Process Management

Process Abstraction

Lecture 2

Overview

- Introduction to Process Management
- Process Abstraction:
  - Memory Context
    - Code & Data
    - Function call
    - Dynamically allocated memory
  - Hardware Context
  - OS Context
    - Process State
  - Process Control Block and Process Table

- OS interaction with Process

Recap: **Efficient Hardware Utilization**

- OS should provide efficient use of the hardware resource:
  - By managing the programs executing on the hardware
- Observation:
  - If there is only **one program executing at any point in time**, how can we utilize hardware resources effectively?
- Solution:
  - Allow **multiple programs to share the hardware**
    - e.g. Multiprogramming, Time-sharing

Introduction to Process Management

- As the OS, to be able to switch from running program ***A*** to program ***B*** requires:
  1. Information regarding the execution of program ***A*** needs to be stored
  2. Program ***A***'s information is replaced with the information required to run program ***B***

- Hence, we need:
  - An **abstraction** to describe a running program
  - aka **process**

Key Topics

Process Abstraction

- Information describing an executing program

Process Scheduling

- Deciding which process get to execute

Inter-Process Communication & Synchronization

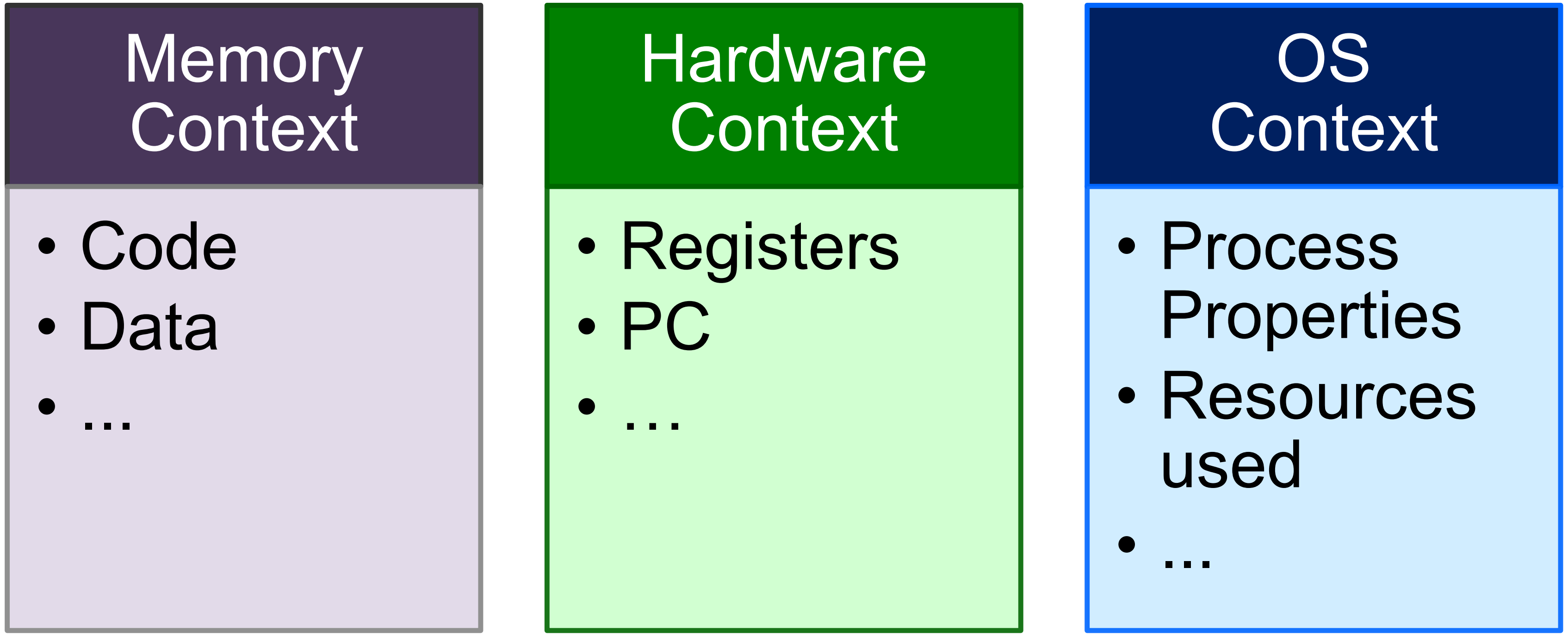
- Passing information between processes

Alternative to Process

- Light-weight process aka Thread

Process Abstraction

- **(Process / Task / Job)** is a dynamic abstraction for executing program
  - **information required** to describe a **running program**



Memory Context

- Code
- Data
- ...

Hardware Context

- Registers
- PC
- …

OS Context

- Process Properties
- Resources used
- ...

