Übung zu Betriebssysteme

Entkäfern mit GDB & GEF

22. November 2023

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Lehrstuhl für Verteilte Systeme
und Betriebssysteme

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

TECHNISCHE FAKULTÄT

Your PC ran into a problem that it couldn't handle, and now it needs to restart.

You can search for the error online: HAL_INITIALIZATION_FAILED

:(

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Your PC ran into a prob[illegible] it couldn't handle, and now it needs to restart.

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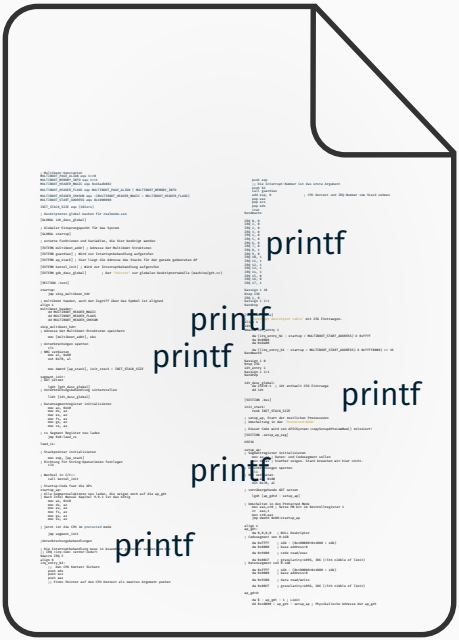
```
├── common.mk
├── kernel
│   ├── boot
│   │   ├── sections.ld
│   │   ├── startup.asm
│   │   └── startup.cc
│   ├── compiler.h
│   ├── config.h
│   ├── debug
│   │   ├── assert.cc
│   │   ├── assert.h
│   │   ├── gdb
│   │   │   ├── handler.asm
│   │   │   ├── handler.cc
│   │   │   ├── init.cc
│   │   │   ├── protocol.cc
│   │   │   └── stub.h
│   │   ├── kernelpanic.h
│   │   ├── null_stream.cc
│   │   ├── null_stream.h
│   │   └── output.h
│   ├── device
│   │   ├── cgastr.cc
│   │   ├── cgastr.h
│   │   ├── console.cc
│   │   ├── console.h
│   │   ├── keyboard.cc
│   │   ├── keyboard.h
│   │   ├── panic.cc
│   │   ├── panic.h
│   │   ├── watch.cc
│   │   └── watch.h
│   ├── guard
│   │   ├── gate.h
│   │   ├── guard.cc
│   │   ├── guard.h
│   │   ├── guardian.cc
│   │   ├── guardian.h
│   │   └── secure.h
│   ├── machine
│   │   ├── acpi.cc
│   │   ├── acpi.h
│   │   ├── apicsystem.cc
│   │   ├── apicsystem.h
│   │   ├── cgascr.cc
│   │   ├── cgascr.h
│   │   ├── cpu.asm
│   │   ├── cpu.h
│   │   ├── gdt.cc
│   │   ├── gdt.h
│   │   ├── ioapic.cc
│   │   ├── ioapic.h
│   │   ├── ioapic_registers.h
│   │   ├── io_port.h
│   │   ├── keyctrl.cc
│   │   ├── keyctrl.h
│   │   ├── keydecoder.cc
│   │   ├── keydecoder.h
│   │   ├── key.h
│   │   ├── lapic.cc
│   │   ├── lapic.h
│   │   ├── lapic_registers.h
│   │   ├── mp_registers.h
│   │   ├── plugbox.cc
│   │   ├── plugbox.h
│   │   ├── serial.cc
│   │   ├── serial.h
│   │   ├── spinlock.h
│   │   ├── ticketlock.h
│   │   ├── toc.asm
│   │   ├── toc.cc
│   │   ├── toc.h
│   │   └── toc.inc
│   ├── main.cc
│   ├── Makefile
│   ├── meeting
│   │   ├── bell.cc
│   │   ├── bell.h
│   │   ├── bellringer.cc
│   │   ├── bellringer.h
│   │   ├── messageinfo.h
│   │   ├── semaphore.cc
│   │   ├── semaphore.h
│   │   ├── waitingroom.cc
│   │   └── waitingroom.h
│   ├── memory
│   │   ├── allocator.cc
│   │   ├── allocator.h
│   │   ├── copy.cc
│   │   ├── copy.h
│   │   ├── initmem.cc
│   │   ├── initmem.h
│   │   ├── kernelpage.h
│   │   ├── malloc.cc
│   │   ├── malloc.h
│   │   ├── multiboot.h
│   │   ├── [illegible]gecont.cc
│   │   ├── [illegible]gecont.h
│   │   ├── [illegible]ur.cc
│   │   ├── [illegible]ur.h
│   │   ├── pagefault.h
│   │   ├── page.h
│   │   ├── pageref.cc
│   │   ├── pageref.h
│   │   ├── range.h
│   │   └── user_buffer.h
│   ├── object
│   │   ├── bbuffer.h
│   │   ├── o_stream.cc
│   │   ├── o_stream.h
│   │   ├── queue.h
│   │   ├── queuelink.h
│   │   ├── strbuf.cc
│   │   └── strbuf.h
│   ├── syscall
│   │   ├── guarded_bell.cc
│   │   ├── guarded_bell.h
│   │   ├── guarded_keyboard.cc
│   │   ├── guarded_keyboard.h
│   │   ├── guarded_scheduler.h
│   │   ├── guarded_semaphore.h
│   │   ├── syscall.cc
│   │   └── syscall.h
│   ├── thread
│   │   ├── assassin.cc
│   │   ├── assassin.h
│   │   ├── dispatcher.cc
│   │   ├── dispatcher.h
│   │   ├── idlethread.cc
│   │   ├── idlethread.h
│   │   ├── scheduler.cc
│   │   ├── scheduler.h
│   │   ├── thread.cc
│   │   ├── thread.h
│   │   └── wakeup.h
│   ├── types.h
│   ├── user
│   │   ├── app1
│   │   │   ├── app1.cc
│   │   │   └── app1.h
│   │   └── app2
│   │       ├── kapp1.cc
│   │       └── kapp1.h
│   └── utils
│       ├── elf.cc
│       ├── elf.h
│       ├── libcc.cc
│       ├── math.h
│       ├── memutil.cc
│       ├── memutil.h
│       ├── sort.h
│       ├── string.cc
│       ├── string.h
│       ├── tar.cc
│       └── tar.h
├── libsys
│   ├── iostream.h
│   ├── Makefile
│   ├── o_stream.cc
│   ├── o_stream.h
│   ├── strbuf.cc
│   ├── strbuf.h
│   ├── syscall_stubs.asm
│   ├── syscall_stubs.cc
│   └── types.h
├── Makefile
├── README.md
├── test-stream
│   ├── console_out.cc
│   ├── console_out.h
│   ├── file_out.cc
│   ├── file_out.h
│   ├── Makefile
│   └── test.cc
└── user
    ├── app0
    │   ├── app0.cc
    │   └── app0.h
    ├── app1
    │   ├── app1.cc
    │   └── app1.h
    ├── app2
    │   ├── app2.cc
    │   └── app2.h
    ├── app3
    │   ├── app3.cc
    │   └── app3.h
    ├── app4
    │   ├── app4.cc
    │   └── app4.h
    ├── imgbuilder.cc
    ├── init.cc
    ├── Makefile
    ├── Makefile.app
    └── sections.ld

24 directories, 172 files
```


