414271Eh
 mov dword ptr [esp+04h], eax
Thread 0x330 (Id: 4016) created at: 0x181000  0x7efa9000
Thread 0x33c (Id: 1744) created at: 0x181000  0x7efac000
Break hit in thread 4016
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 jmp 74EB1457h
 jmp dword ptr [74EB085Ch]
 mov eax, dword ptr [eax+24h]
 ret
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 or cl, byte ptr [edx]
 add byte ptr [eax], al
 mov edi, edi
 push ebp
 mov ebp, esp
 pop ebp
 jmp 74EC123Dh
 jmp dword ptr [74EB0840h]
 mov edi, edi
 push ebp
 mov ebp, esp
 sub esp, 20h
 mov eax, dword ptr [ebp+10h]
 mov dword ptr [ebp-04h], eax
 mov eax, dword ptr [ebp+0Ch]
 push esi
 xor esi, esi
 neg eax
 sbb eax, eax
 and eax, 02h
 mov dword ptr [ebp-14h], eax
 lea eax, dword ptr [ebp-08h]
```

Figure 12. Test case 3 – thread synchronization

Observation → The thread synchronization does not affect working of the debugger in any way. Threads continue to be scheduled in a regular fashion.

In the previous test cases, the multithreaded program was designed using appropriate parallel programming constructs. But I also wanted to test the debugger functionality with programs that might incur multithreading bugs such as deadlocks and race conditions. What follows are the observations in those cases.

5.4 **Race condition →** In this test case, I removed the use of mutex for synchronizing shared variable access between the threads. With no mutex to monitor this access, a race condition is bound to occur. Depending upon the order in which threads get to access this variable, the result can be an incorrect calculation of the final value of *count.*


C:\Windows\system32\cmd.exe - SDebugger2.exe Multithread.exe

