Linux Reversing Disassembly Reconstruction

Accelerated

Second Edition

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Software Diagnostics Services

Prerequisites

- Working C or classic C++ knowledge
- Basic assembly language knowledge

Audience

- Novices

Improve x64 (x86_64, AMD64) and A64 (AArch64, ARM64) assembly language knowledge

- Experts

Learn the new pattern language approach

Pattern-Oriented RDR

- Complex crashes and hangs (victimware analysis)
- Malware analysis
- Studying new products

Training Goals

- Review fundamentals
- Learn patterns and techniques

Training Principles

- Talk only about what I can show
- Lots of pictures
- Lots of examples
- Original content and examples

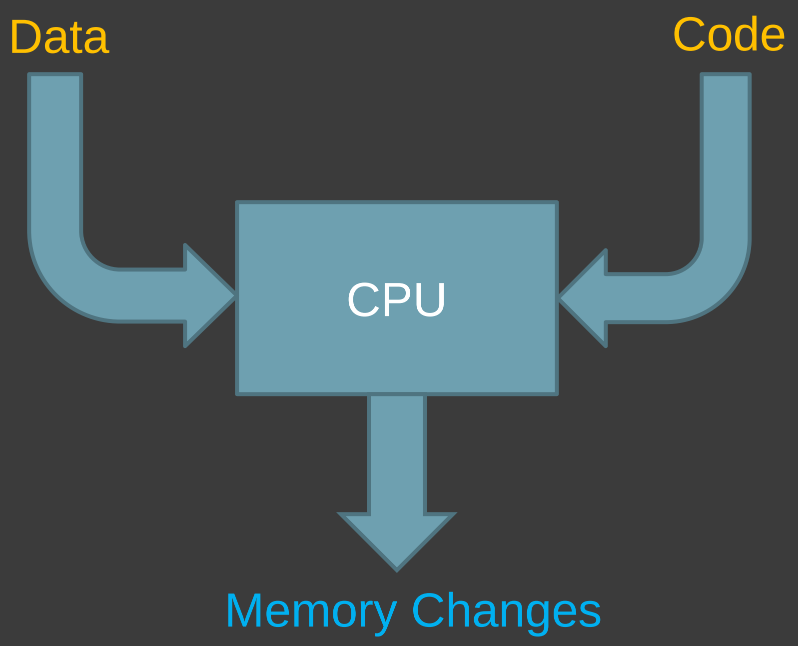
Course Idea

- Accelerated Linux Core Dump Analysis, Third Edition (x64 and A64)

- Accelerated Disassembly, Reconstruction and Reversing, Second Edition, Revised and Extended (Windows x64)

Part 1: Theory

Computation



Disassembly

Data/Code numbers

Data/Code symbolic

```
48 8d 05 a1 b4 07 00    lea    0x7b4a1(%rip),%rax        # 0x47d004
48 89 05 36 68 0a 00    mov    %rax,0xa6836(%rip)        # 0x4a83a0 <name>


         e0 53 00 91    add    x0, sp, #0x14
         e0 0f 00 f9    str    x0, [sp, #24]
```

Annotated Disassembly memory analysis pattern

The Problem of Reversing

- Compilation to **M**achine Language_M

$\text{Language}_1 \Rightarrow \text{Language}_M \Leftarrow \text{Language}_2$

- Decompilation

$\text{Language}_M \Rightarrow ?$

The Solution to Reversing

- **M**emory Language_M Semantics

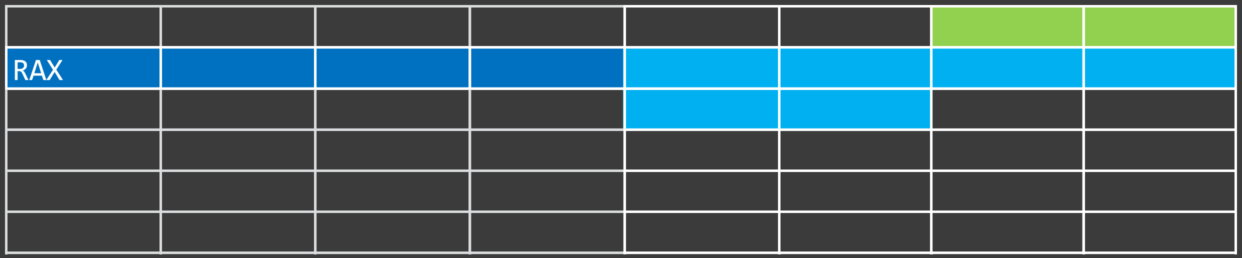
Language_1 → Language_M ← Language_2

- Decompilation

Understanding of Language_M

The Reversing Tool

Memory Cell Diagrams



Idea when reading The Mathematical Structure of Classical and Relativistic Physics: A General Classification Diagram book

Re(De)construction

- Time dimension: sequence diagrams

- Space dimension: component diagrams

How does it work temporally and structurally?

ADDR Patterns

- Accelerated
- Disassembly patterns
- De(Re)construction patterns
- Reversing patterns

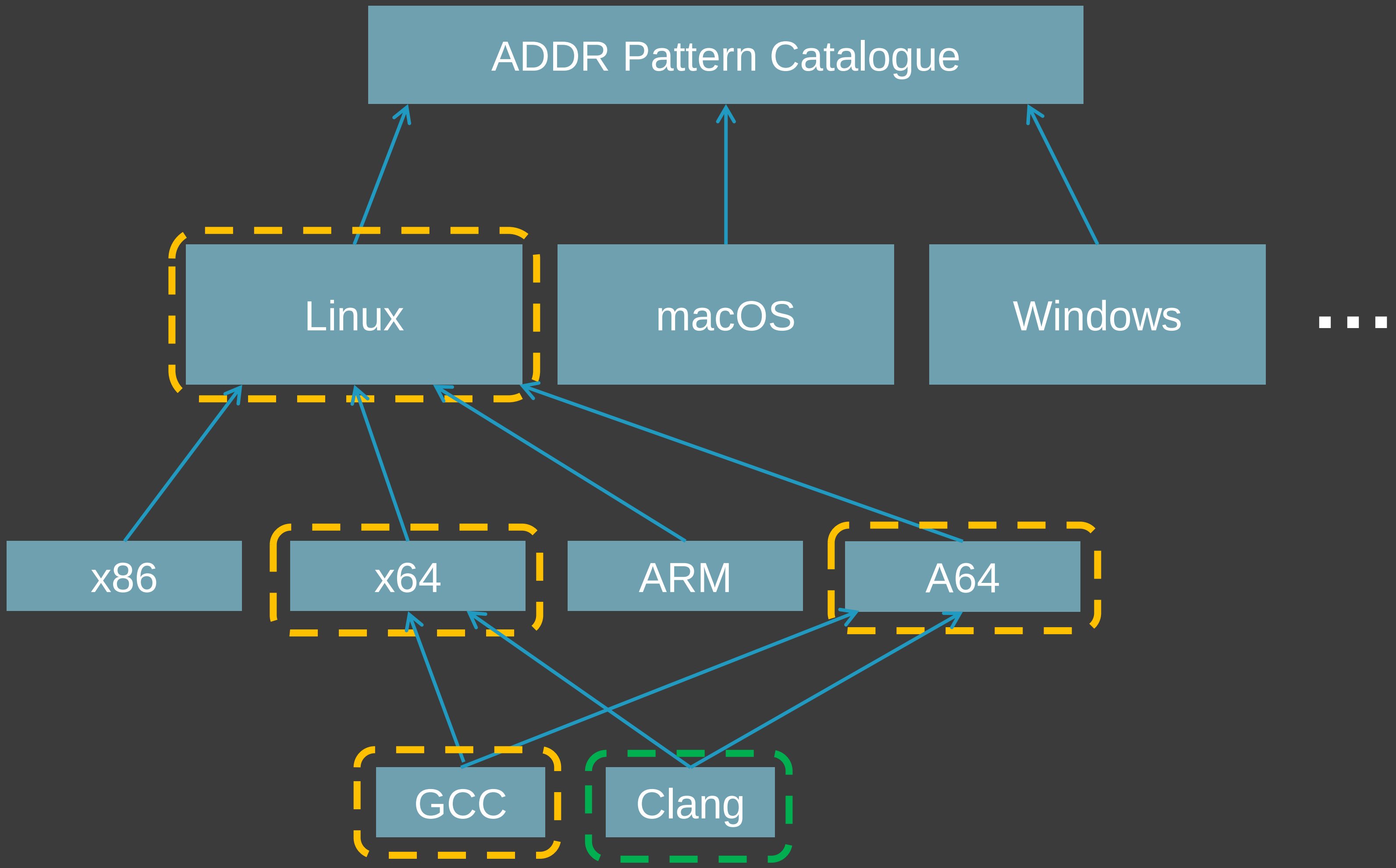
ADDR Patterns (II)