printf
printf


printf
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printf

Entkäfern mit GDB & GEF

GNU Debugger (GDB)

- \+ Inspizieren des Systemzustands während das System läuft
- \- Nur rudimentäres TUI

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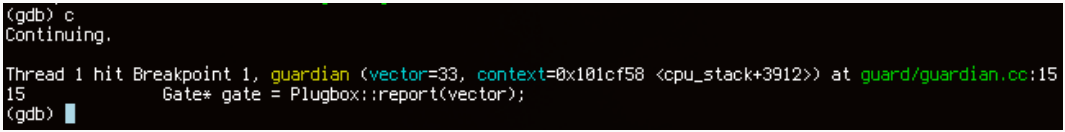
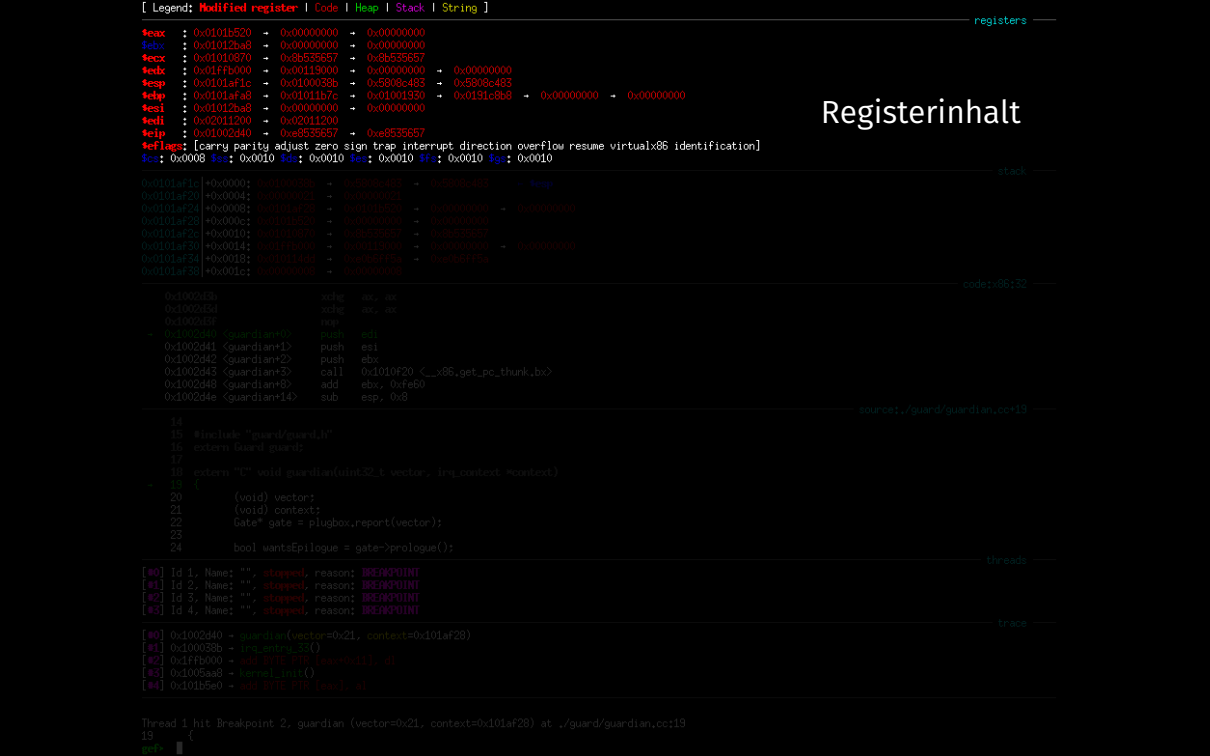
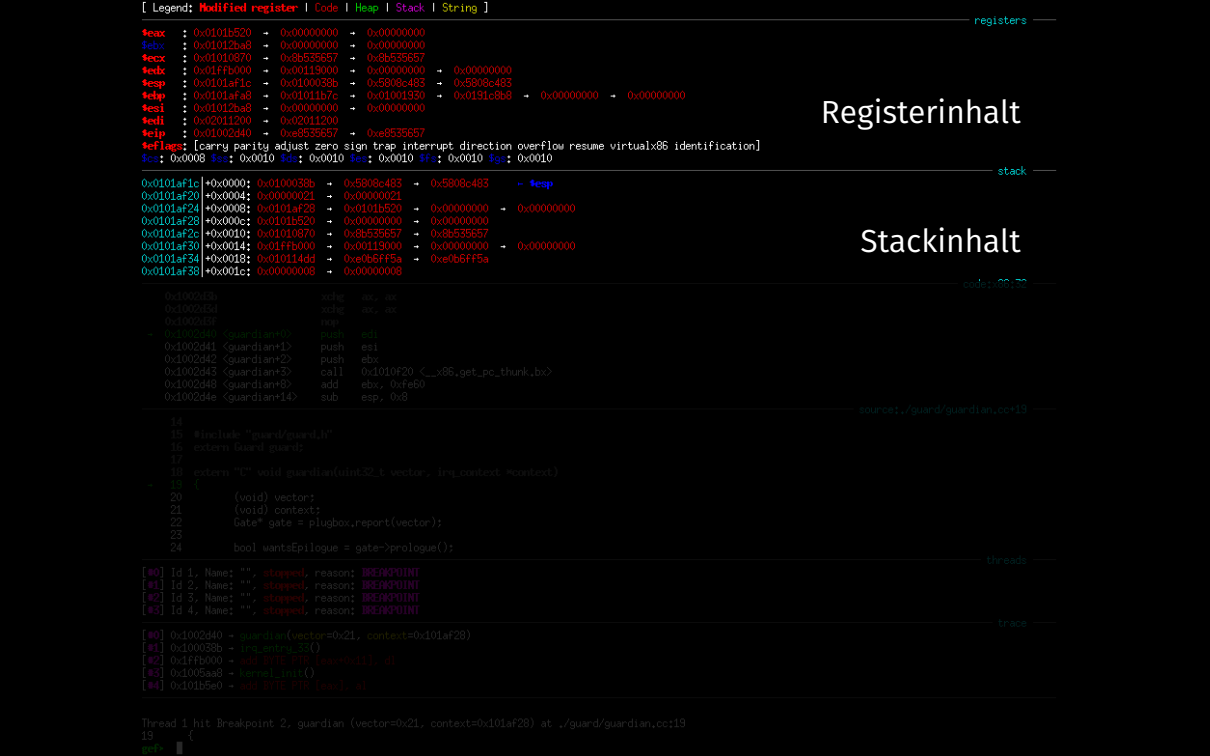


GDB Enhanced Features (GEF)