```
 xor ecx, ecx
 lea edx, dword ptr [esp+04h]
 call dword ptr fs:[000000C0h]
 jmp far 0033h : 7414271Eh
 mov dword ptr [esp+04h], eax
Thread 0x170 (Id: 2684) created at: 0x181000  0x7efd7000
Thread Going to sleep...
Break hit in thread 2684
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 jmp 74EB1457h
 jmp dword ptr [74EB085Ch]
 mov eax, dword ptr fs:[00000018h]
 mov eax, dword ptr [eax+24h]
 ret
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 or cl, byte ptr [edx]
 add byte ptr [eax], al
 mov edi, edi
 push ebp
 mov ebp, esp
 pop ebp
 jmp 74EC123Dh
 jmp dword ptr [74EB0840h]
 mov edi, edi
 push ebp
 mov ebp, esp
 sub esp, 20h
 mov eax, dword ptr [ebp+10h]
 mov dword ptr [ebp-04h], eax
 mov eax, dword ptr [ebp+0Ch]
```

Figure 13. Test case 4 – race condition

Observation → Even in this case, there was no effect on the debugger functionality. Since race condition is not a bug that only leads to incorrect output, and does not affect the normal execution of the program as such, the debugger works as it is supposed to and outputs the code of whatever thread is running.

5.5 Deadlock → In this test case, I tried to cause a deadlock amongst the threads on purpose by using 2 mutexes. Each thread tries to gain access to both the mutexes. Depending upon how the scheduler swaps between these threads, a deadlock can happen if each thread gains access to one mutex and waits for the other mutex.

Thread T1	**Thread T2**
waitforMutex(Mutex1)	waitforMutex(Mutex2)
waitforMutex(Mutex2)	waitforMutex(Mutex1)
//critical section	//critical section
count++;	count++;
ReleaseMutex(Mutex2)	ReleaseMutex(Mutex1)
ReleaseMutex(Mutex1)	ReleaseMutex(Mutex2)

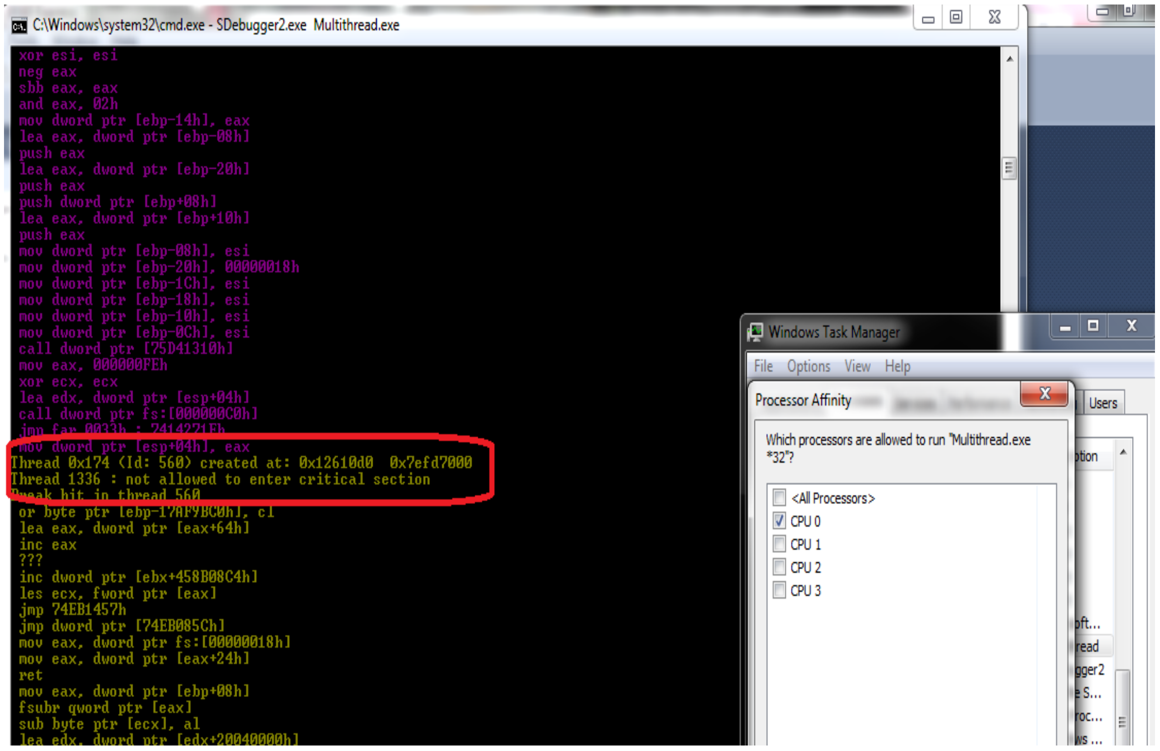
/*Thread1 Code snippet*/

```
if(WaitForSingleObject(hMutex1, INFINITE)==WAIT_OBJECT_0)
{
     if(WaitForSingleObject(hMutex2, INFINITE) == WAIT_OBJECT_0)
     {
          printf("Thread %d in critical
          section\n",GetCurrentThreadId());
          while(count>0)
          count--;
          Sleep(10000);
     }
     else
     {
          printf("Thread %d : not allowed to enter critical
          section\n", GetCurrentThreadId());
          ExitThread(0);
     }
 }
```

/*Thread2 code snippet*/

```
if(WaitForSingleObject(hMutex2, INFINITE)==WAIT_OBJECT_0)
{
     if(WaitForSingleObject(hMutex1, INFINITE) == WAIT_OBJECT_0)
     {
          printf("Thread %d in critical
          section\n",GetCurrentThreadId());
          while(count>0)
          count--;
          Sleep(10000);
     }
     else
```

```
        {
            printf("Thread %d : not allowed to enter critical
            section\n", GetCurrentThreadId());
        ExitThread(0);
        }
    }
```



C:\Windows\system32\cmd.exe - SDebugger2.exe Multithread.exe