- Accelerated
- Disassembly patterns
- Decompilation patterns
- Reconstruction patterns

ADDR Schemas

- Function Prologue → Function Epilogue
- Call Prologue → Function Call → Call Epilogue
- Potential Functionality → Call Skeleton → Call Path
- Call Parameter → Function Parameter → Local Variable

ADDR Implementations



Pattern Catalogues

- Elementary Software Diagnostics Patterns
- Memory Analysis Patterns
- Trace and Log Analysis Patterns
- Unified Debugging Patterns
- ADDR Patterns

Pattern Orientation

- Pattern-Driven ADDR
- Pattern-Based ADDR

Part 2: x64 Disassembly

CPU Registers (x64)

Illustrated in memory cell diagrams: \ADDR-Linux\MCD-R1-x64.xlsx

- **RAX** ⊃ **EAX** ⊃ **AX** ⊇ {**AH**, **AL**}

RAX 64-bit	EAX 32-bit

- ALU: **RAX**, **RDX**
- Counter: **RCX**
- Memory copy: **RSI** (src), **RDI** (dst)
- Stack: **RSP**, **RBP**
- Next instruction: **RIP**
- New: **R8** – **R15**, **Rx**(**D**|**W**|**L**)

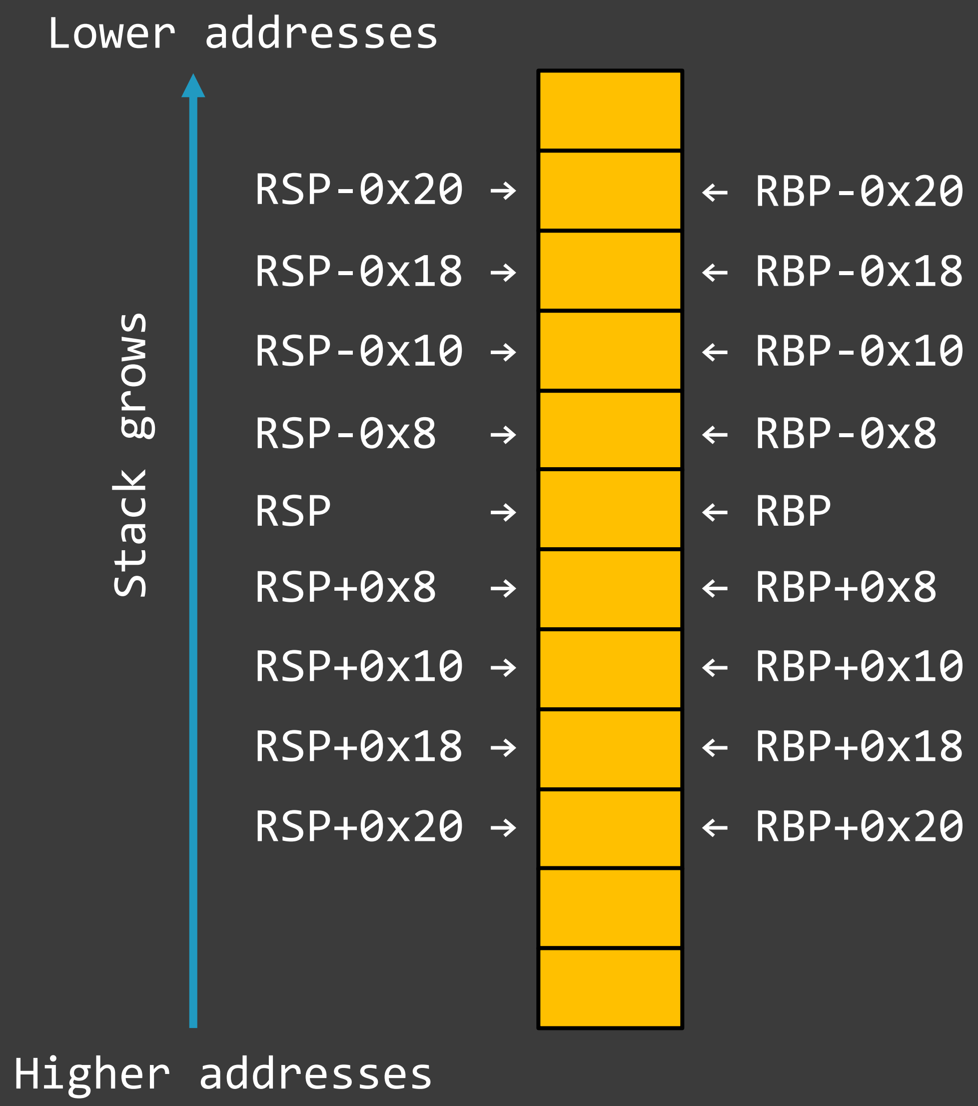
Instructions: registers (x64)

- `Opcode SRC, DST # default AT&T flavour`

- Examples:

```
mov   $0x10, %rax            # 0x10 → RAX
mov   %rsp, %rbp             # RSP → RBP
add   $0x10, %r10            # R10 + 0x10 → R10
imul  %ecx, %edx             # ECX * EDX → EDX
callq *%rdx                  # RDX already contains
                             #    the address of func (&func)
                             # PUSH RIP; &func → RIP
sub   $0x30, %rsp            # RSP-0x30 → RSP
                             # make a room for local variables
```

Memory and Stack Addressing



Instructions: memory load (x64)

- `Opcode Offset(SRC), DST`
- `Opcode DST`
- Examples:

```
mov    0x10(%rsp), %rax       # value at address RSP+0x10 → RAX
mov    -0x10(%rbp), %rcx      # value at address RBP-0x10 → RCX
add    (%rax), %rdx           # RDX + value at address RAX → RDX
pop    %rdi                   # value at address RSP → RDI
                              # RSP + 8 → RSP
lea    0x20(%rbp), %r8        # address RBP+0x20 → R8
```

Instructions: memory store (x64)

- `Opcode SRC, Offset(DST)`
- `Opcode SRC|DST`
- Examples:

```
mov   %rcx, -0x20(%rbp)     # RCX → value at address RBP-0x20
addl  $1, (%rax)            # 1 + 32-bit value at address RAX →
                            #     32-bit value at address RAX
push  %rsi                  # RSP - 8 → RSP
                            # RSI → value at address RSP
inc   (%rcx)                # 1 + value at address RCX →
                            #     value at address RCX
```

Instructions: flow (x64)

