Programming Paradigms

Control Abstraction

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Control vs. Data Abstraction

- Abstract a well-defined operation
- E.g., a subroutine or an exception handler

- Abstract how to represent information
- E.g., types and classes

Control vs. Data Abstraction

- Abstract a well-defined operation
- E.g., a subroutine or an exception handler

Focus of this and next lecture

- Abstract how to represent information
- E.g., types and classes

Overview

- **Calling Sequences** ←
- **Parameter Passing**
- **Exception Handling**
- **Coroutines**
- **Promises, Async, and Await**

Terminology

- **Subroutine: Mechanism for control abstraction**
  - Function: Subroutine that returns a value
  - Procedure: Subroutine that doesn't return a value
- **Parameters**
  - Actual parameters = arguments: Data passed by caller
  - Formal parameters: Data received by callee

Calling Sequences

- **Low-level code executed to maintain call stack**
  - Before subroutine call in caller
  - At beginning of subroutine in callee ("prologue")
  - At end of subroutine in callee ("epilogue")
  - After subroutine call in caller

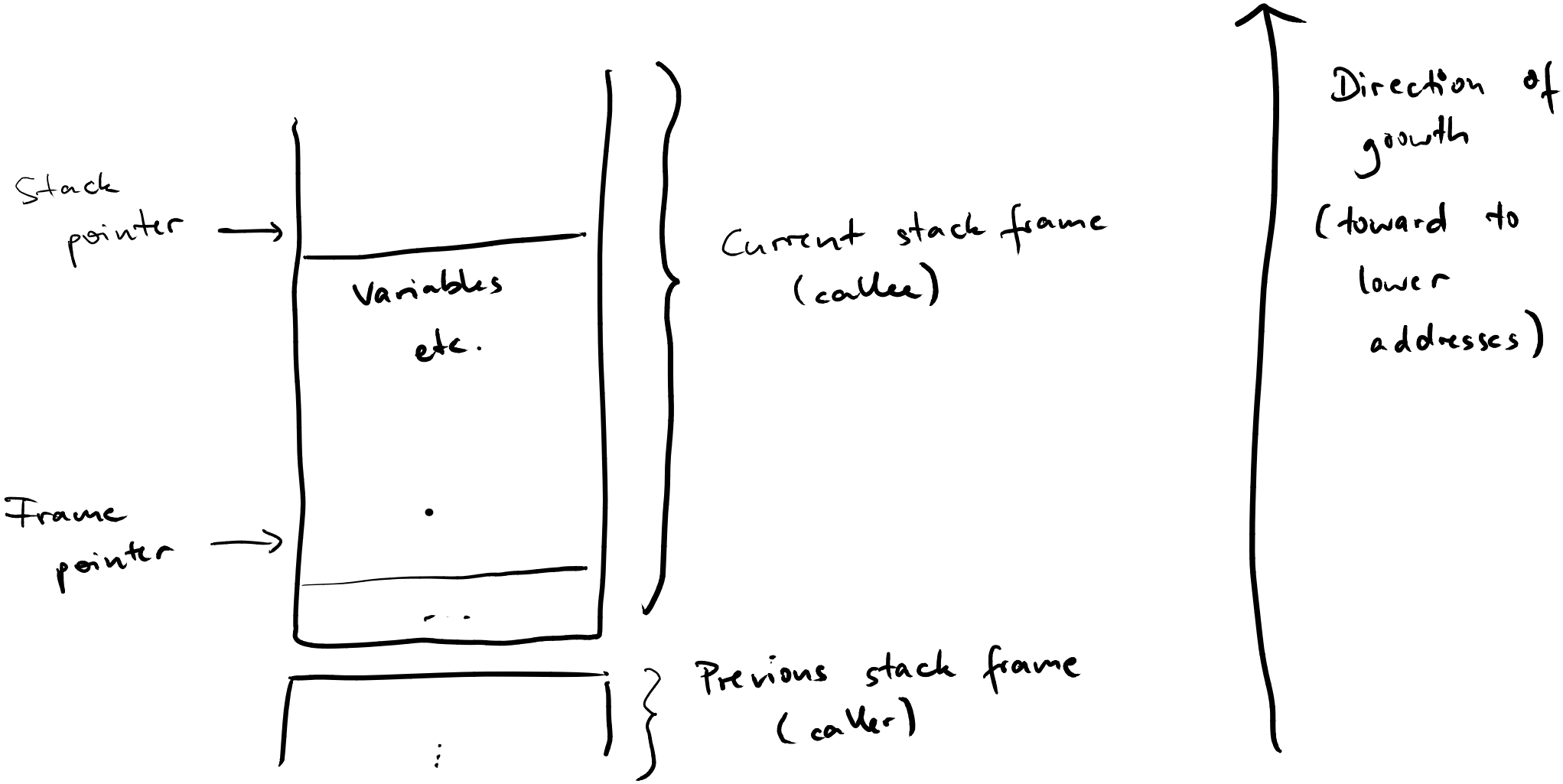
Why Does It Matter?