+ Erweitert GDB um ein brauchbar(er)es Interface


[Legend: Modified register | Code | Heap | Stack | String]
registers
$eax : 0x0101b520 → 0x00000000 → 0x00000000
$ebx : 0x01012ba8 → 0x00000000 → 0x00000000
$ecx : 0x01010870 → 0x8b535657 → 0x8b535657
$edx : 0x01ffb000 → 0x00119000 → 0x00000000 → 0x00000000
$esp : 0x0101af1c → 0x100038b → 0x5808e483 → 0x5808e483
$ebp : 0x0101af28 → 0x01011b7c → 0x01001930 → 0x0191c8b8 → 0x00000000 → 0x00000000
$esi : 0x01012ba8 → 0x00000000 → 0x00000000
$edi : 0x02011200 → 0x02011200
$eip : 0x0102d40 → 0xe8535657 → 0xe8535657
$eflags: [carry parity adjust zero sign trap interrupt direction overflow resume virtualx86 identification]
$cs: 0x0008 $ss: 0x0010 $ds: 0x0010 $es: 0x0010 $fs: 0x0010 $gs: 0x0010
Registerinhalt
stack
code:x86:32
source:./guard/guardian.cc+19
threads
trace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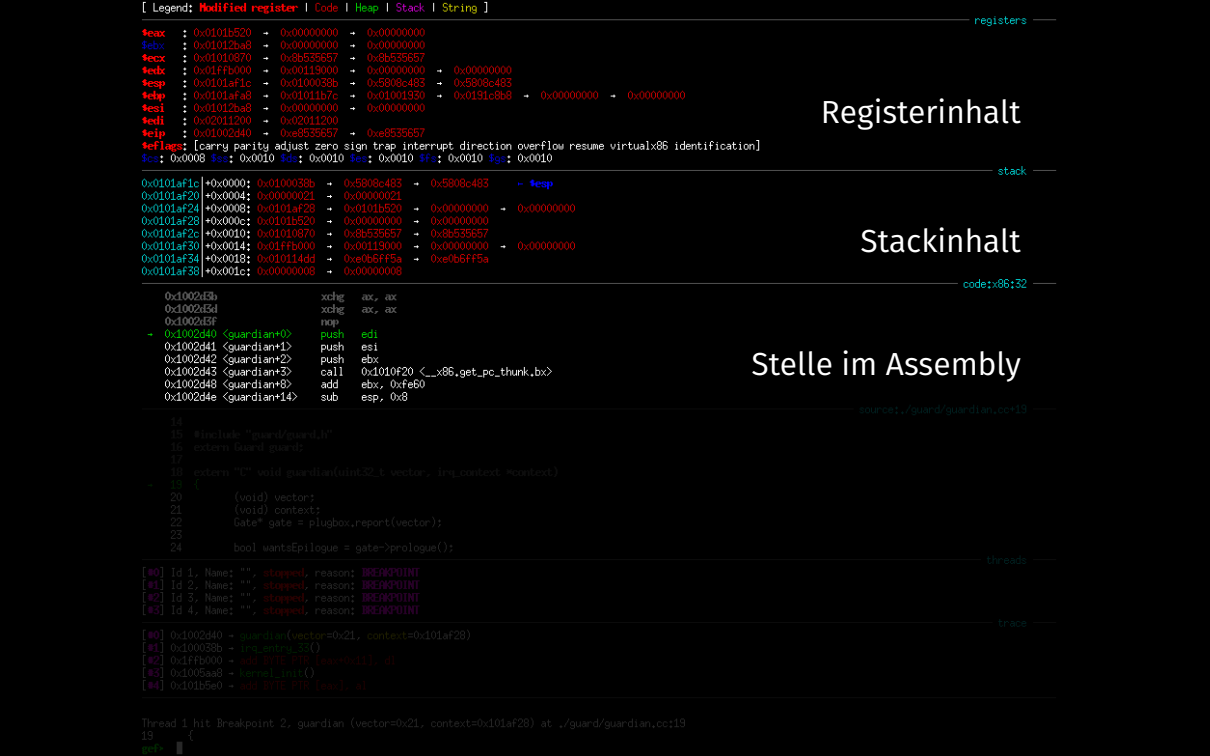
Registerinhalt
stack
0x0101af1c|+0x0000: 0x0100038b → 0x5808c483 → 0x5808c483 ← $esp
0x0101af20|+0x0004: 0x00000021 → 0x00000021
0x0101af24|+0x0008: 0x0101af28 → 0x0101b520 → 0x00000000 → 0x00000000
0x0101af28|+0x000c: 0x0101b520 → 0x00000000 → 0x00000000
0x0101af2c|+0x0010: 0x01010870 → 0x8b535657 → 0x8b535657
0x0101af30|+0x0014: 0x01ffb000 → 0x00119000 → 0x00000000 → 0x00000000
0x0101af34|+0x0018: 0x010114dd → 0xe0b6ff5a → 0xe0b6ff5a
0x0101af38|+0x001c: 0x00000008 → 0x00000008
Stackinhalt
code:x86:32
0x1002d36 xchg ax, ax
0x1002d38 xchg ax, ax
0x1002d3a nop
0x1002d3c nop
→ 0x1002d40 <guardian+0> push edi
0x1002d41 <guardian+1> push esi
0x1002d42 <guardian+2> push ebx