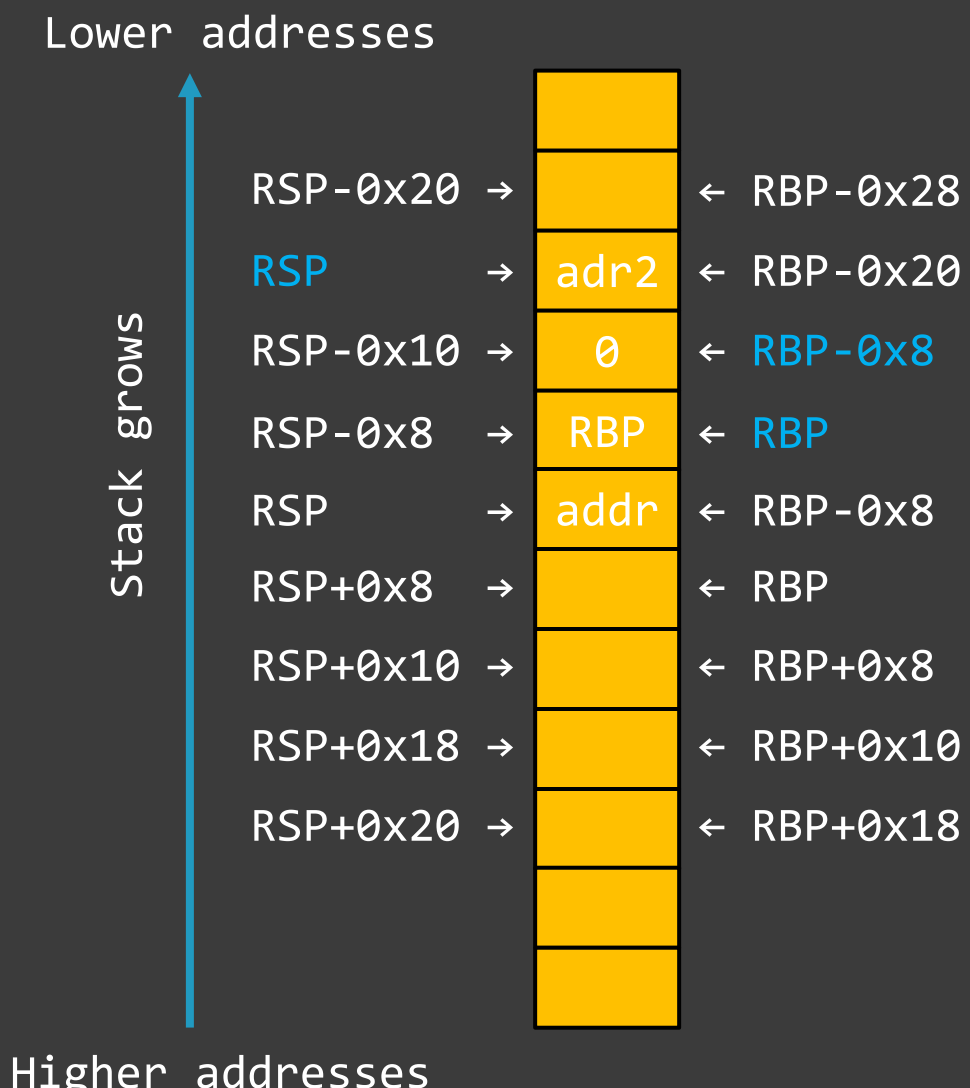
- `Opcode DST`

- Examples:

```
jmp     0x10493fc1c        # 0x10493fc1c → RIP
                           # (goto 0x10493fc1c)

call    0x10493ff74        # RSP – 8 → RSP
0x10493fc14:               # 0x10493fc14 → value at address RSP
                           # 0x10493ff74 → RIP
                           # (goto 0x10493ff74)
```

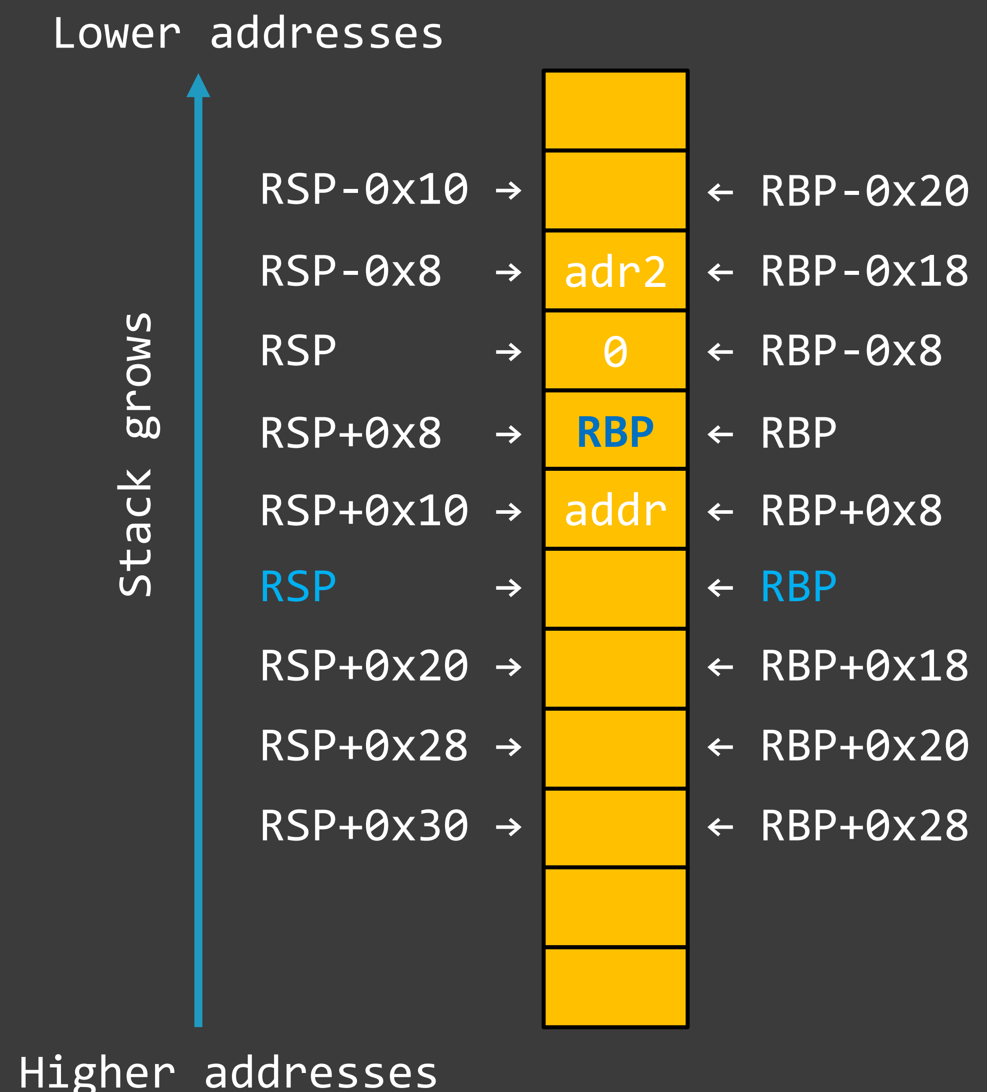
Function Call and Prolog (x64)

```
# void proc(int p1, long p2);
mov  $0x1, %edi
mov  $0x2, %rsi
call proc
addr:

# void proc2();
# void proc(int p1, long p2) {
#   long local = 0;
#   proc2();
# }
proc:
push %rbp
mov  %rsp, %rbp
sub  $0x8, %rsp
mov  $0, -0x8(%rbp)
call proc2
adr2:
...
```