- **Important to**
  - Understand performance implications
  - Understand security implications, e.g., stack smashing attacks
  - Choose/design/implement compilers

Reminder: Stack Layout

- **Each procedure call:**
  One stack frame (or activation record)
- **Frame pointer: Base address used to access data in current stack frame**
- **Stack pointer: First unused (or, sometimes, last used) location in current stack frame**

Example: Stack Layout



Tasks to Perform

- Pass parameters and return value(s)
- Update program counter
- Save return address
- Save and restore registers
- Update stack and frame pointers

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Program counter: Address of code to execute next

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Otherwise, don't know what code location to return back to

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Registers: Very fast but limited intermediate memory

Tasks to Perform

- Pass **parameters** and **return value(s)**
- Update **program counter**
- Save **return address**
- Save and restore **registers**
- Update **stack and frame pointers**

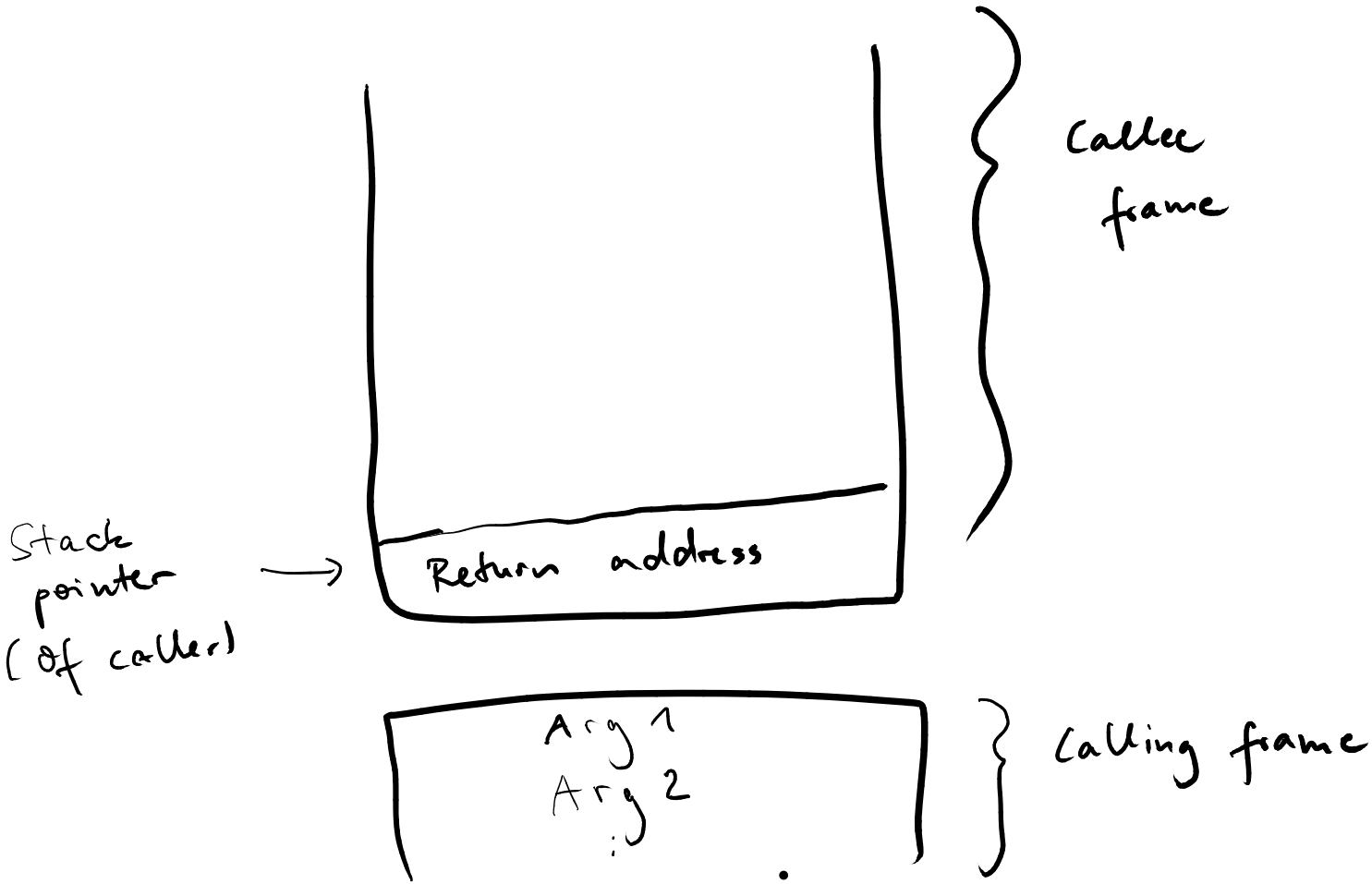
Where to perform those?

- Possibly either in caller or in callee
- Preferably in callee: Requires space only once per subroutine, not at each call site

Typical Calling Sequence (1/4)

- **Steps performed by caller before the call**
  - Save registers whose values may be needed after the call
  - Compute values of arguments and move them into stack or registers
  - Pass return address and jump to subroutine