0x1002d43 <guardian+3> call 0x1010f20 <__x86.get_pc_thunk.bx>
0x1002d48 <guardian+8> add ebx, 0xfe60
0x1002d4e <guardian+14> sub esp, 0x8
source:./guard/guardian.cc+19
14
15 #include "guard/guard.h"
16 extern board guard;
17
18 extern "C" void guardian(uint32_t vector, irq_context *context)
→ 19 {
20 (void) vector;
21 (void) context;
22 Gate* gate = plugbox.report(vector);
23
24 bool wantsEpilogue = gate->prologue();
threads
[#0] Id 1, Name: "", stopped, reason: BREAKPOINT
[#1] Id 2, Name: "", stopped, reason: BREAKPOINT
[#2] Id 3, Name: "", stopped, reason: BREAKPOINT
[#3] Id 4, Name: "", stopped, reason: BREAKPOINT
trace
[#0] 0x1002d40 → guardian(vector=0x21, context=0x101af28)
[#1] 0x100038b → irq_entry.33()
[#2] 0x1ffb000 → add BYTE PTR [eax+0x11], dl
[#3] 0x1005aa8 → kernel_init()
[#4] 0x101b5e0 → add BYTE PTR [eax], al
Thread 1 hit Breakpoint 2, guardian (vector=0x21, context=0x101af28) at ./guard/guardian.cc:19
19 {
gef➤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0x0101af34|+0x0018: 0x010114dd → 0xe0b6ff5a → 0xe0b6ff5a
0x0101af38|+0x001c: 0x00000008 → 0x00000008
Stackinhalt
code:x86:32
0x1002d3b xchg ax, ax
0x1002d3d xchg ax, ax
0x1002d3f nop
→ 0x1002d40 <guardian+0> push edi
0x1002d41 <guardian+1> push esi
0x1002d42 <guardian+2> push ebx
0x1002d43 <guardian+3> call 0x1010f20 <__x86.get_pc_thunk.bx>
0x1002d48 <guardian+8> add ebx, 0xfe60
0x1002d4e <guardian+14> sub esp, 0x8
Stelle im Assembly
source:./guard/guardian.cc+19
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15 #include "guard/guard.h"
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[#2] 0x1ffb000 → add BYTE PTR [eax+0x31], dl