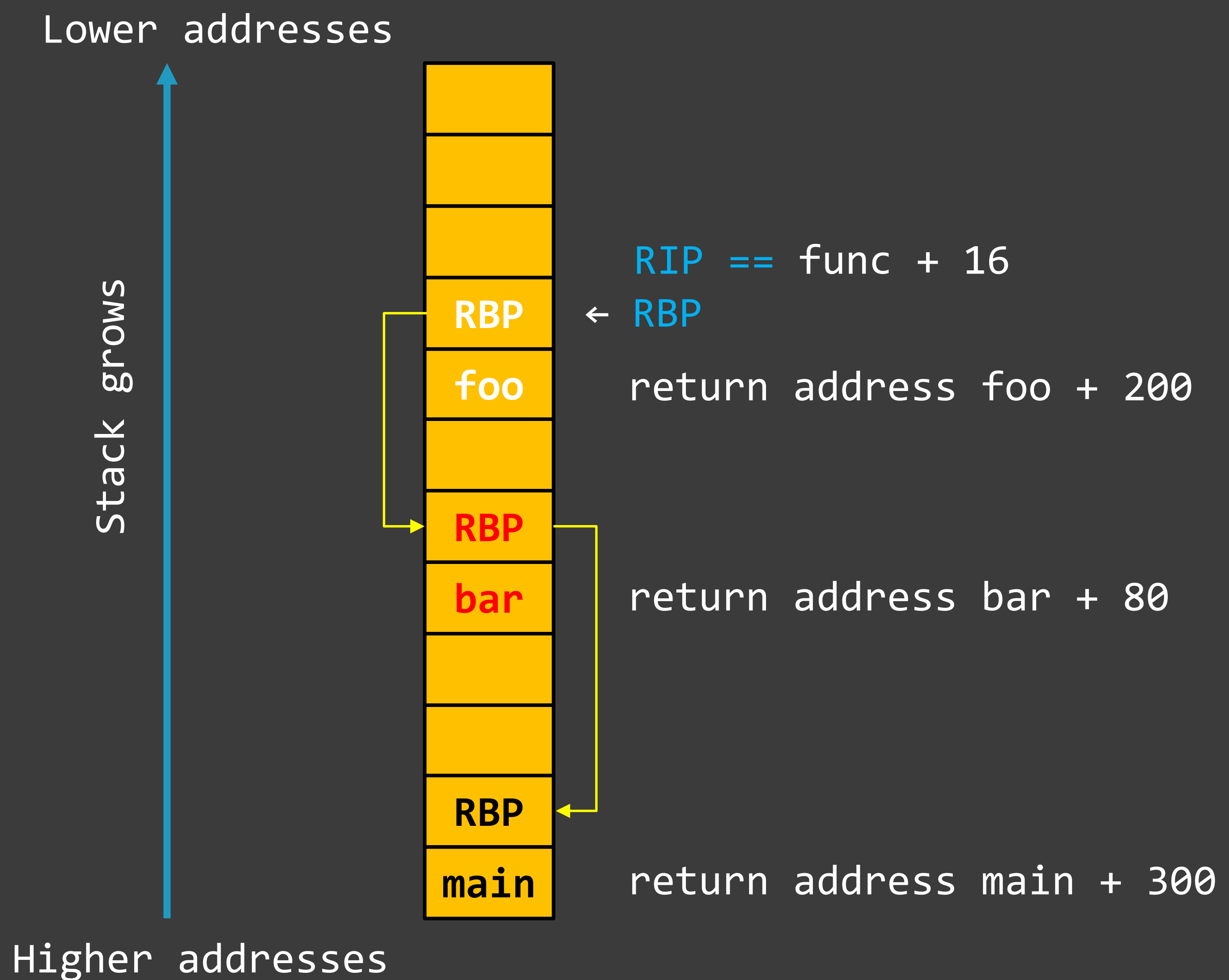
Function Epilog and Return (x64)

```
# void proc2();
# void proc(int p1, long p2) {
#   long local = 0;
#   proc2();
# }
proc:
push %rbp
mov  %rsp, %rbp
sub  $0x8, %rsp
mov  $0, -0x8(%rbp)
call proc2
adr2:
...
leaveq                # GCC
retq

adr2:
...
add  $0x8, %rsp     # Clang
pop  $rbp
retq
```



Stack Trace Reconstruction (x64)

```
(gdb) bt
func + 16
foo + 200
bar + 80
main + 300
```



Part 3: A64 Disassembly

CPU Registers (A64)

Illustrated in memory cell diagrams: \ADDR-Linux\MCD-R1-ARM64.xlsx

- **X0** – **X28**, **W0** – **W28**
- Stack: **SP**, **X29** (**FP**)
- Next instruction: **PC**
- Link register: **X30** (**LR**)
- Zero register: **XZR**, **WZR**
- 64-bit floating point registers **D0** – **D31**
- 128-bit **Q0** – **Q31**

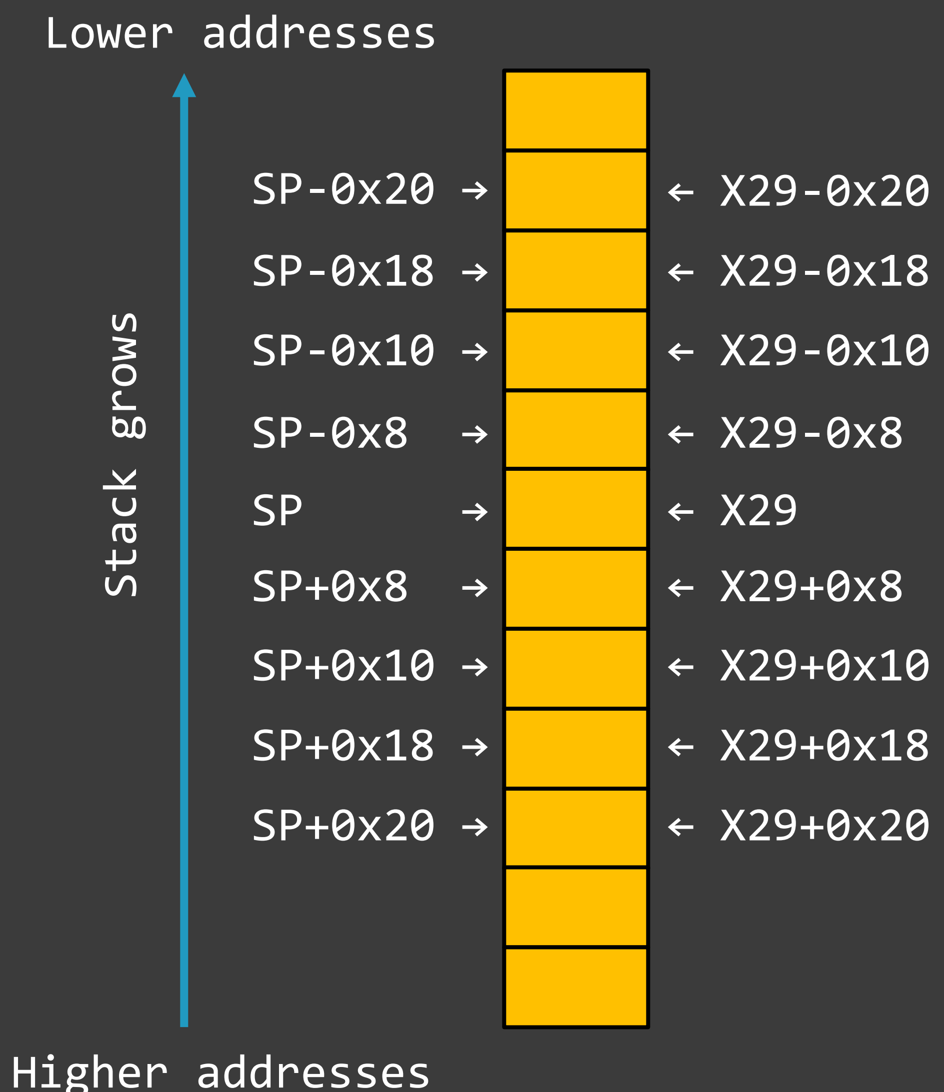
X 64-bit	W 32-bit

Instructions: registers (A64)

- Opcode DST, SRC, SRC_2
- Examples:

```
mov   x0, #16            // X0 ← 16 (0x10)
mov   x29, sp            // X29 ← SP
add   x1, x2, #16        // X1 ← X2+16 (0x10)
mul   x1, x2, x3         // X1 ← X2*X3
blr   x8                 // X8 already contains
                         //    the address of func (&func)
                         // LR ← PC+4; PC ← &func
sub   sp, sp, #48        // SP ← SP-48 (-0x30)
                         // make a room for local variables
```

Memory and Stack Addressing



Instructions: memory load (A64)

- `Opcode DST, DST2, [SRC, Offset]`
- `Opcode DST, DST2, [SRC], Offset // Postincrement`
- Examples:

```
ldr   x0, [sp]                // X0 ← value at address SP+0
ldr   x0, [x29, #-8]          // X0 ← value at address X29-0x8
ldp   x29, x30, [sp, #32]     // X29 ← value at address SP+32 (0x20)
                              // X30 ← value at address SP+40 (0x28)
ldp   x29, x30, [sp], #16     // X29 ← value at address SP+0
                              // X30 ← value at address SP+8
                              // SP ← SP+16 (0x10)
```

Instructions: memory store (A64)

- Opcode SRC, SRC_2, [DST, Offset]
- Opcode SRC, SRC_2, [DST, Offset]! // Preincrement
- Examples:

```
str   x0, [sp, #16]          // x0 → value at address SP+16 (0x10)
str   x0, [x29, #-8]         // x0 → value at address X29-8
stp   x29, x30, [sp, #32]    // x29 → value at address SP+32 (0x20)
                             // x30 → value at address SP+40 (0x28)
stp   x29, x30, [sp, #-16]!  // SP ← SP-16 (-0x10)
                             // x29 → set value at address SP
                             // x30 → set value at address SP+8
```

Instructions: flow (A64)