Recap: C Sample Program and Assembly Code

```
int i = 0;

i = i + 20;
```

C Code Fragment

lw: load memory to register

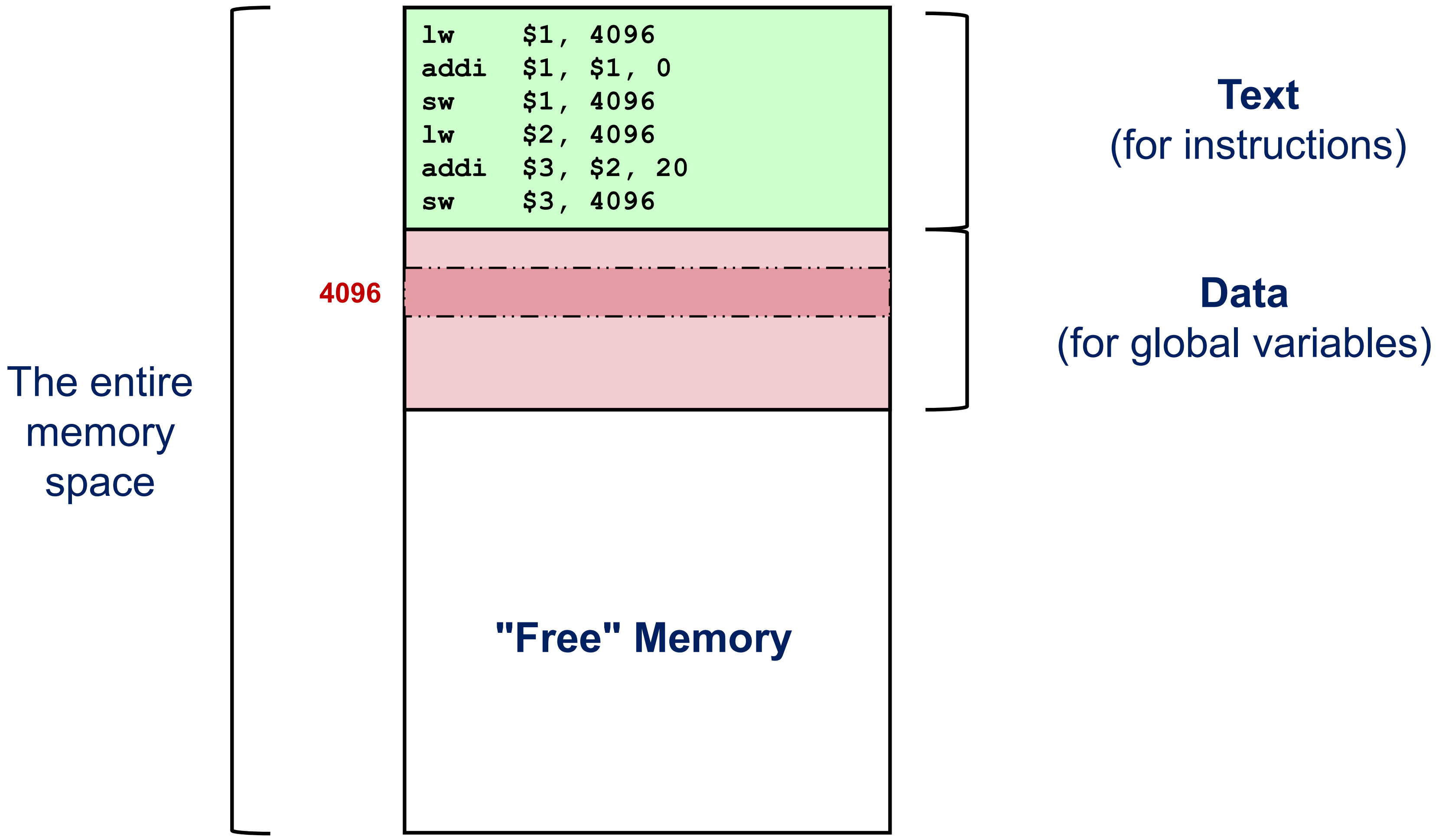
i address: 4096

```
lw     $1, 4096               //Assume address of i = 4096
addi   $1, $0, 0              //register $1 = 0
sw     $1, 4096               //i = 0

lw     $2, 4096               //read i
addi   $3, $2, 20             //$3 = $2 + 20
sw     $3, 4096               //i = i + 20
```