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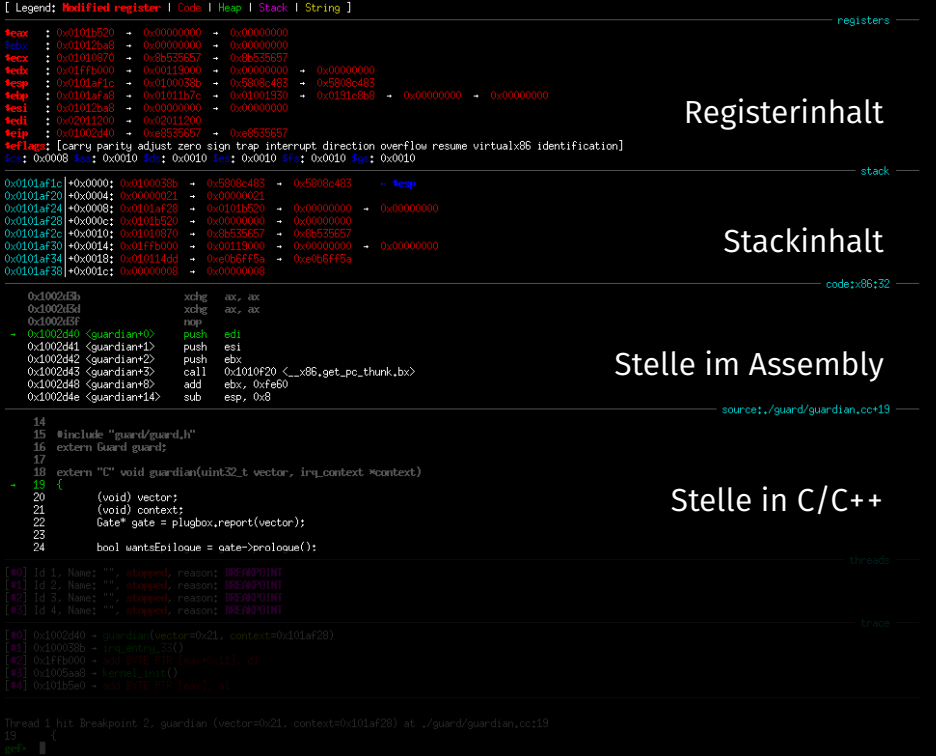
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0x0101af2c|+0x0010: 0x01010870 → 0x8b535657 → 0x8b535657
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Stelle in C/C++
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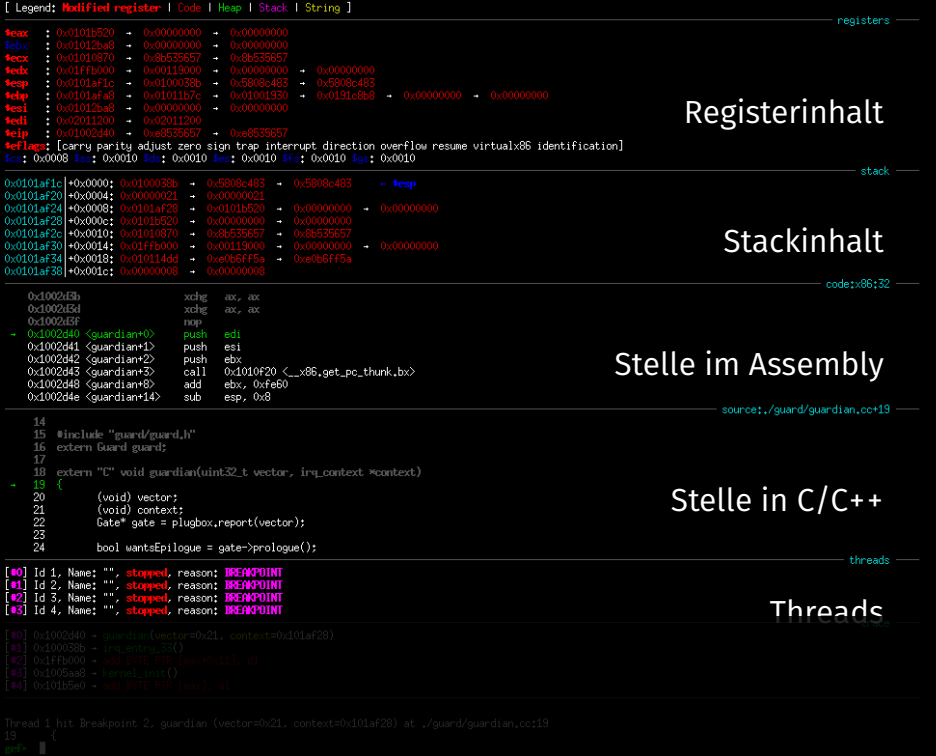
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Stackinhalt
code:x86:32
0x1002d3b xchg ax, ax
0x1002d3d xchg ax, ax
0x1002d3f nop
→ 0x1002d40 <guardian+0> push edi
0x1002d41 <guardian+1> push esi
0x1002d42 <guardian+2> push ebx
0x1002d43 <guardian+3> call 0x1010f20 <__x86.get_pc_thunk.bx>
0x1002d48 <guardian+8> add ebx, 0xfe60
0x1002d4e <guardian+14> sub esp, 0x8
Stelle im Assembly
source:./guard/guardian.cc+19
14
15 #include "guard/guard.h"
16 extern Guard guard;
17
18 extern "C" void guardian(uint32_t vector, irq_context *context)
→ 19 {
20 (void) vector;
21 (void) context;
22 Gate* gate = plugbox.report(vector);
23
24 bool wantsEpilogue = gate->prologue();
Stelle in C/C++
threads
[#0] Id 1, Name: "", stopped, reason: BREAKPOINT
[#1] Id 2, Name: "", stopped, reason: BREAKPOINT
[#2] Id 3, Name: "", stopped, reason: BREAKPOINT
[#3] Id 4, Name: "", stopped, reason: BREAKPOINT
Threads
[#0] 0x1002d40 → guardian(vector=0x21, context=0x101af28)
[#1] 0x100038b → irq_entry_33()
[#2] 0x1ffb000 → add BYTE PTR [eax],al
[#3] 0x1005aa8 → kernel_init()
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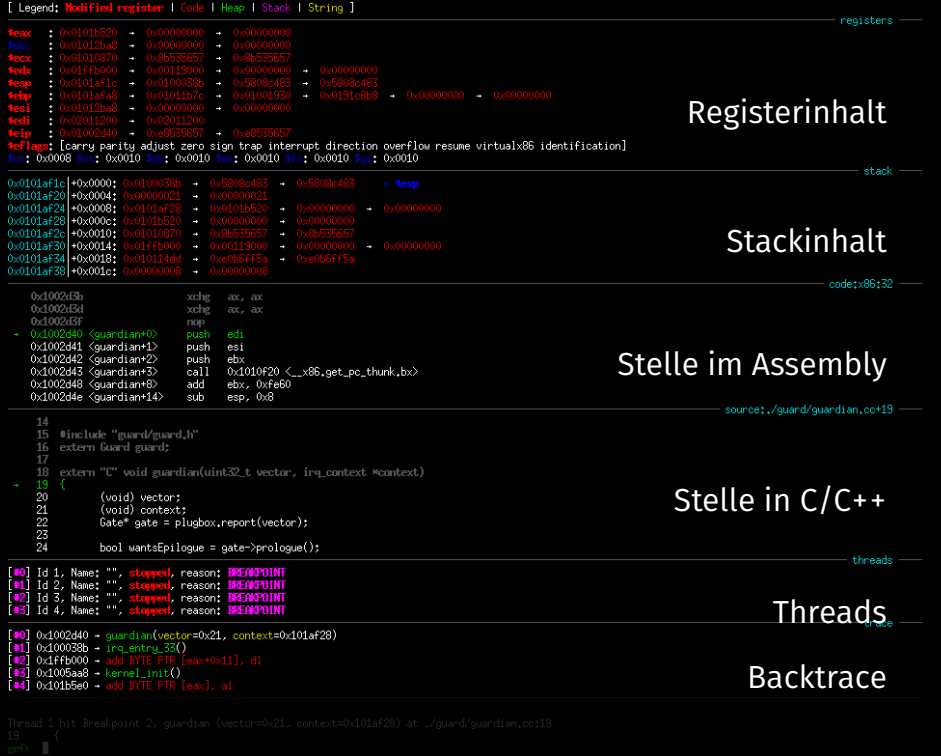
Thread 1 hit Breakpoint 2, guardian (vector=0x21, context=0x101af28) at ./guard/guardian.cc:19
19 {
gef➤