- `Opcode DST, SRC`

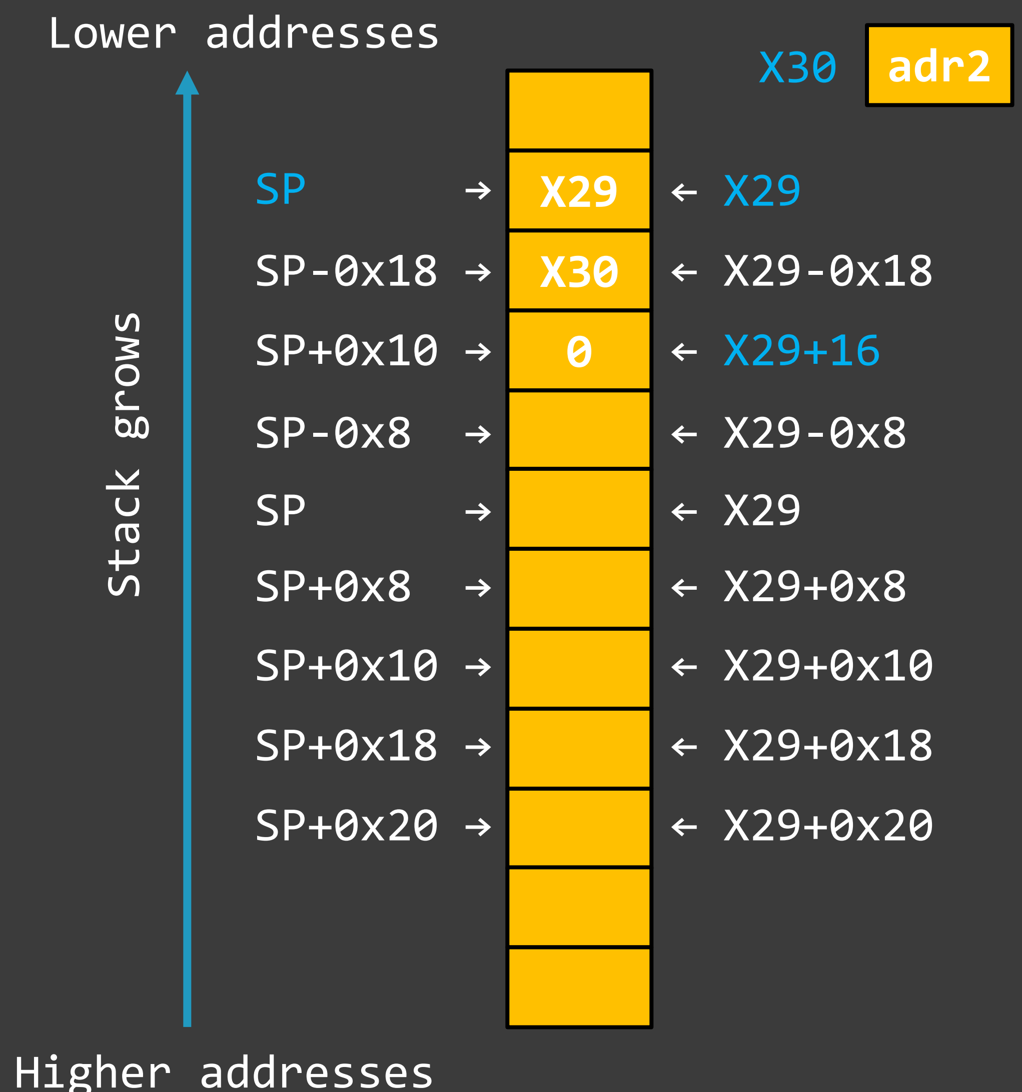
- Examples:

```
adrp  x0, 0x420000      // x0 ← 0x420000

b     0x10493fc1c       // PC ← 0x10493fc1c
                        // (goto 0x10493fc1c)
br    x17               // PC ← the value of X17

0x10493fc14:            // PC == 0x10493fc14
bl    0x10493ff74       // LR ← PC+4 (0x10493fc18)
                        // PC ← 0x10493ff74
                        // (goto 0x10493ff74)
```

Function Call and Prolog (A64)

GCC

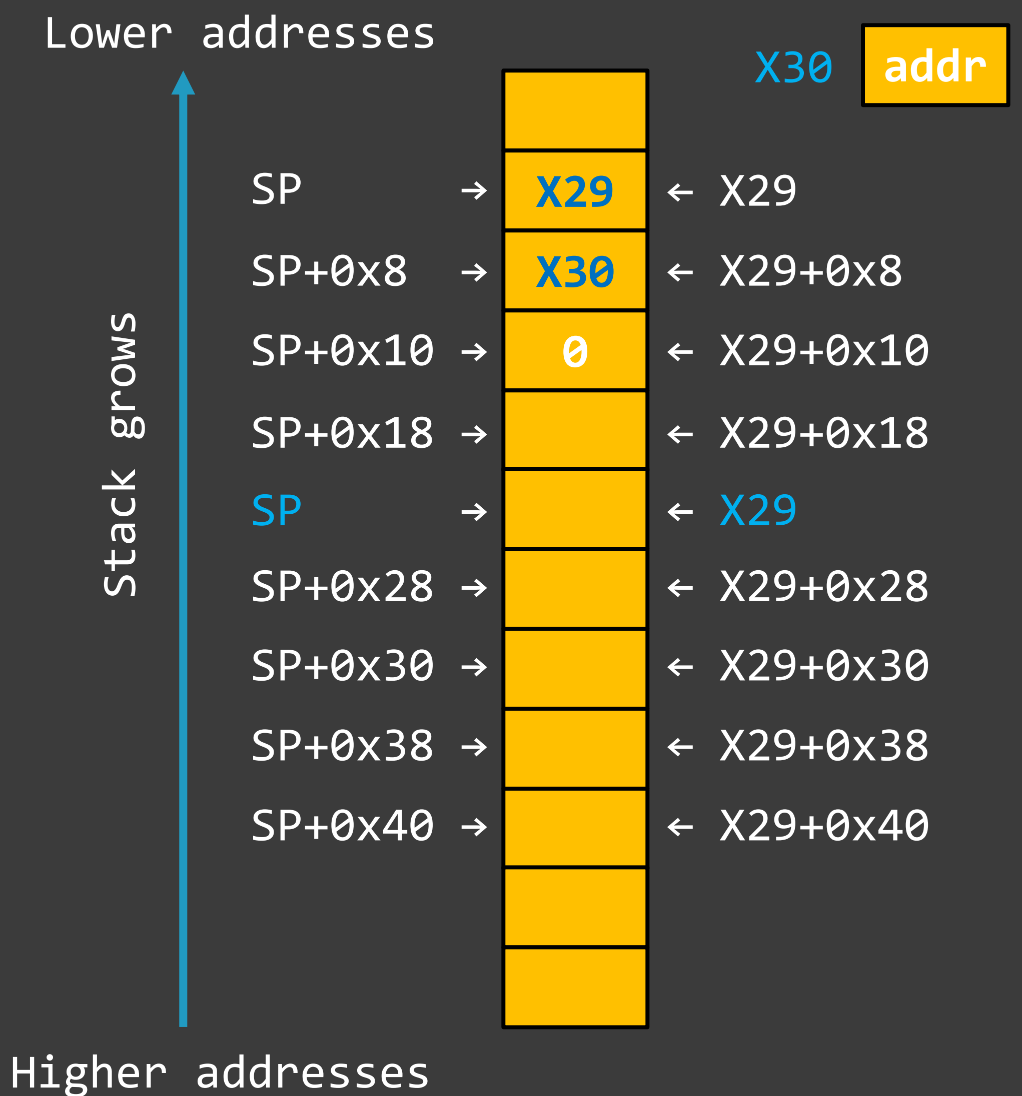
```
// void proc(int p1, long p2);
mov  w0, #0x1
mov  x1, #0x2
bl   proc
addr:

// void proc2();
// void proc(int p1, long p2) {
//   long local = 0;
//   proc2();
// }
proc:
stp  x29, x30, [sp, #-32]!
mov  x29, sp
str  zxr, [x29, #16]
bl   proc2
adr2:
...
```



Function Epilog and Return (A64)