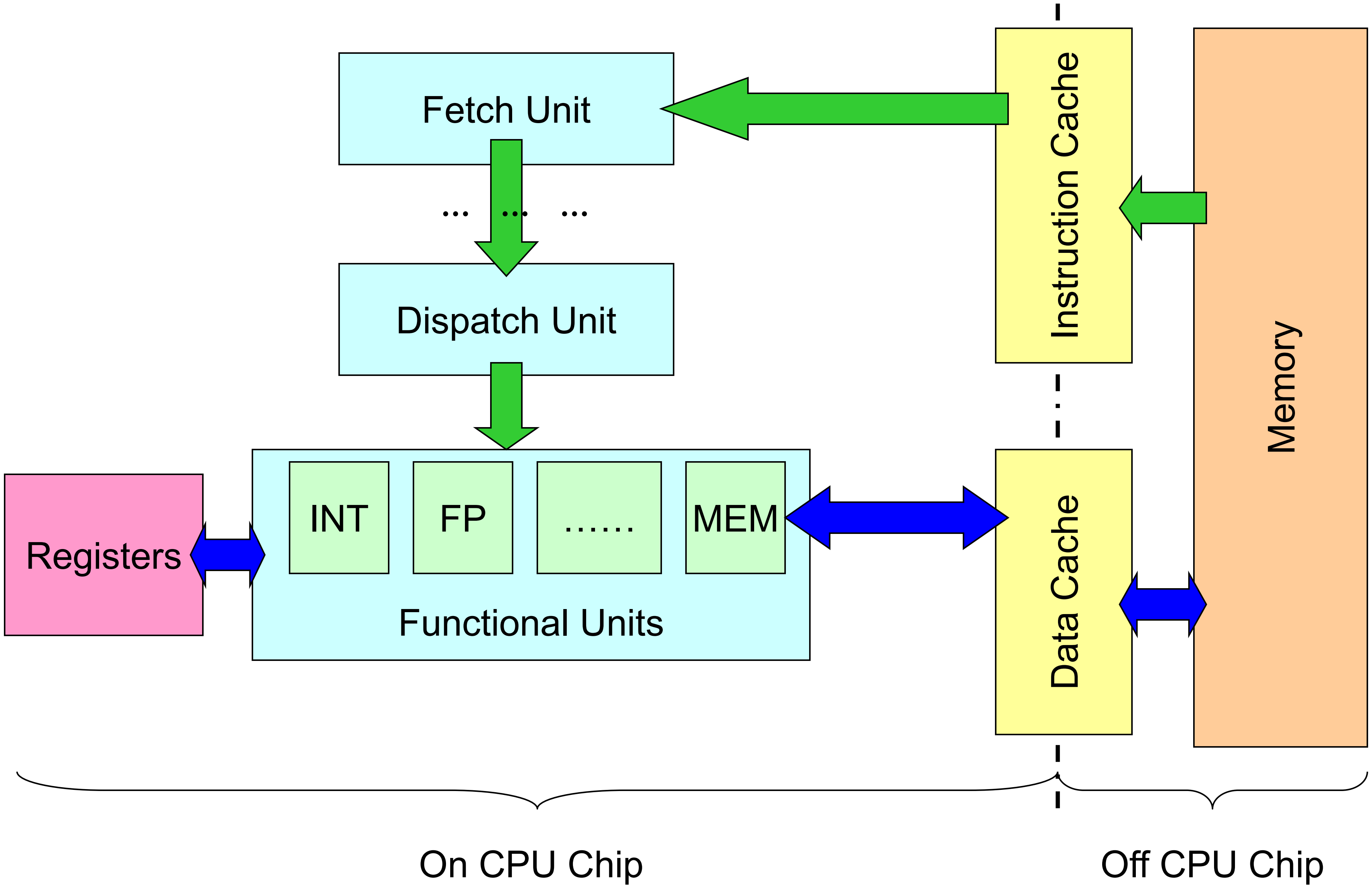
Corresponding MIPS-like Assembly Code

Recap: Program Execution (Memory)



```
lw    $1, 4096
addi  $1, $1, 0
sw    $1, 4096
lw    $2, 4096
addi  $3, $2, 20
sw    $3, 4096
```

Recap: Generic Computer Organization



Recap: Component Description

- Memory:
  - Storage for instruction and data

- Cache:
  - Duplicate part of the memory for faster access
  - Usually split into instruction cache and data cache

- Fetch unit:
  - Loads instruction from memory
  - Location indicated by a special register: **P**rogram **C**ounter (PC)

Recap: Component Description (cont)

- Functional units:
  - Carry out the instruction execution
  - Dedicated to different instruction type

- Registers:
  - Internal storage for the fastest access speed
  - General Purpose Register (GPR):
    - Accessible by user program (i.e. visible to compiler)
  - Special Register:
    - **Program Counter** (PC)
    - etc

Recap: Basic Instruction Execution

- Instruction X is fetched
  - Memory location indicated by **P**rogram **C**ounter
- Instruction X dispatched to the corresponding Functional Unit
  - Read operands if applicable
    - Usually from memory or GPR
  - Result computed
  - Write value if applicable
    - Usually to memory or GPR
- Instruction X is completed
  - PC updated for the next instruction

Recap: What you should know ☺

- An executable (binary) consists of two major components:
  - Instructions and Data

- When a program is **under execution**, there are **more information**:
  - Memory context:
    - **Text** and **Data**, …
  - Hardware context:
    - **General purpose registers, Program Counter**, …

- Actually, there are **other types of memory usage** during program execution
  - Coming up next

Memory Context

Function Call

What if `f()` calls `u()` calls `n()`?