[Legend: Modified register | Code | Heap | Stack | String]
registers
$eax : 0x0101b520 → 0x00000000 → 0x00000000
$ebx : 0x01012ba8 → 0x00000000 → 0x00000000
$ecx : 0x01010870 → 0x8b535657 → 0x8b535657
$edx : 0x01ffb000 → 0x00119000 → 0x00000000 → 0x00000000
$esp : 0x0101af1c → 0x0100038b → 0x5808c483 → 0x5808c483
$ebp : 0x0101af28 → 0x01011b7c → 0x01001930 → 0x0191e8b8 → 0x00000000 → 0x00000000
$esi : 0x01012ba8 → 0x00000000 → 0x00000000
$edi : 0x02011200 → 0x02011200
$eip : 0x01002d40 → 0xe8535657 → 0xe8535657
$eflags: [carry parity adjust zero sign trap interrupt direction overflow resume virtualx86 identification]
$cs: 0x0008 $ss: 0x0010 $ds: 0x0010 $es: 0x0010 $fs: 0x0010 $gs: 0x0010
Registerinhalt
stack
0x0101af1c|+0x0000: 0x0100038b → 0x5808c483 → 0x5808c483 ← $esp
0x0101af20|+0x0004: 0x00000021 → 0x00000021
0x0101af24|+0x0008: 0x0101af28 → 0x0101b520 → 0x00000000 → 0x00000000
0x0101af28|+0x000c: 0x01011b520 → 0x00000000 → 0x00000000
0x0101af2c|+0x0010: 0x01010870 → 0x8b535657 → 0x8b535657
0x0101af30|+0x0014: 0x01ffb000 → 0x00119000 → 0x00000000 → 0x00000000
0x0101af34|+0x0018: 0x010114dd → 0xe0b6ff5a → 0xe0b6ff5a
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Threads
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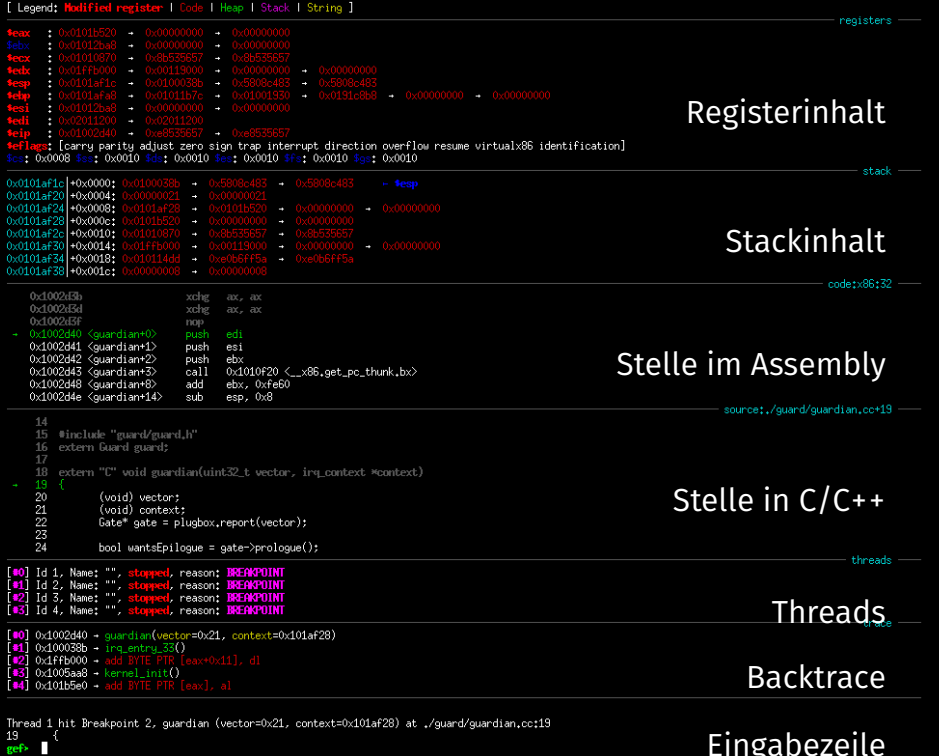
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Backtrace
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19 {
gef➤
Eingabezeile