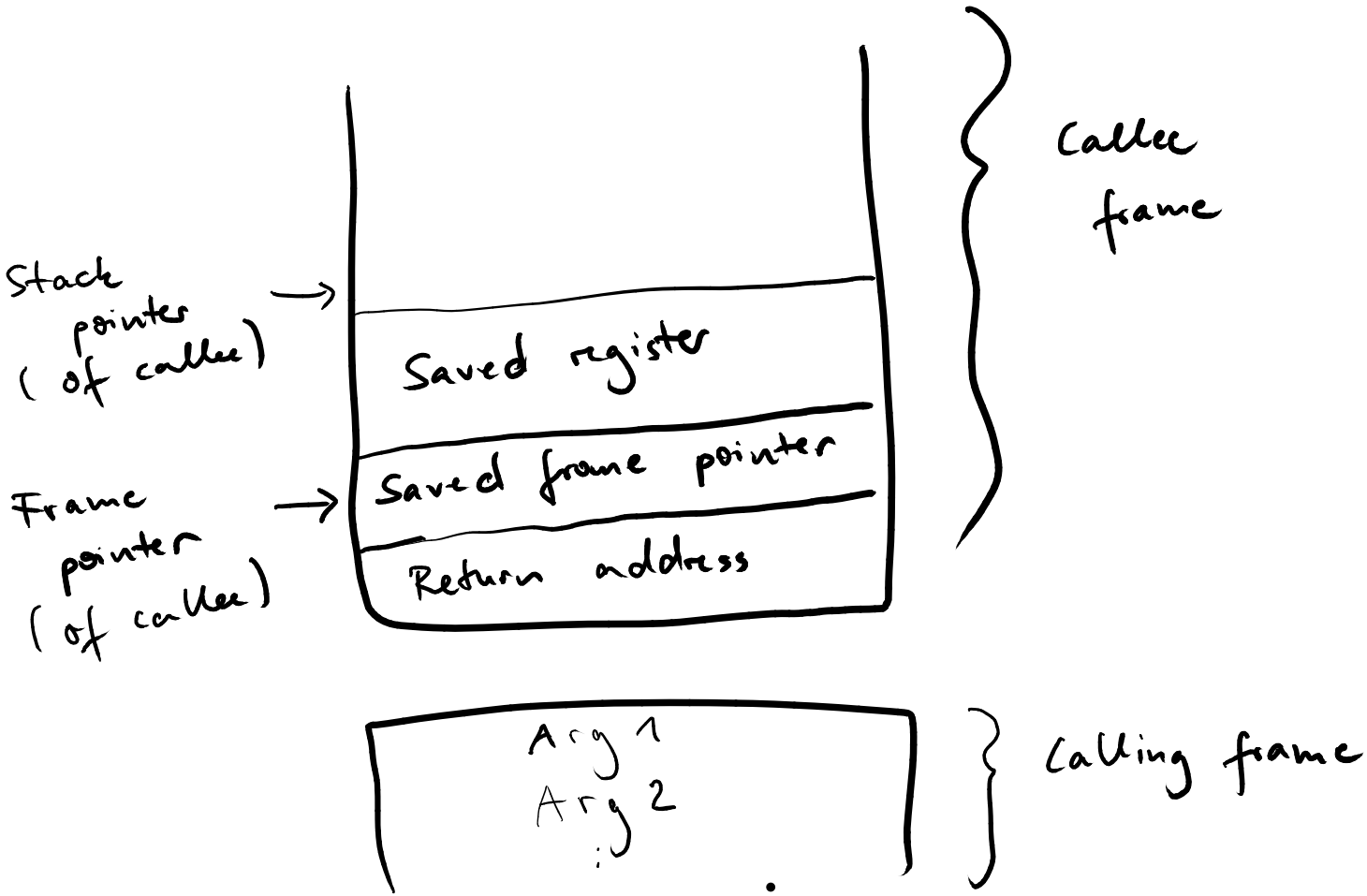
Stack before call



Typical Calling Sequence (2/4)

- **Steps performed by callee in prologue**
  - Allocate a frame: Subtract an appropriate constant from the stack pointer
  - Save old frame pointer on stack and update it to point to newly allocated frame
  - Save registers that may be overwritten by current subroutine

Stack after prologue



Quiz: Stack Frames

Assume the frame pointer is stored in register `ebp`, addresses are 4 bytes long, and all arguments are 32-bit integers.

What is the address the callee uses to access the third argument?