GCC

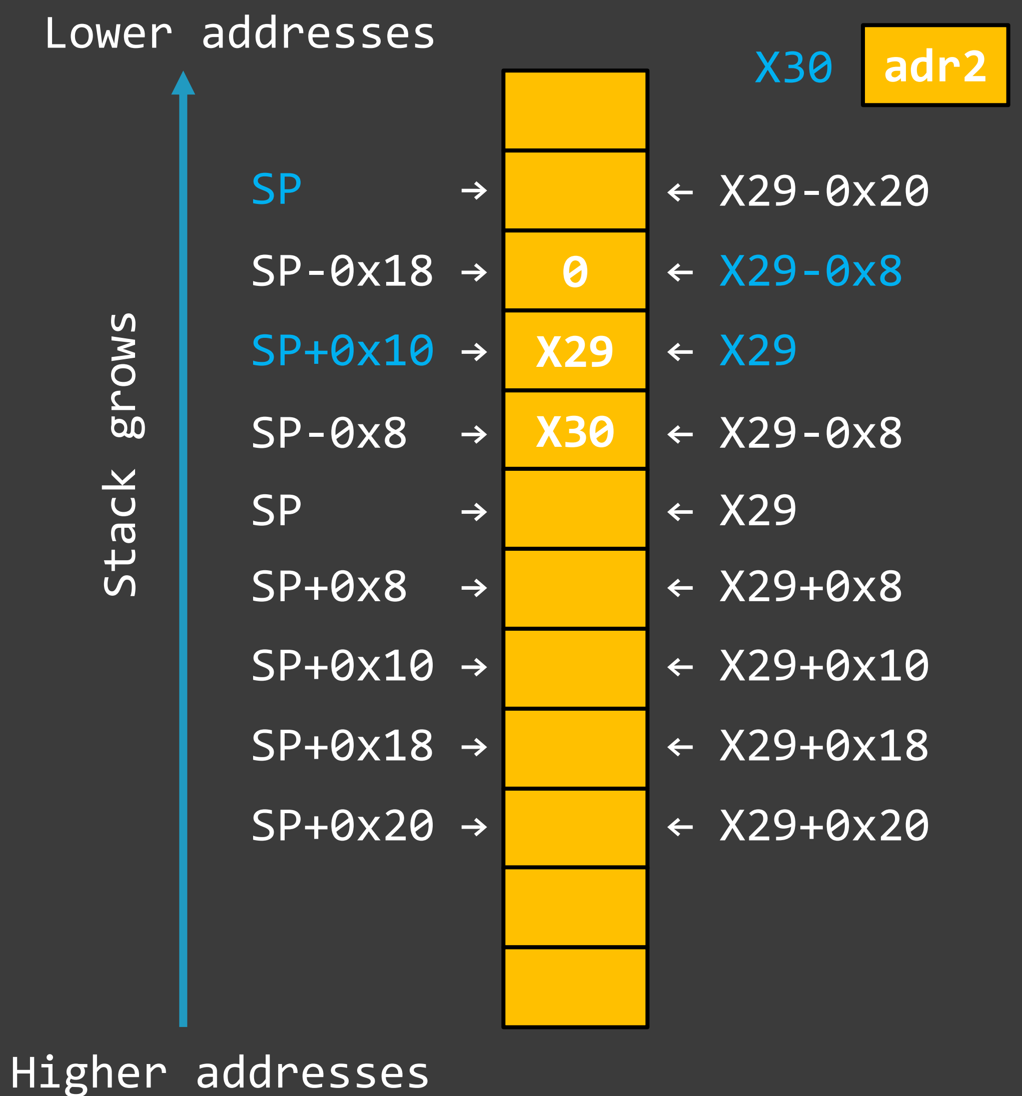
```
// void proc(int p1, long p2);
mov   w0, #0x1
mov   x1, #0x2
bl    proc
addr:

// void proc2();
// void proc(int p1, long p2) {
//    long local = 0;
//    proc2();
// }
proc:
stp   x29, x30, [sp, #-32]!
mov   x29, sp
str   zxr, [x29, #16]
bl    proc2
adr2:
...
ldp      x29, x30, [sp], #32
ret
```



Function Call and Prolog (A64)

Clang

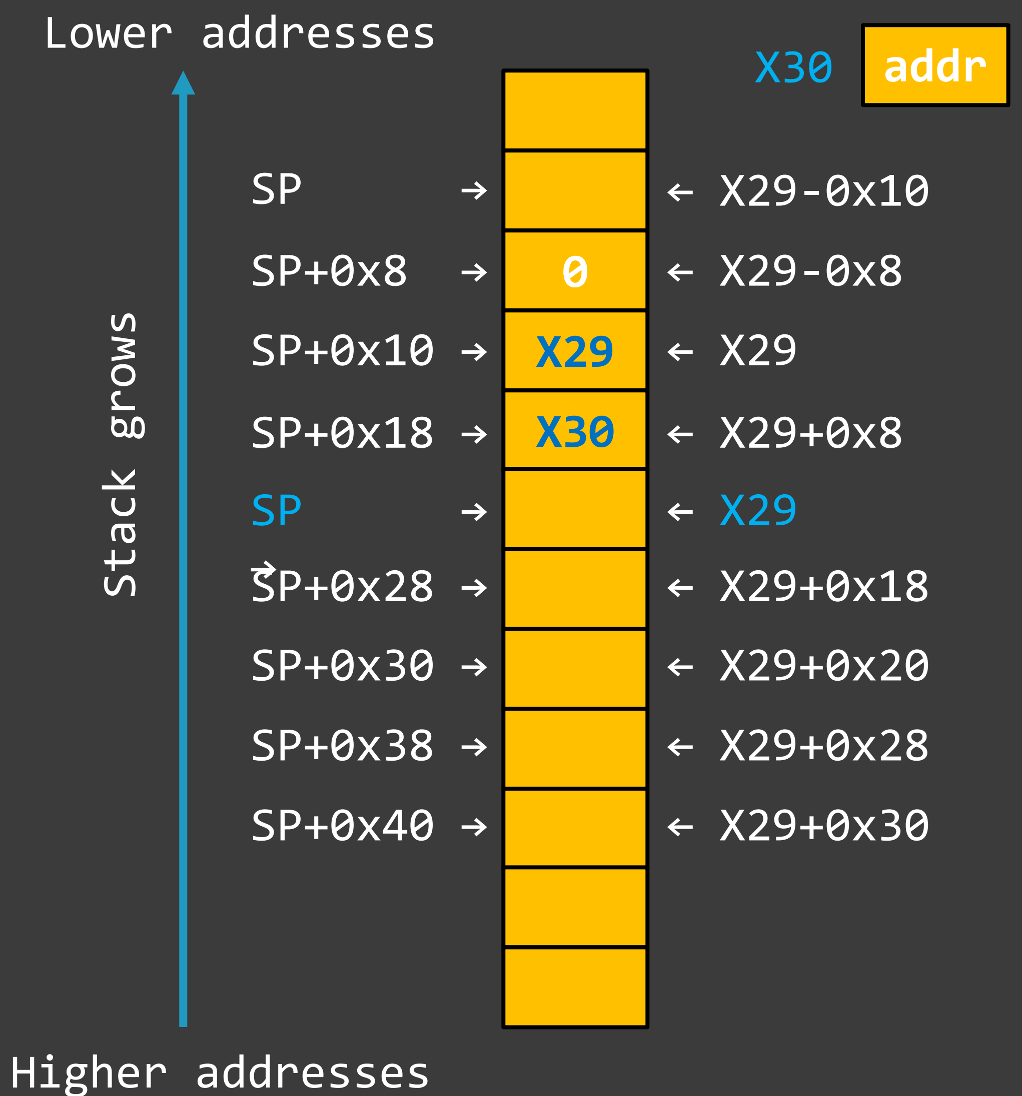
```
// void proc(int p1, long p2);
mov  w0, #0x1
mov  x1, #0x2
bl   proc
addr:

// void proc2();
// void proc(int p1, long p2) {
//   long local = 0;
//   proc2();
// }
proc:
sub  sp, sp, #0x20
stp  x29, x30, [sp, #16]
add  x29, sp, #0x10
str  zxr, [x29, #-8]
bl   proc2
adr2:
...
```



Function Epilog and Return (A64)