Breakpoints: (gdb) break <location>

Breakpoints

Unterbrechen der Ausführung, sobald eine bestimmte **Codestelle** erreicht wird.

- Funktionsname
- absolute/relative Codezeile
- *Adresse

} optionaler Prefix: Quelldatei

Unterbricht vor dem Ausführen von...

`(gdb) b main`	Funktion `main`
`(gdb) b main.cc:main`	... aus main.cc
`(gdb) b 63`	Zeile 63 in aktueller Datei
`(gdb) b main.cc:63`	Zeile 63 in main.cc
`(gdb) b +3`	In 3 Zeilen
`(gdb) b *0x100a9ca`	An Adresse 0x100a9ca

Temporäre & Bedingte Breakpoints

Temporäre Breakpoints: `(gdb) tbreak <location>`

Werden nach dem 1. Auslösen entfernt, sonst wie „normale“ Breakpoints.

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Bedingte Breakpoints: `(gdb) break <location> if <cond>`

Unterbrechung nur falls Bedingung erfüllt ist, z.B:

```
(gdb) break interrupt_handler if vector == 33
```

Unterbricht nur, falls die Funktion interrupt_handler aufgrund von Tastatureingabe (Vektor 33) betreten wurde.

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(gdb) break interrupt_handler if vector == 33
```

Unterbricht nur, falls die Funktion interrupt_handler aufgrund von Tastatureingabe (Vektor 33) betreten wurde.

Achtung: Nichttriviale Break- oder Watchpoints werden ohne Hardwareunterstützung umgesetzt → Langsam!

Watchpoints (Data Breakpoints)

Unterbricht wenn Speicherbereich geschrieben (oder gelesen) wird:

watch <location>	Schreibzugriff
rwatch <location>	Lesezugriff
awatch <location>	Schreib- oder Lesezugriff

```
(gdb) watch guard
(gdb) watch guard if guard.locked == 1
```

Verwalten von Break-/Watchpoints

ignore	<id> <N>	Breakpoint N mal ignorieren
enable	<id> <id> ..	Breakpoints aktivieren
disable	<id> <id> ..	Breakpoints deaktivieren
delete	<id> <id> ..	Breakpoints löschen

Schrittweise Ausführung

step *count* – Nächste Zeile
step**i** *count* – Nächste Instruktion
next *count* – Nächste Zeile (ohne Funktionen zu betreten)
next**i** *count* – Nächste Instruktion (ohne Funktionen zu betreten)
until *count* – Wiederhole **n**ext bis zur **textuell** nächsten Zeile

Optional: Anzahl Wiederholungen

finish – Bis zum return des aktuellen Stackframes
advance <location> – Bis zu <location>
continue – Ausführung (zum nächsten Breakpoint) fortsetzen

Der `skip` Befehl