```
xor esi, esi
neg eax
sbb eax, eax
and eax, 02h
mov dword ptr [ebp-14h], eax
lea eax, dword ptr [ebp-08h]
push eax
lea eax, dword ptr [ebp-20h]
push eax
push dword ptr [ebp+08h]
lea eax, dword ptr [ebp+10h]
push eax
mov dword ptr [ebp-08h], esi
mov dword ptr [ebp-20h], 00000018h
mov dword ptr [ebp-1Ch], esi
mov dword ptr [ebp-18h], esi
mov dword ptr [ebp-10h], esi
mov dword ptr [ebp-0Ch], esi
call dword ptr [75D41310h]
mov eax, 000000FEh
xor ecx, ecx
lea edx, dword ptr [esp+04h]
call dword ptr fs:[000000C0h]
jmp far 0033h : 7414221Eh
mov dword ptr [esp+04h], eax
Thread 0x174 (Id: 560) created at: 0x12610d0  0x7efd7000
Thread 1336 : not allowed to enter critical section
Break hit in thread 560
or byte ptr [ebp-17AF9BC0h], cl
lea eax, dword ptr [eax+64h]
inc eax
???
inc dword ptr [ebx+458B08C4h]
les ecx, fword ptr [eax]
jmp 74EB1457h
jmp dword ptr [74EB085Ch]
mov eax, dword ptr fs:[00000018h]
mov eax, dword ptr [eax+24h]
ret
mov eax, dword ptr [ebp+08h]
fsubr qword ptr [eax]
sub byte ptr [ecx], al
lea edx, dword ptr [edx+20040000h]
```

Windows Task Manager

Processor Affinity

Which processors are allowed to run "Multithread.exe *32"?

<All Processors>
[✓ CPU 0]
CPU 1
CPU 2
CPU 3

Figure 14. Test case 5 - deadlock