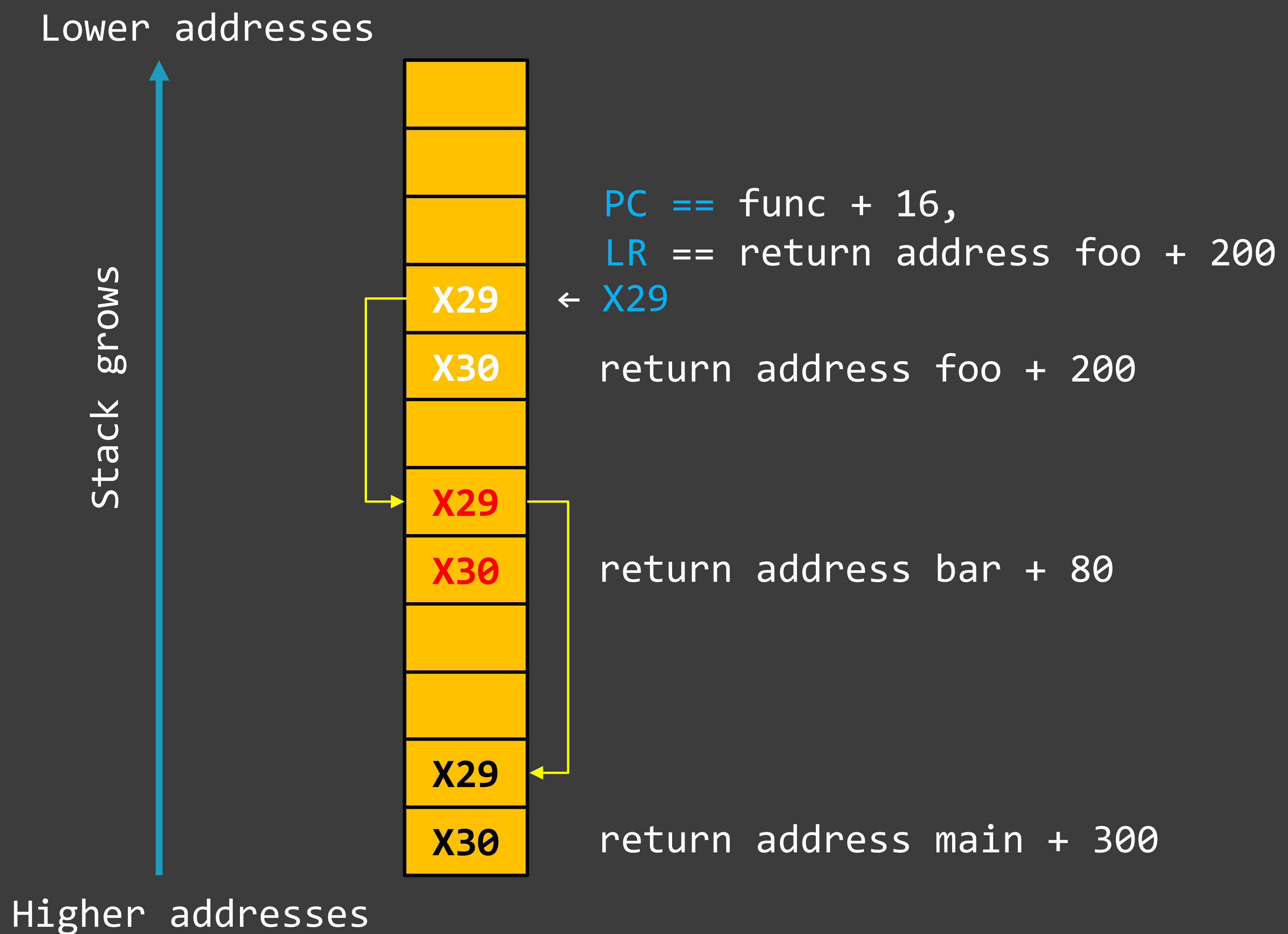
Clang

```
// void proc(int p1, long p2);
mov   w0, #0x1
mov   x1, #0x2
bl    proc
addr:

// void proc2();
// void proc(int p1, long p2) {
//    long local = 0;
//    proc2();
// }
proc:
sub   sp, sp, #0x20
stp   x29, x30, [sp, #16]
add   x29, sp, #0x10
str   zxr, [x29, #-8]
bl    proc2
adr2:
...
ldp       x29, x30, [sp, #16]
add       sp, sp, #0x20
ret
```



Stack Trace Reconstruction (A64)

```
(gdb) bt
func + 16
foo + 200
bar + 80
main + 300
```



Part 4: Practice Exercises

Links

- Memory dumps:

Download links are in the exercise R0.

- Exercise Transcripts:

Included in this book.

Exercise R0

- **Goal:** Install GDB and check if GDB loads a core dump correctly
- \ADDR-Linux\Exercise-R0-x64-GDB.pdf
- \ADDR-Linux\Exercise-R0-ARM64-GDB.pdf

Exercise R1

- **Goal:** Review x64 and AArch64 assembly fundamentals; learn how to reconstruct stack trace manually

- **ADDR Patterns:** Universal Pointer, Symbolic Pointer S^2, Interpreted Pointer S^3, Context Pyramid

- **Memory Cell Diagrams:** Register, Pointer, Stack Frame

- \ADDR-Linux\Exercise-R1-x64-GDB.pdf
- \ADDR-Linux\MCD-R1-x64.xlsx

- \ADDR-Linux\Exercise-R1-ARM64-GDB.pdf
- \ADDR-Linux\MCD-R1-ARM64.xlsx

Stack Reconstruction (x64)

1. Top frame from the current RIP_1, RSP_1 (**info reg**)
2. Disassemble around the current RIP_n (**disass** RIP_n)*
3. Find out the beginning of the function prologue*
4. Check RSP_n usage (**sub**, **push**) and count offsets
5. Get RIP_{n+1} for the next frame (**x/a** RSP_n + offset)
6. Get RSP_{n+1} for the next frame (RSP_n + offset + 8)
7. ++n
8. goto #2

* If symbols are available, disassemble the function corresponding to RIP_n (**disass name**)

If symbols are not available, disassemble backwards until the function prologue is found

Stack Reconstruction (A64)

1. Top frame from the current PC_1, $X29_1$ (**info reg**)
2. Get PC_{n+1} for the next frame (**x/a** $X29_n$ + 8)
3. Get $X29_{n+1}$ for the next frame (**x/gx** $X29_n$)
4. ++n
5. goto #2

ADDR: Universal Pointer

- A memory cell value interpreted as a pointer to memory cells
- A memory address that was not specifically designed as a pointer

ADDR: Symbolic Pointer, S^2

- A memory cell value associated with a symbolic value from a symbol file or a binary file (exported symbol)

ADDR: Interpreted Pointer, S^3

- Interpretation of a memory cell pointer value and its symbol
- Implemented via a typed structure or debugger (extension) command

ADDR: Context Pyramid

- When we move down stack trace frames, we can recover less and less contextual memory information due to register and memory overwrites

Exercise R2

- **Goal:** Learn how to map source code to disassembly
- **ADDR Patterns:** Function Skeleton, Function Call, Call Path, Local Variable, Static Variable, Pointer Dereference
- **Memory Cell Diagrams:** Pointer Dereference
- \ADDR-Linux\Exercise-R2-x64-GDB.pdf
- \ADDR-Linux\MCD-R2-x64.xlsx
- \ADDR-Linux\Exercise-R2-ARM64-GDB.pdf
- \ADDR-Linux\MCD-R2-ARM64.xlsx

ADDR: Function Skeleton

- Function calls (or branch and links) inside a function body
- Splits a function body into regions
- Helps in understanding a function

ADDR: Function Call

- Simply the call of (or branch and link to) a function
- Call (bl, blr) or unconditional jmp (b) instructions

ADDR: Call Path

- Following a sequence of Function Calls
- Example: call procA, call procC (or bl procA, bl procC)

```
…
call procA
call procB
…

procA:
…
call procC
…
```

```
…
bl procA
bl procB
…

procA:
…
bl procC
…
```

ADDR: Local Variable

- A variable is a memory cell with an address
- A variable with stack region storage
- Usually, a local variable memory cell is referenced by stack pointer or frame pointer registers

ADDR: Static Variable

- A variable is a memory cell with an address
- A variable with non-stack and non-register storage
- Usually, there is a direct memory reference

ADDR: Pointer Dereference

- A pointer is a memory cell that contains the address of (references) another memory cell
- Dereference is a sequence of instructions to get a value from a memory cell referenced by another memory cell