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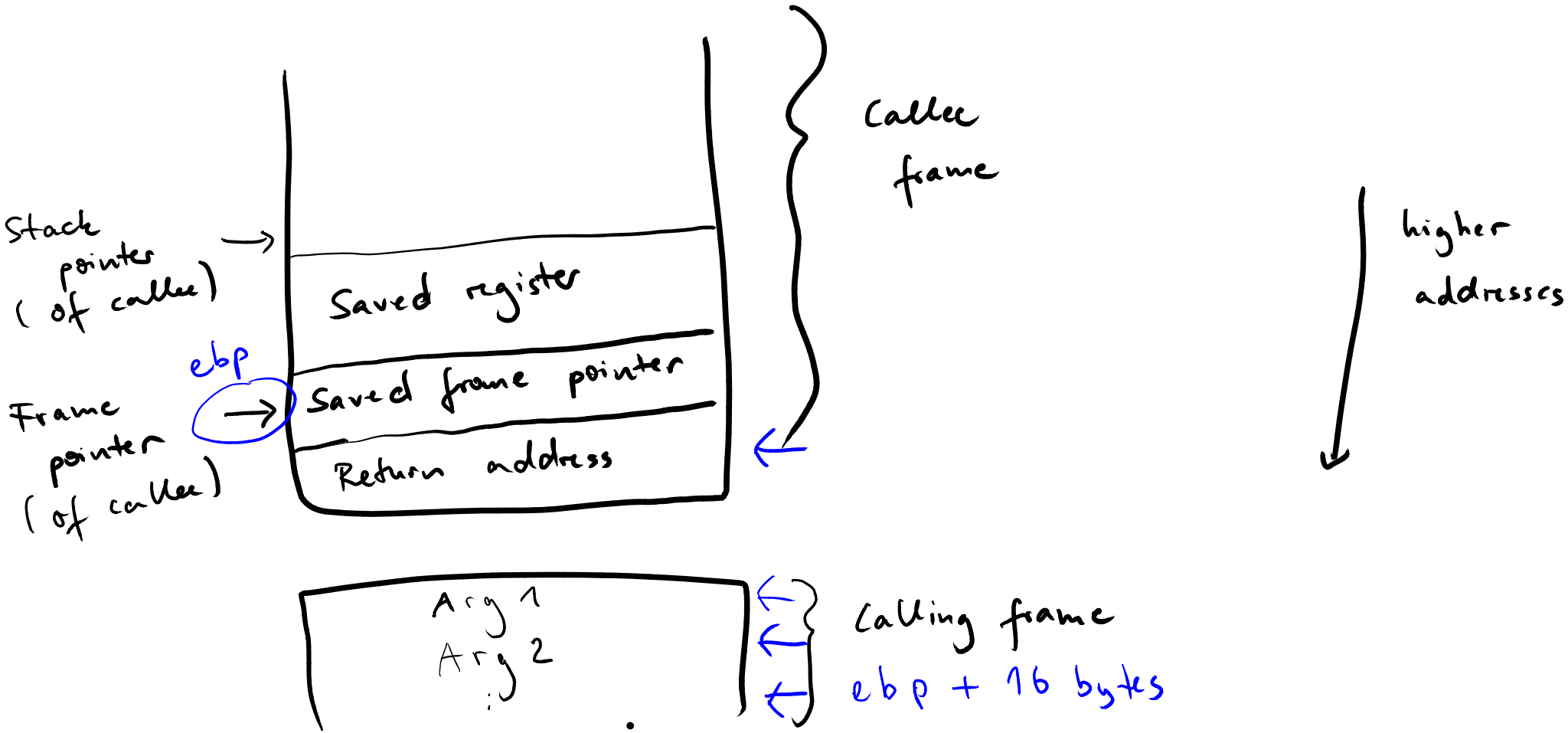
What is the address the callee uses to access the third argument?