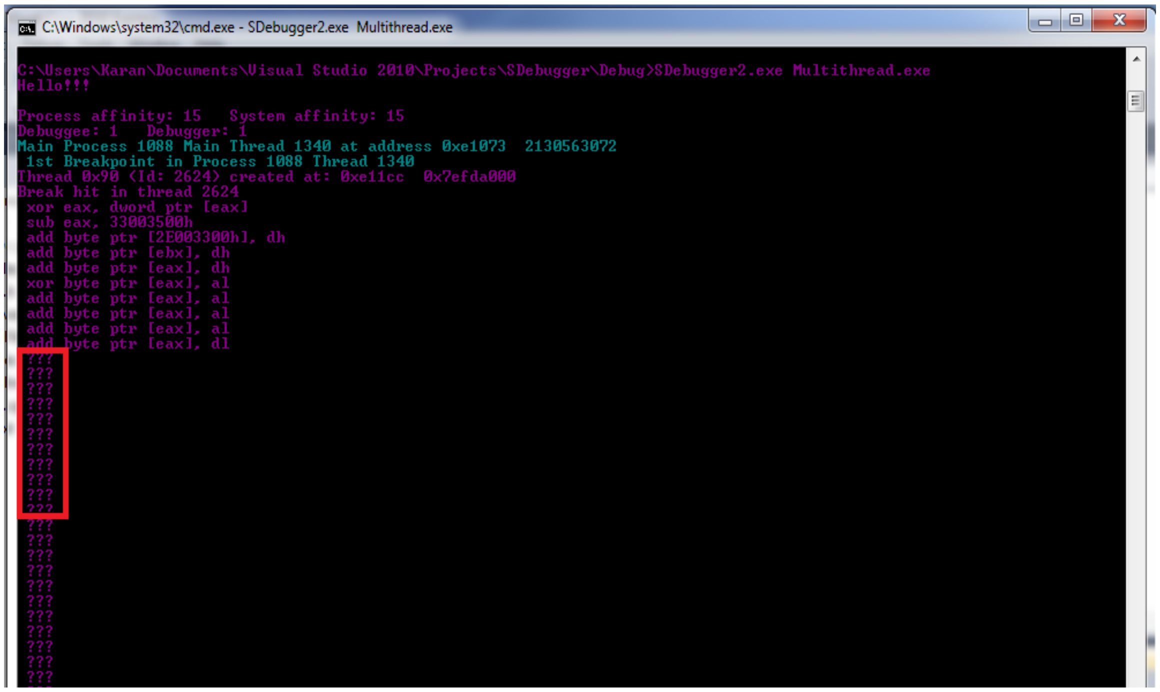
Observation → Even in this case, the debugger does its job of tracing the execution path of the program. If there is a deadlock and a thread is blocked, the scheduler will swap out that thread and run some other thread in its place. Accordingly, the output on the screen will also differ with corresponding assembly code of that thread.

6. Known issues

Multithreading comes with its own set of irreproducible bugs. These programs often fail in an unexpected, non-deterministic fashion. While developing my debugger prototype, a two such bugs were encountered. These bugs surface unexpectedly and I have not been able to find a resolution to the same.

5.5.1 No man’s land

The operating system allocates memory addresses 00000000 through 0000FFFF as “No man’s land”. Assuming that programmer’s are bound to make mistakes, this no man’s land prevents the programs that try to reference NULL from crashing altogether and exit gracefully. I encountered this sometimes when the memory instruction could not be interpreted by the disassembler routine. It printed ‘?’ at such addresses.



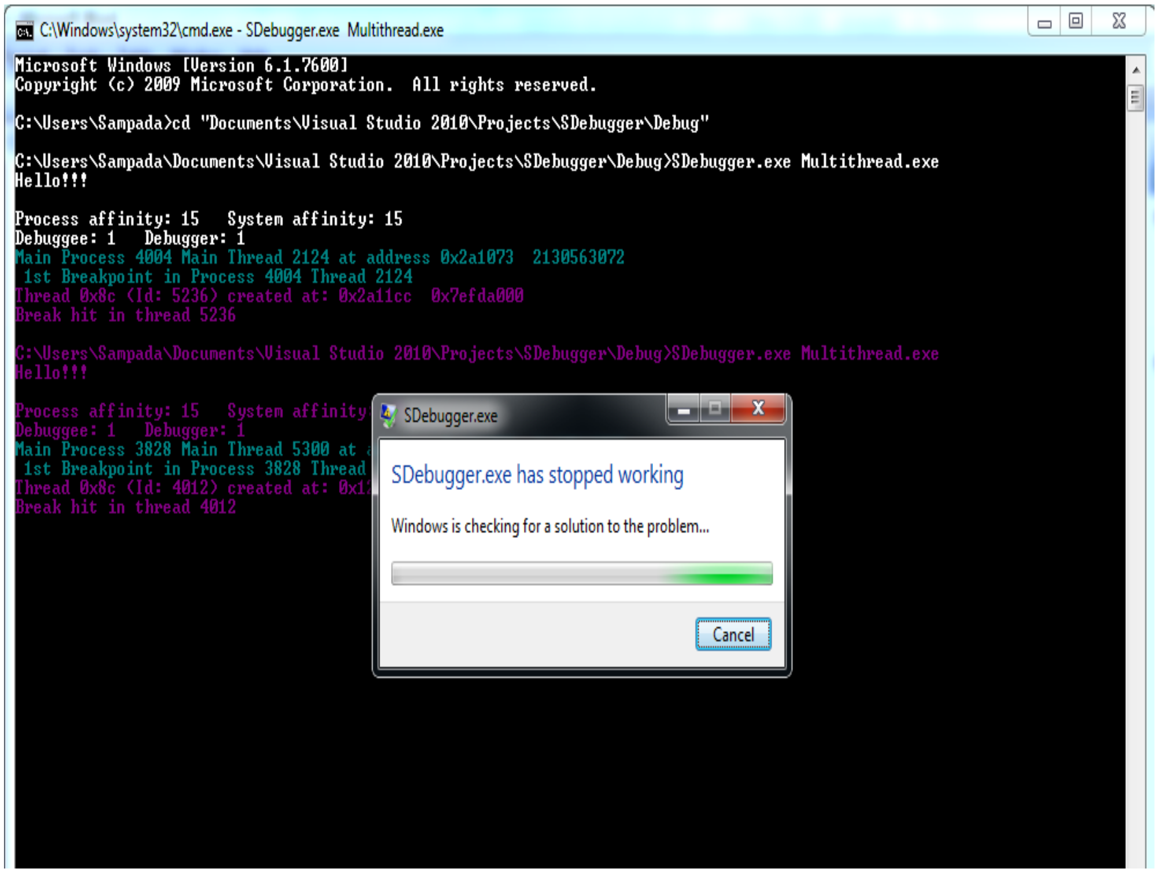
C:\Windows\system32\cmd.exe - SDebugger2.exe Multithread.exe