Function Call : **Challenges**

```
int i = 0;

i = i + 20;
```

C Code Fragment

VS

```
int g(int i, int j)
{
    int a;

    a = i + j
    return a;
}
```

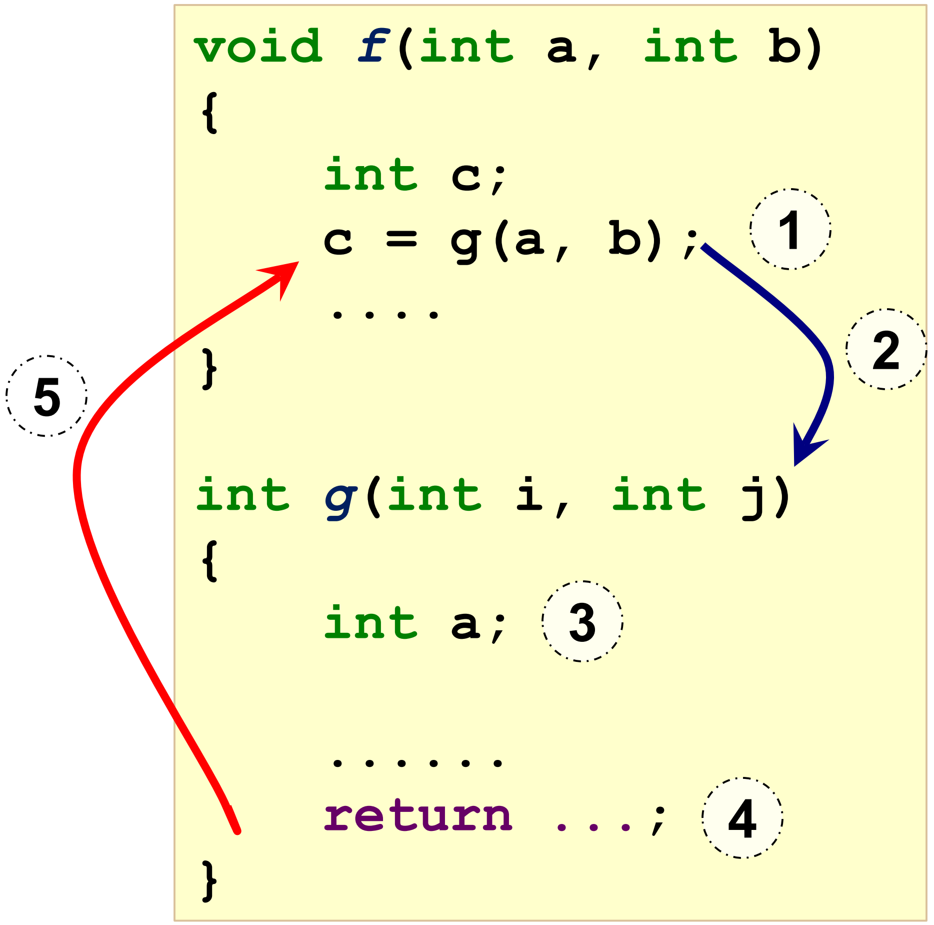
C Code with Function

- Consider:
  - How do we allocate memory space for variables **`i`**, **`j`** and **`a`**?
    - Can we just make use of the "**data**" memory space?
  - What are the key issues?

Function Call : **Control Flow and Data**

- `f()` calls `g()`
  - `f()` is the **caller**
  - `g()` is the **callee**

- Important Steps:
  1. Setup the parameters
  2. Transfer control to callee
  3. Setup local variable
  4. Store result if applicable
  5. Return to caller



```
void f(int a, int b)
{
    int c;
    c = g(a, b);
    ....
}

int g(int i, int j)
{
    int a;

    ......
    return ...;
}
```

Function Call : **Control Flow and Data**

- Control Flow Issues:
  - Need to jump to the function body
  - Need to resume when the function call is done
  - ➔ Minimally, need to store the PC of the caller

- Data Storage Issues:
  - Need to pass parameters to the function
  - Need to capture the return result
  - May have local variables declaration

➔ Need a **new region of memory** that dynamically used by function invocations

Introducing **Stack Memory**

- **Stack Memory Region**:
  - The new memory region to store information function invocation

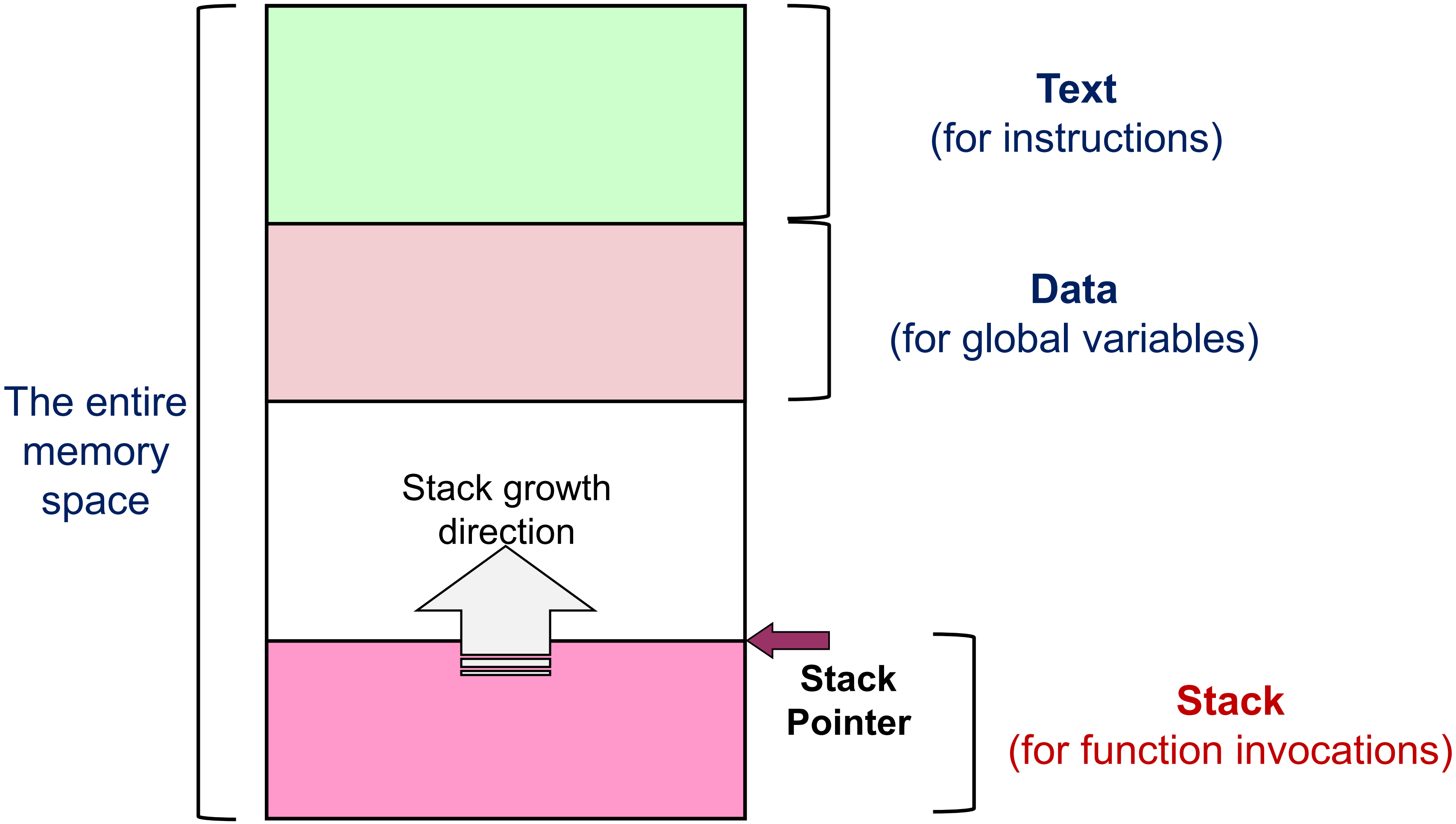
- Information of a function invocation is described by a **stack frame**