Exercise R3

- **Goal:** Learn a function structure and associated memory operations
- **ADDR Patterns:** Function Prologue, Function Epilogue, Variable Initialization, Memory Copy
- **Memory Cell Diagrams:** Function Prologue, Function Epilogue
- \ADDR-Linux\Exercise-R3-x64-GDB.pdf
- \ADDR-Linux\MCD-R3-x64.xlsx
- \ADDR-Linux\Exercise-R3-ARM64-GDB.pdf
- \ADDR-Linux\MCD-R3-ARM64.xlsx

ADDR: Function Prologue

- The code emitted by a compiler that is necessary to set up the working internals of a function
- Such code doesn't have a real counterpart in actual source code
- Example: allocating memory on the stack for all local variables

ADDR: Function Epilogue

- The code emitted by a compiler that is necessary to finish the working internals of a function
- Such code doesn’t have a real counterpart in actual source code
- Example: deallocating memory on the stack for all local variables

ADDR: Variable Initialization

- Code to initialize an individual local variable
- Not part of a function prologue

ADDR: Memory Copy

- Repeated memory move instructions

Exercise R4

- **Goal:** Learn how to recognize call and function parameters and track their data flow
- **ADDR Patterns:** Call Prologue, Call Parameter, Call Epilogue, Call Result, Control Path, Function Parameter
- \ADDR-Linux\Exercise-R4-x64-GDB.pdf
- \ADDR-Linux\Exercise-R4-ARM64-GDB.pdf

ADDR: Call Prologue

- The code emitted by a compiler that is necessary to set up a function call (or branch and link) and its parameters

ADDR: Call Parameter

- Data passed to a function before a function call (or branch and link)

ADDR: Call Epilogue

- The code emitted by a compiler to finish a function call (or branch and link) and processing of its return results

ADDR: Call Result

- Data returned by a function

ADDR: Control Path

- A possible execution path inside a function consisting of direct and conditional jumps or branches

ADDR: Function Parameter

- Data passed to a function inside a function (on the receiver side)
- Such a parameter can be translated to a local variable if passed by stack or copied to a stack location

Exercise R5

- **Goal:** Master memory cell diagrams as an aid to understanding complex disassembly logic
- **ADDR Patterns:** Last Call, Loop, Memory Copy
- **Memory Cell Diagrams:** Memory Copy
- \ADDR-Linux\Exercise-R5-x64-GDB.pdf
- \ADDR-Linux\MCD-R5-x64.xlsx
- \ADDR-Linux\Exercise-R5-ARM64-GDB.pdf
- \ADDR-Linux\MCD-R5-ARM64.xlsx

ADDR: Last Call

- A function possibly called (or branched and linked to) before the current instruction pointer

ADDR: Loop

- An unconditional jump or branch to the previous code address

Exercise R6

- **Goal:** Learn how to map code to execution residue and reconstruct past behaviour; recognise previously introduced ADDR patterns in the context of compiled classic C++ code

- **ADDR Patterns:** Virtual Call

- **Memory Cell Diagrams:** Virtual Call

- \ADDR-Linux\Exercise-R6-x64-GDB.pdf
- \ADDR-Linux\MCD-R6-x64.xlsx

- \ADDR-Linux\Exercise-R6-ARM64-GDB.pdf
- \ADDR-Linux\MCD-R6-ARM64.xlsx

ADDR: Virtual Call

- A call (or branch and link) through virtual function table structure field
- Usually involves a double Pointer Dereference

Additional ADDR Patterns

ADDR: Potential Functionality

- A list of function symbols, for example, a list of imported functions, a list of callbacks, a structure or table with function pointers

ADDR: Structure Field

- An offset to the structure memory address

ADDR: Separator Frames

- Frames that divide a stack trace into separate analysis units

Live Debugging Techniques

- **ADDR Patterns:** Component Dependencies, API Trace, Fiber Bundle (trace analysis pattern)
- Some dependencies can be learnt from crash dump stack traces
- Debugging.TV / YouTube
- Live debugging training: Accelerated Linux Debugging[4]

Memory Analysis Patterns

Regular Data

Injected Symbols

Execution Residue

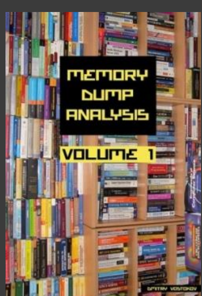
Rough Stack Trace

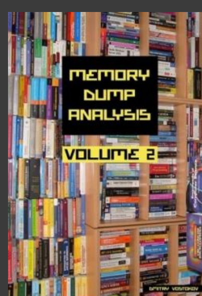
Annotated Disassembly

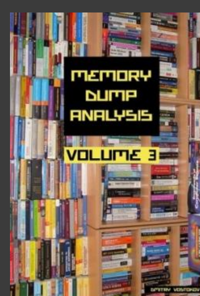
Historical Information

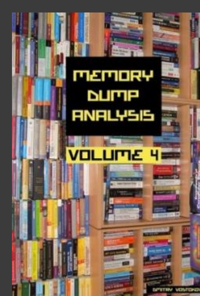
Resources

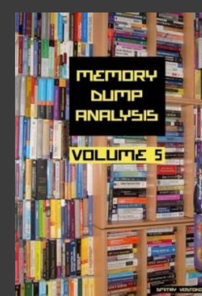
- [DumpAnalysis.org] / [SoftwareDiagnostics.Institute]
- [PatternDiagnostics.com]
- [Debugging.TV] / [YouTube.com/DebuggingTV] / [YouTube.com/PatternDiagnostics]
- [A64 Instruction Set Architecture]
- [A64 Base Instructions]
- GDB Pocket Reference
- [Accelerated Linux Core Dump Analysis, Third Edition]
- [Debugging, Disassembly & Reversing in Linux for x64 Architecture]
- [Foundations of Linux Debugging, Disassembling, and Reversing]
- [Foundations of ARM64 Linux Debugging, Disassembling, and Reversing]
- [Memory Dump Analysis Anthology (Diagnomicon)] articles in volumes 1, 7, 9A cover GDB

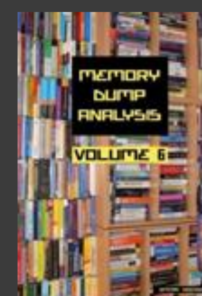


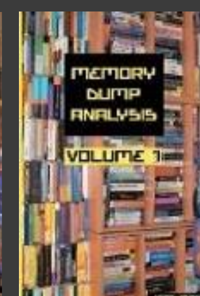


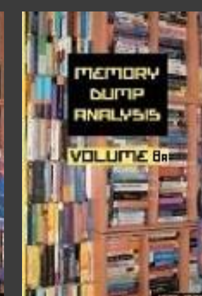


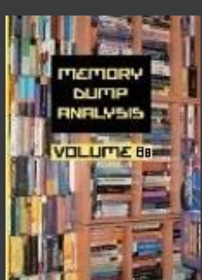


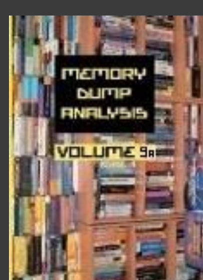


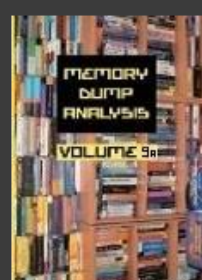


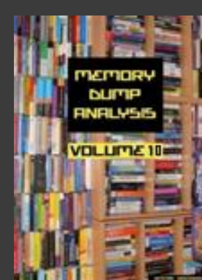


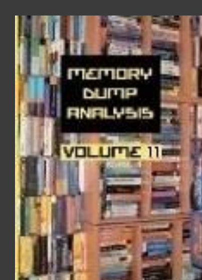


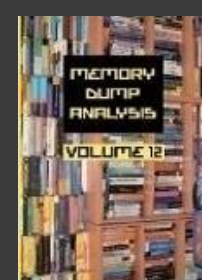


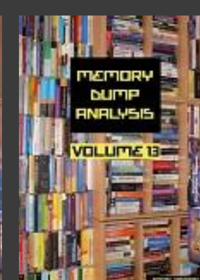


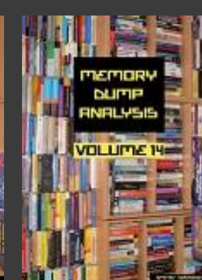












Q&A

Please send your feedback using the contact form on PatternDiagnostics.com

Thank you for attendance!