```
C:\Users\Karan\Documents\Visual Studio 2010\Projects\SDebugger\Debug>SDebugger2.exe Multithread.exe
Hello!!!

Process affinity: 15   System affinity: 15
Debuggee: 1   Debugger: 1
Main Process 1088 Main Thread 1340 at address 0xe1073  2130563072
 1st Breakpoint in Process 1088 Thread 1340
Thread 0x90 (Id: 2624) created at: 0xe11cc  0x7efda000
Break hit in thread 2624
 xor eax, dword ptr [eax]
 sub eax, 33003500h
 add byte ptr [2E003300h], dh
 add byte ptr [ebx], dh
 add byte ptr [eax], dh
 xor byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], al
 add byte ptr [eax], dl
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
 ???
```

Figure 15. No man’s land error

5.5.2 Access violation error

An intermittent side-effect of the previously mentioned “no mans land” access was an access violation exception. This exception is the operating system’s way of telling you that the program has tried to access no man’s land that is off-limits. As a direct result, sometimes the program threw the exception `EXCEPTION_ACCESS_VIOLATION`. At other times, the program abruptly stopped working and showed the same error when opened in a third-party debugger.

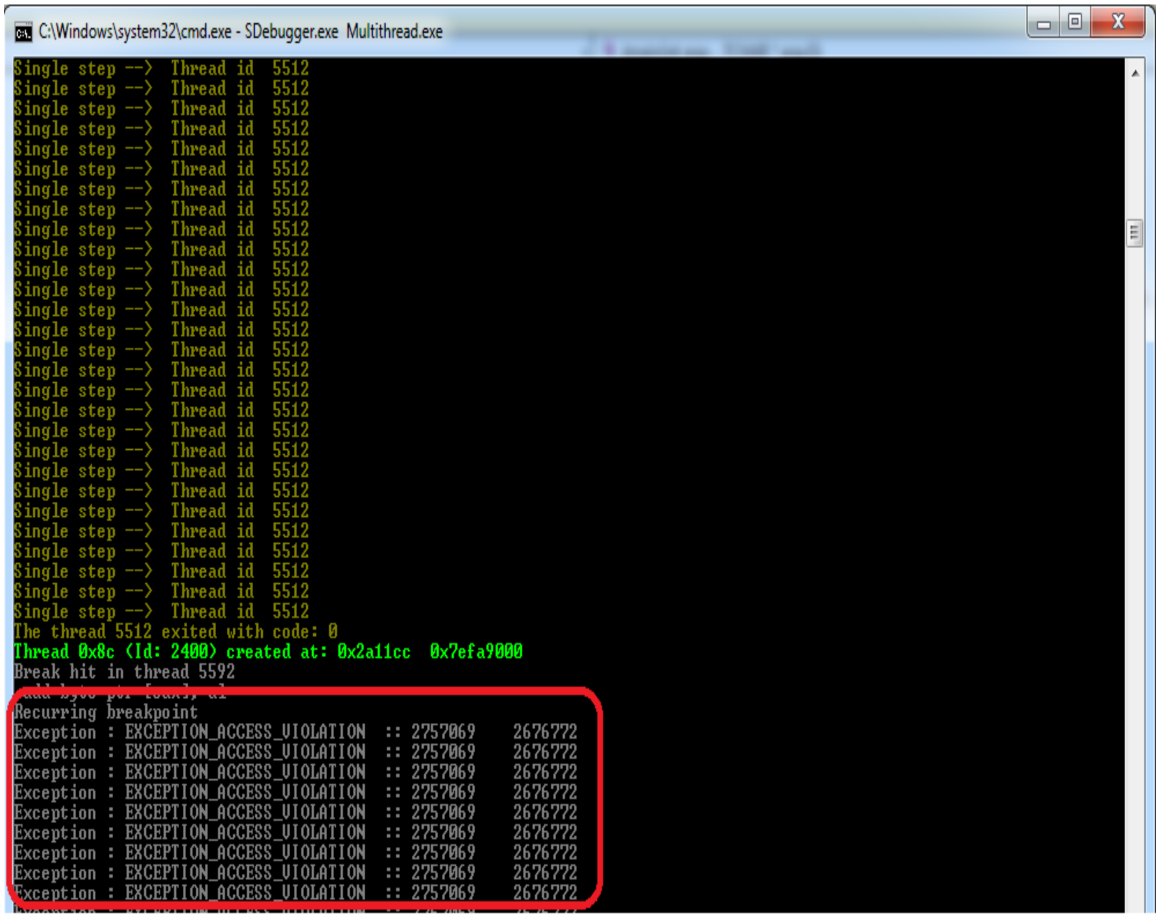