- Stack frame contains:
  - Return address of the caller
  - Arguments (Parameters) for the function
  - Storage for local variables
  - Other information…. (more later)

Stack Pointer

- The top of stack region (first unused location) is logically indicated by a **Stack Pointer**:
  - Most CPU has a specialized register for this purpose
  - Stack frame is added on top when a function is invoked
    - Stack “grows”
  - Stack frame is removed from top when a function call ends
    - Stack "shrinks"

Illustration: **Stack Memory**



- The memory layout on some systems is flipped, i.e. stack on top, text on the bottom

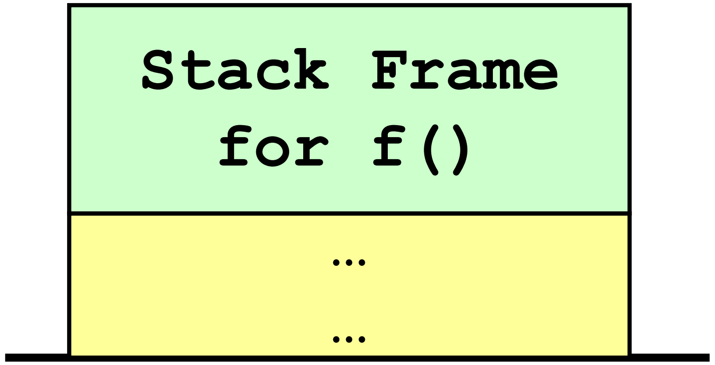
Illustration: **Stack Memory Usage** (1 / 5)

```
void f()
{
    ...
    g();
    ...
}

void g()
{
    h();
    ...
}

void h()
{
    ...
}
```

At this point


Stack Frame for f()

...

...

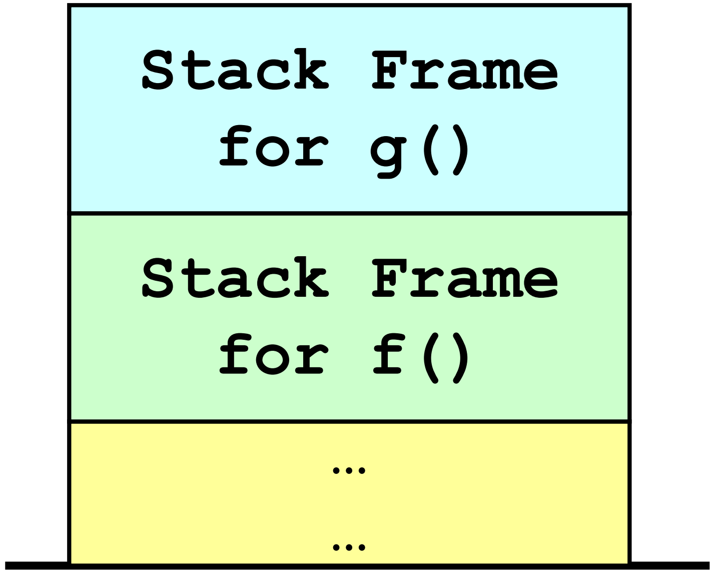
Illustration: **Stack Memory Usage** (2 / 5)

```
void f()
{
    ...
    g();
    ...
}

void g()
{
    h();
    ...
}

void h()
{
    ...
}
```

At this point



Stack Frame for g()

Stack Frame for f()

...

...

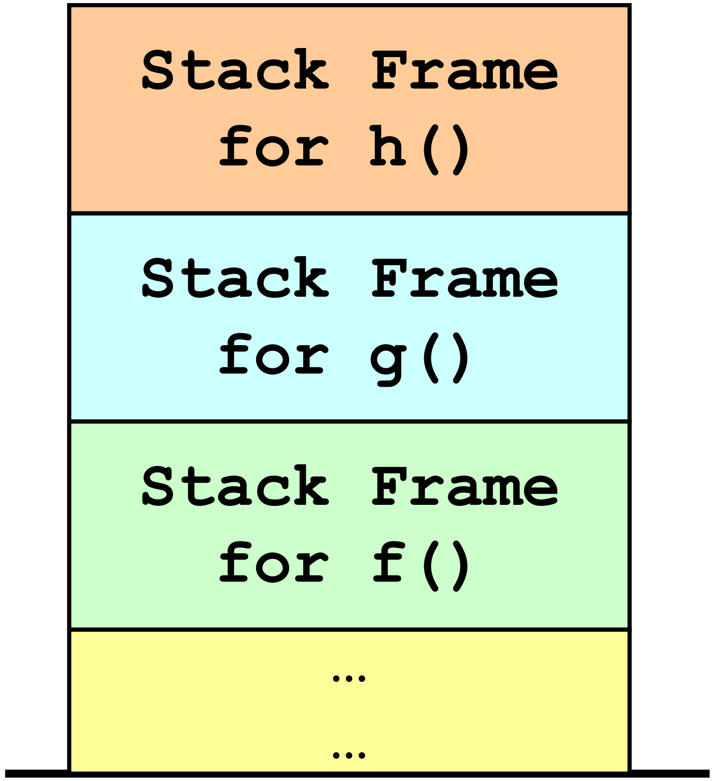
Illustration: **Stack Memory Usage** (3 / 5)

```
void f()
{
    ...
    g();
    ...
}

void g()
{
    h();
    ...
}

void h()
{
    ...
}
```