Answer: `ebp` + 16 bytes

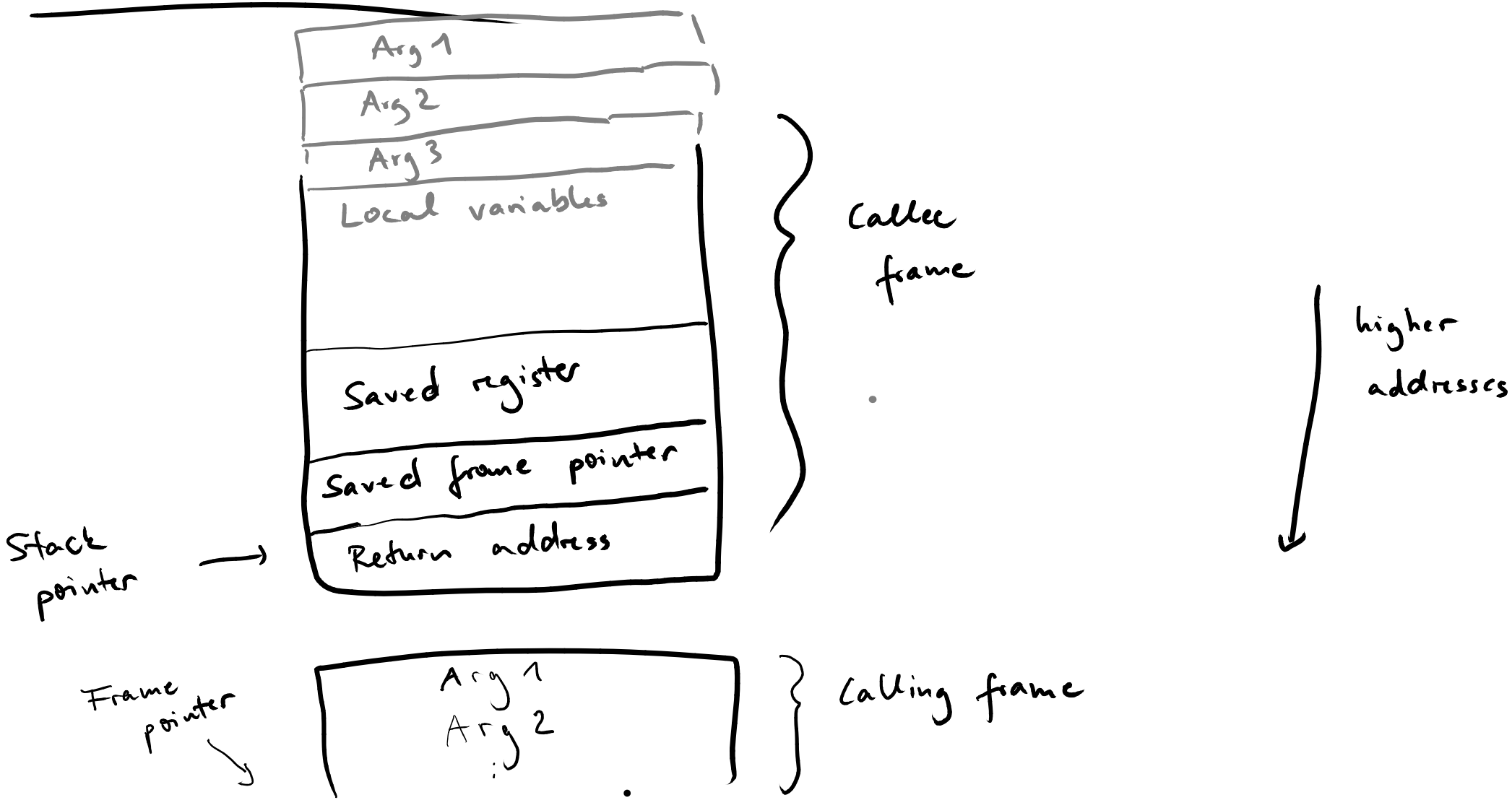
Quiz


Stack pointer (of callee)
ebp
Frame pointer (of callee)
Saved register
Saved frame pointer
Return address
Callee frame
higher addresses
Arg 1
Arg 2
Calling frame
ebp + 16 bytes

Typical Calling Sequence (3/4)

- **Steps performed by callee in epilogue**
  - Move return value into register or reserved location in stack
  - Restore registers (to state before call)
  - Restore frame pointer and stack pointer
  - Jump back to return address

Stack after epilogue



Typical Calling Sequence (4/4)

- **Steps performed by caller after the call**
  - Move return value to where it is needed
  - Restore registers (to state before call)

Saving and Restoring Registers

- **Which registers to save and restore?**
  - E.g., x86 has 8 general purpose registers
  - Ideally, save iff both hold:
    - Caller may use them after the call
    - Callee needs them for other purposes
  - In practice, compiler safely overapproximates
    - Better to store once too much then to loose data