```
Microsoft Windows [Version 6.1.7600]
Copyright (c) 2009 Microsoft Corporation.  All rights reserved.

C:\Users\Sampada>cd "Documents\Visual Studio 2010\Projects\SDebugger\Debug"

C:\Users\Sampada\Documents\Visual Studio 2010\Projects\SDebugger\Debug>SDebugger.exe Multithread.exe
Hello!!!

Process affinity: 15   System affinity: 15
Debuggee: 1   Debugger: 1
Main Process 4004 Main Thread 2124 at address 0x2a1073  2130563072
 1st Breakpoint in Process 4004 Thread 2124
Thread 0x8c (Id: 5236) created at: 0x2a11cc  0x7efda000
Break hit in thread 5236

C:\Users\Sampada\Documents\Visual Studio 2010\Projects\SDebugger\Debug>SDebugger.exe Multithread.exe
Hello!!!

Process affinity: 15   System affinity
Debuggee: 1   Debugger: 1
Main Process 3828 Main Thread 5300 at a
 1st Breakpoint in Process 3828 Thread
Thread 0x8c (Id: 4012) created at: 0x1
Break hit in thread 4012
```

SDebugger.exe has stopped working

Windows is checking for a solution to the problem...

Figure 16. Access violation error



```
C:\Windows\system32\cmd.exe - SDebugger.exe  Multithread.exe
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
Single step -->  Thread id  5512
The thread 5512 exited with code: 0
Thread 0x8c (Id: 2400) created at: 0x2a11cc  0x7efa9000
Break hit in thread 5592
add byte ptr [eax], al
Recurring breakpoint
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
Exception : EXCEPTION_ACCESS_VIOLATION  :: 2757069    2676772
```

Figure 17. Access violation exception

6 Recommendations for future work

Since my debugger was developed by me alone, it only has the basic capabilities of debugging. When compared with the commercially available debuggers that are developed by larger teams over a period of time, following are the features that could be added to make it a complete functional debugger:

- User interaction
- Ability to pause/resume the debugging
- Display the register values
- Display the call stack
- Ability to patch the code

Secondly, my debugger has been developed using Windows APIs. The IDE used for writing both the debugger and the debuggee was Microsoft Visual Studio Express Edition. As part of future work, it can be tested upon programs that have been written in other IDEs. The debugger logic can also be tried on a different platform like Linux, to test the validity of the framework.

The disassembler that I have used to develop the code-display feature of my debugger is not a well-known software. To be able to literally break a software using my debugger, it will be required to use a better and reliable disassembler. Also, the user will have to be skilled at assembly language programming, to interpret the instructions being displayed on the output screen and patch it accordingly.

7. Conclusion

Multithreaded programming is a non-avoidable phenomenon. Following Amdahl's law, as the number of cores increases, parallel programming is the way to be for future softwares. However, the complexity of parallel programming should not obstruct the curiosity of finding ways to debug such a software. With more number of tools to assist this, the challenge of developers to develop a hack-proof software also increases. My project was an attempt in this direction. I have tried to overturn the assumption that merely making the software multithreaded can be a strong anti-reverse engineering technique.

References

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