At this point



Stack Frame for h()

Stack Frame for g()

Stack Frame for f()

…
…

Illustration: **Stack Memory Usage** (4 / 5)

```
void f()
{
    ...
    g();
    ...
}

void g()
{
    h();
    ...
}

void h()
{
    ...
}
```

At this point

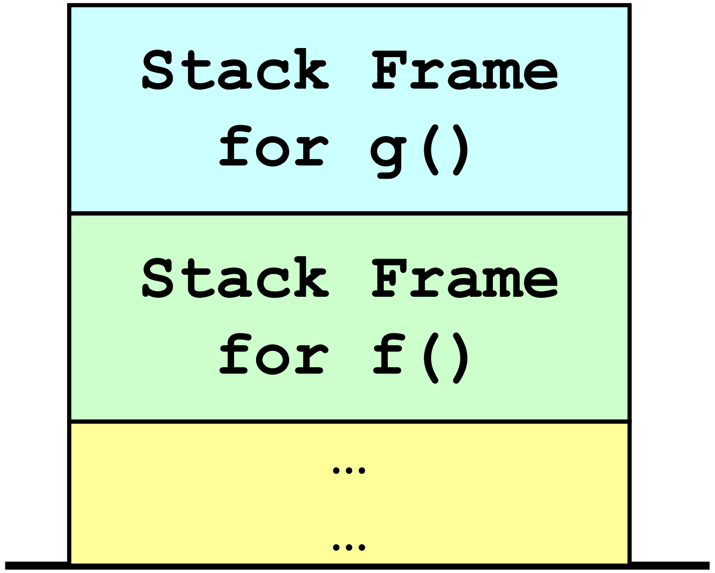


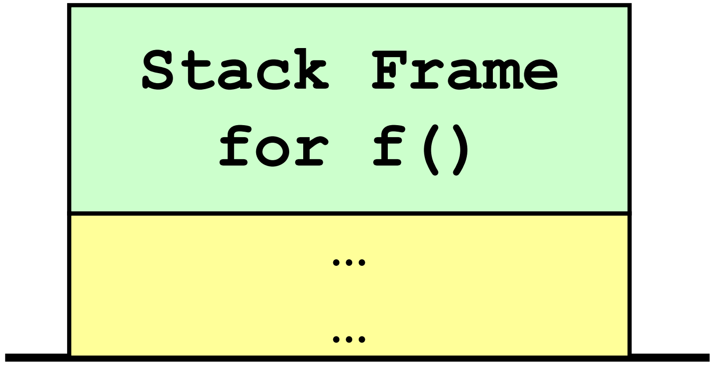
Illustration: **Stack Memory Usage** (5 / 5)

```
void f()
{
    ...
    g();
    ...
}

void g()
{
    h();
    ...
}

void h()
{
    ...
}
```