```
unsigned int numCPUs = System::getNumberOfCPUs();
kout << "numCPUs: " << numCPUs << endl;
ApplicationProcessor::boot();
```

Der `skip` Befehl

```
unsigned int numCPUs = System::getNumberOfCPUs();
kout << "numCPUs: " << numCPUs << endl;
ApplicationProcessor::boot();
```

Übergehe aktuell Funktion:

```
(gdb) skip
```

Übergehe eine einzelne Funktion:

```
(gdb) skip function OutputStream::operator<<
```

Übergehe alle Funktionen aus einer Datei:

```
(gdb) skip file object/outputstream.cc
```

Der `info` Befehl

info **a**rgs	Auflistung der Aufrufargumente
info **lo**cals	Auflistung aller lokalen Variablen
info **r**egisters	Auflistung der Registerwerte
info **b**reakpoints	Auflistung der Breakpoints
info **t**hreads	Auflistung der Threads/CPUs
info **sk**ip	Auflistung der zu überspringenden Funktionen
...	siehe (gdb) **h**elp **i**nfo

Ergänzend:

frame <id>	Wechsel zu Stackframe
thread <id>	Wechsel zu Thread/CPU

Ausgabe von Werten in Speicher / Register

```
(gdb) print/<Format> <Ausdruck>
(gdb) x/<Anzahl><Format><Einheit> <Ausdruck>
```

Werte für <Format>

x	Ganzzahl (hex)
d	Ganzzahl (mit VZ, dezimal)
u	Ganzzahl (ohne VZ, dezimal)
t	Ganzzahl (binär) (**t**wo)
a	Adresse (hex) + Offset zum Startsymbol
f	Float
i	Instruktion

Werte für <Einheit>

b	Byte	8-bit
h	Halfword	16-bit
w	Word	32-bit
g	Giant word	64-bit

Bestimmen des Typs eines Symbols

ptype <Symbol>

Verändern des Zielsystems: (gdb) set

Verändern eines Registers

```
(gdb) set $esp = 0xdeadbeef
```

Verändern einer Variable / Speicherbereichs

```
(gdb) set numCPUs = 2
(gdb) set *((int *) 0x1013fdc) = 42
```

GDB vs. Optimierungen

Generell: Optimierungen sind doof fürs Debuggen:

- Inlining von Funktionen
- Elimination von Variablen
- ...

Relevante Compileroptionen

-g	Generiere Debuginformationen
-Oo	Optimierungen aus
-Og	Nur Optimierungen, die das Debuggen nicht stören

GDB vs. Optimierungen

Generell: Optimierungen sind doof fürs Debuggen:

- Inlining von Funktionen
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Relevante Compileroptionen

-g	Generiere Debuginformationen
-O0	Optimierungen aus
-Og	Nur Optimierungen, die das Debuggen nicht stören
-O2	Fast alle Optimierungen

Laden der `.gdbinit`

Automatische Ausführung von gdb-Befehlen in `.gdbinit`

- Vordefinierte Breakpoints
- Eigene Skripte

`~/.config/gdb/gdbinit` oder `~/.gdbinit`

auto-load local-gdbinit	Lade lokale `.gdbinit`-Datei
add-auto-load-safe-path ~/stubs	Schalte Pfad zum Laden frei
set disassembly-flavor intel	Nutzte Intel-, statt AT&T-Syntax
set print asm-demangle on	Löse Name Mangling auf

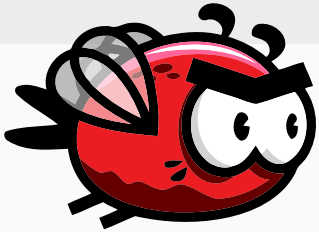
Beispielhafte `.gdbinit`

```
b assertion_failed
b Core::die
```

GDB & GEF in BS

Die bittere Wahrheit...

Ihr werdet entkäfern müssen



GDB & GEF in BS

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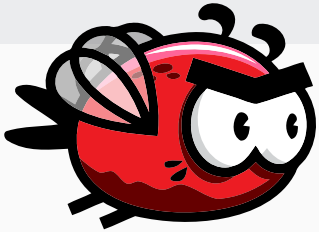

- `make qemu-gdb-noopt`

→ Profit?

- `make qemu-gdb`
- `make VERBOSE= QEMUCPUS=1 all`

.gdbinit

```
source /proj/i4stubs/tools/gdbinit
```

Fragen?

Anhang

Snippet: Ausgabe von Details zur Exception im Interrupt Handler

```
// Optional: Print exceptions on DBG stream to support debugging
if (vector <= Core::Interrupt::SECURITY_EXCEPTION) {
  DBG << "Exception " << dec << vector;
  switch (vector) {
    case 0:  DBG << " (Div by 0)"; break;
    case 6:  DBG << " (Invalid Opcode)"; break;
    case 10: DBG << " (Invalid TSS)"; break;
    case 13: DBG << " (General Protection Fault)"; break;
    case 14: DBG << " (Page Fault)"; break;
    default: break;
  }
  if (context->error_code != 0) {
    DBG << " [" << bin << context->error_code << "]";
  }
  DBG << " @ " << hex << context->ip << flush;
  DBG << endl;
}
```