Saving and Restoring Registers

- **Where to save and restore registers?**
  - Caller could save (and then restore) all registers that are in use
  - Callee could save (and then restore) all registers it overwrites
  - In practice: Calling sequence conventions for each architecture
    - E.g., on x86, three registers are caller-saved, others are callee-saved

Inlining

- **Calling sequences are expensive**
- **Optimization, in particular for small functions: Inlining**
  - Copy of callee becomes part of caller
  - Avoids overhead of calling sequence
  - Enables other optimizations across subroutine boundaries
  - But: Increases code size

Example: Inlining Hints in C

- Programmer may suggest which subroutine to inline
- Example:

```
inline int max(int a, int b) {
  return a > b ? a : b;
}
```

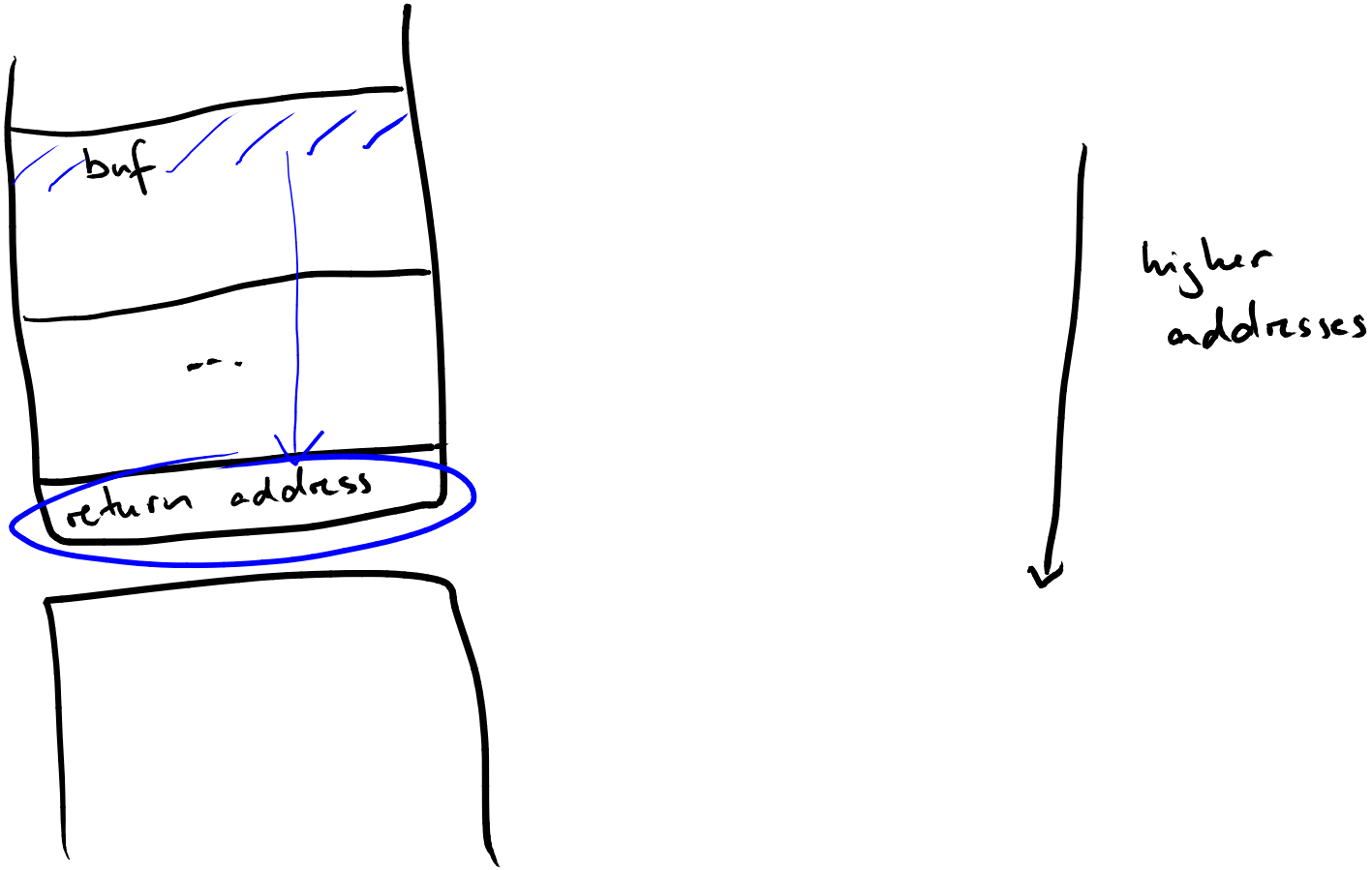
Application: Stack Smashing

- **Special kind of buffer overflow vulnerability**
  - Lack of bounds checking: May write beyond space allocated for a local variable
  - Malicious input can overwrite return address
  - Program can jump into malicious code

Example: Stack Smashing

```
int read_nb_from_file(FILE *s) {
  char buf[100];
  char *p = buf;
  do {
    /* read from stream s */
   *p = getc(s);
  } while (*p++ != '\n');
  *p = '\0';
  return atoi(buf);
}
```

Example: Stack Smashing



Overview

- Calling Sequences
- Parameter Passing ←
- Exception Handling
- Coroutines
- Promises, Async, and Await

Parameter Passing

- **What does it mean if a parameter is passed to a callee?**
- **Different PLs have different parameter passing modes**
  - Call by value
  - Call by reference
  - Call by value/result
  - Call by sharing

Call by Value

- Caller passes copy of value to callee
- Once in callee, formal parameter is independent of the actual parameter

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```
x : list
procedure foo(y : list)
  y := [3]
  print x
...
x := [1,2]
foo(x)
print(x)
```

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- Once in callee, formal parameter is independent of the actual parameter

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```

Assignment has no visible effect

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```

Prints `[1,2]` twice

Call by Reference

- **Formal parameter is new name of actual parameter**
- **Both names refer to the same value**