At this point

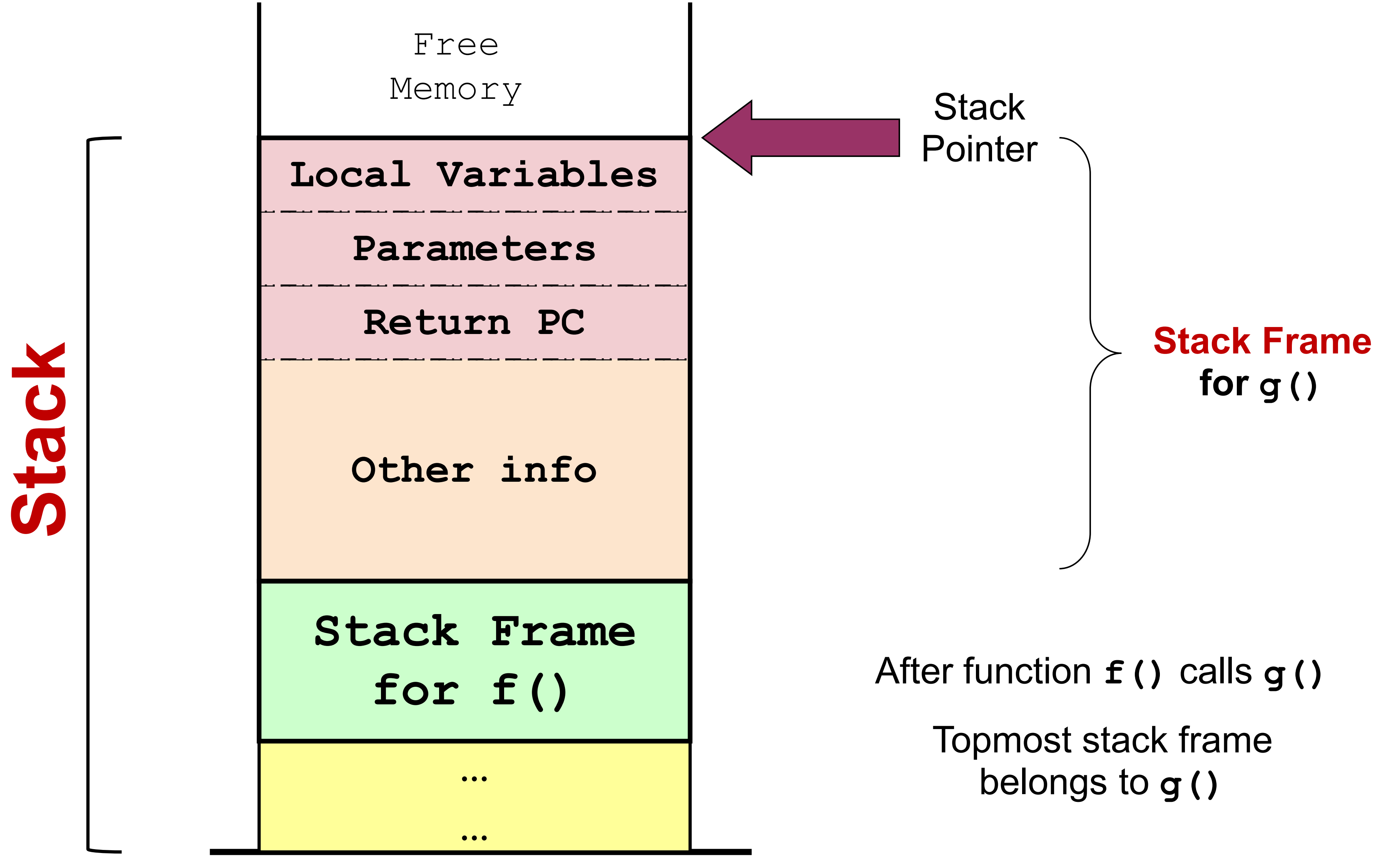


Stack Frame for f()

…

…

Illustration: **Stack Frame v1.0**



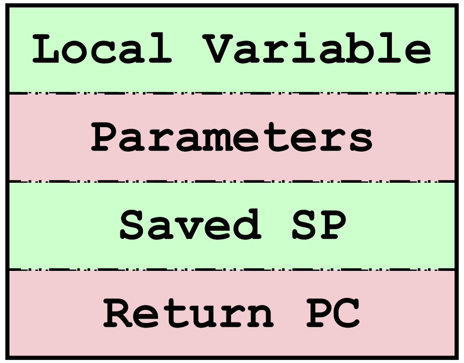
After function `f()` calls `g()`

Topmost stack frame
belongs to `g()`

Function Call Convention

- Different ways to setup stack frame:
  - Known as **function call convention**
  - Main differences:
    - What information is stored in stack frame or registers?
    - Which portion of stack frame is prepared by caller / callee?
    - Which portion of stack fame is cleared by caller / callee?
    - Who between caller / callee to adjust the stack pointer?
- No universal way
  - Hardware and programming language dependent
- An example scheme is described next

Stack Frame Setup



Local Variable

Parameters

Saved SP

Return PC

- Prepare to make a function call:
  - ❑ **Caller**: Pass parameters with registers and/or stack
  - ❑ **Caller**: Save Return PC on stack
  - ❑ **Transfer Control from Caller to Callee**
  - ❑ **Callee**: Save the old Stack Pointer (SP)
  - ❑ **Callee**: Allocate space for local variables of callee on stack
  - ❑ **Callee**: Adjust SP to point to new stack top

who dose the setup?
operating system

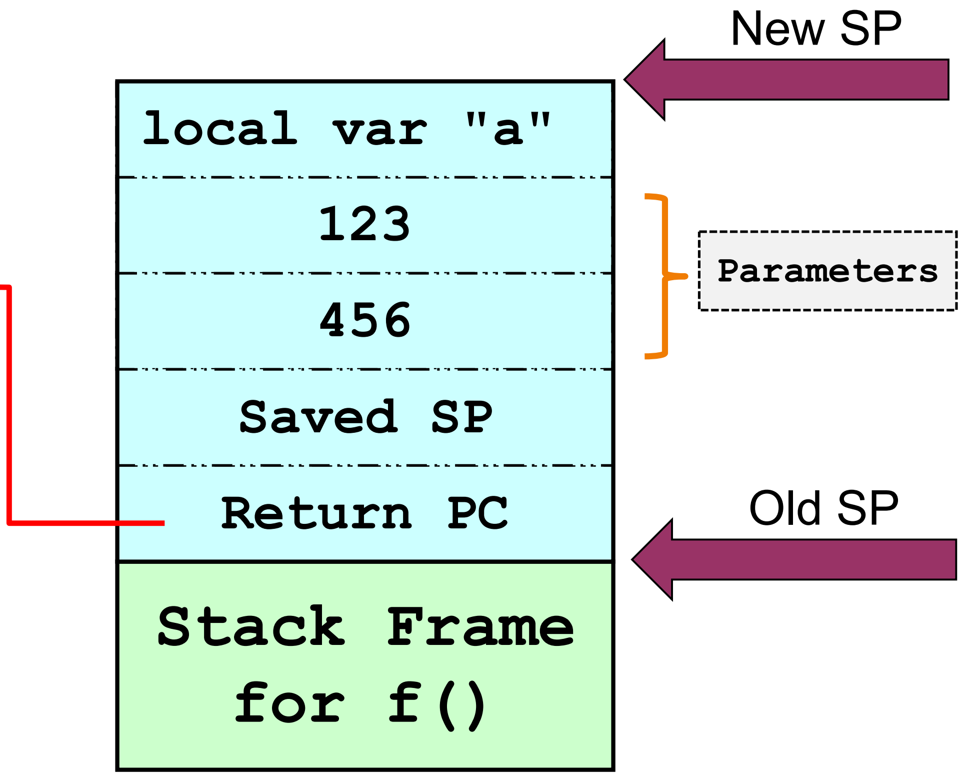
Illustration: Calling function *g* ( )

```
void f(int a, int b)
{
    int c;

    a = 123;
    b = 456;
    c = g(a, b);
    ....
}

int g(int i, int j)
{
    int a;

    a = i + j
    return a * 2;
}
```