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Refers to same value as outer variable `x`

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x : list
procedure foo(y : list)
  y := [3]
  print x
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```

Prints `[3]` twice

Call by Value/Result

- Argument is copied on call
- Resulting value is copied back to argument on return

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Quiz: What does the code print?

Call by Value/Result

- Argument is copied on call
- Resulting value is copied back to argument on return

```
x : list
procedure foo(y : list)
  y := [3]
  print x
...
x := [1,2]
foo(x)
print(x)
```

Refers to value different from outer variable `x`

Call by Value/Result

- **Argument is copied on call**
- **Resulting value is copied back to argument on return**

```
x : list
procedure foo(y : list)
  y := [3]
  print x
...
x := [1,2]
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print(x)
```

Prints `[1,2]`

Prints `[3]`

Call by Sharing

- **In PLs with reference model of variables**
  - Arguments are passed as values, but the values are references

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x : list
procedure foo(y : list)
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Call by Sharing

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  y := [3]
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...
x := [1,2]
foo(x)
print(x)
```

Prints `[1,2]` twice

Call by Sharing

- **In PLs with reference model of variables**
  - Arguments are passed as values, but the values are references

```
x : list
procedure foo(y : list)
  y.append(3)
  print x
...
x := [1,2]
foo(x)
print(x)
```

Call by Sharing

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  - Arguments are passed as values, but the values are references

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x : list
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x := [1,2]
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print(x)
```

Prints `[1,2,3]`

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Passing Models in Popular PLs

- **C: By value, except arrays are passed by reference**
  - Passing pointers can emulate call by reference
- **Fortran: All arguments are passed by reference**
- **Java: Hybrid passing model**
  - Built-in, primitive types: By value
  - Instances of classes: By sharing