New SP

local var "a"

123

456

Parameters

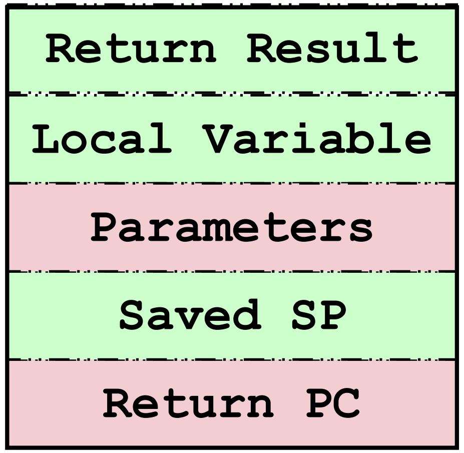
Saved SP

Return PC

Old SP

Stack Frame for f()

Stack Frame Teardown



Return Result

Local Variable

Parameters

Saved SP

Return PC

- On returning from function call:
  - **Callee:** Place return result on stack (if applicable)
  - **Callee**: Restore saved Stack Pointer
  - Transfer control back to caller using saved PC
  - **Caller**: Utilize return result (if applicable)
  - **Caller:** Continues execution in caller

Illustration: Function *g* ( ) finishes

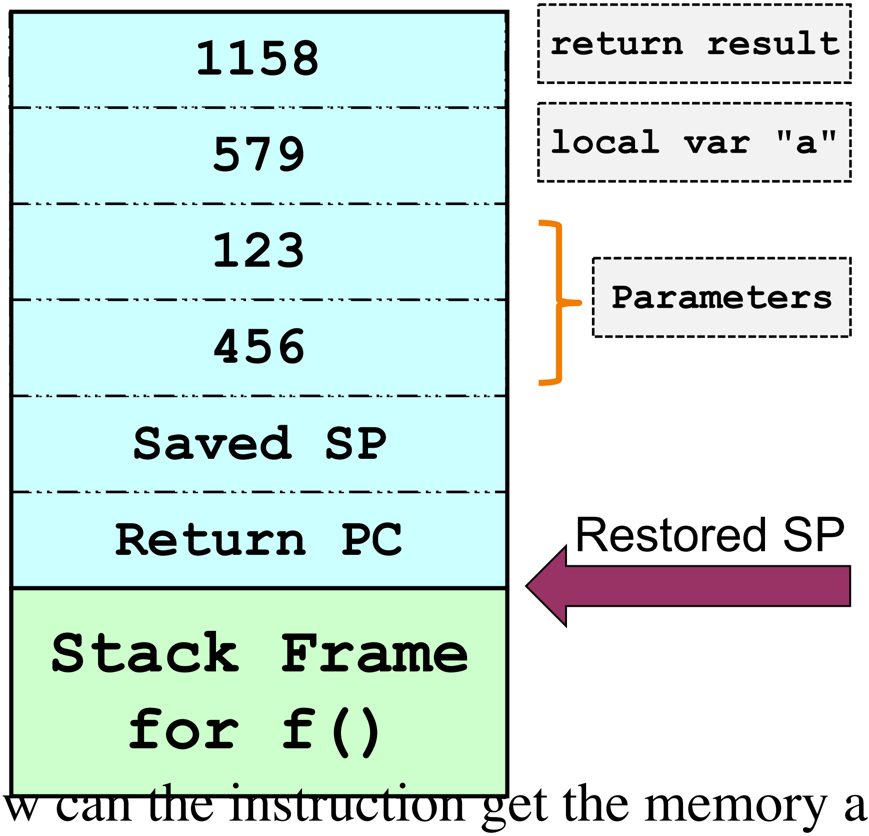
```
void f(int a, int b)
{
    int c;

    a = 123;
    b = 456;
    c = g(a, b);
    ....
}

int g(int i, int j)
{
    int a;

    a = i + j
    return a * 2;
}
```

Execution resumes here



How can the instruction get the memory address of local variable "a" from function "g"?

Stack pointer and offset (correct)

Absolute memory address

Program counter and offset

Other Information in Stack Frame

- We have described the basic idea of:
  - Stack frame
  - Calling Convention: Setup and Teardown

- Let us look at a few common additional information in the stack frame:
  - Frame Pointer not the same for all programming language
  - Saved Registers

Frame Pointer

- To facilitate the access of various stack frame items:
  - Stack Pointer is hard to use as it can change
  - ➔ Some processors provide a dedicated register ***Frame Pointer***

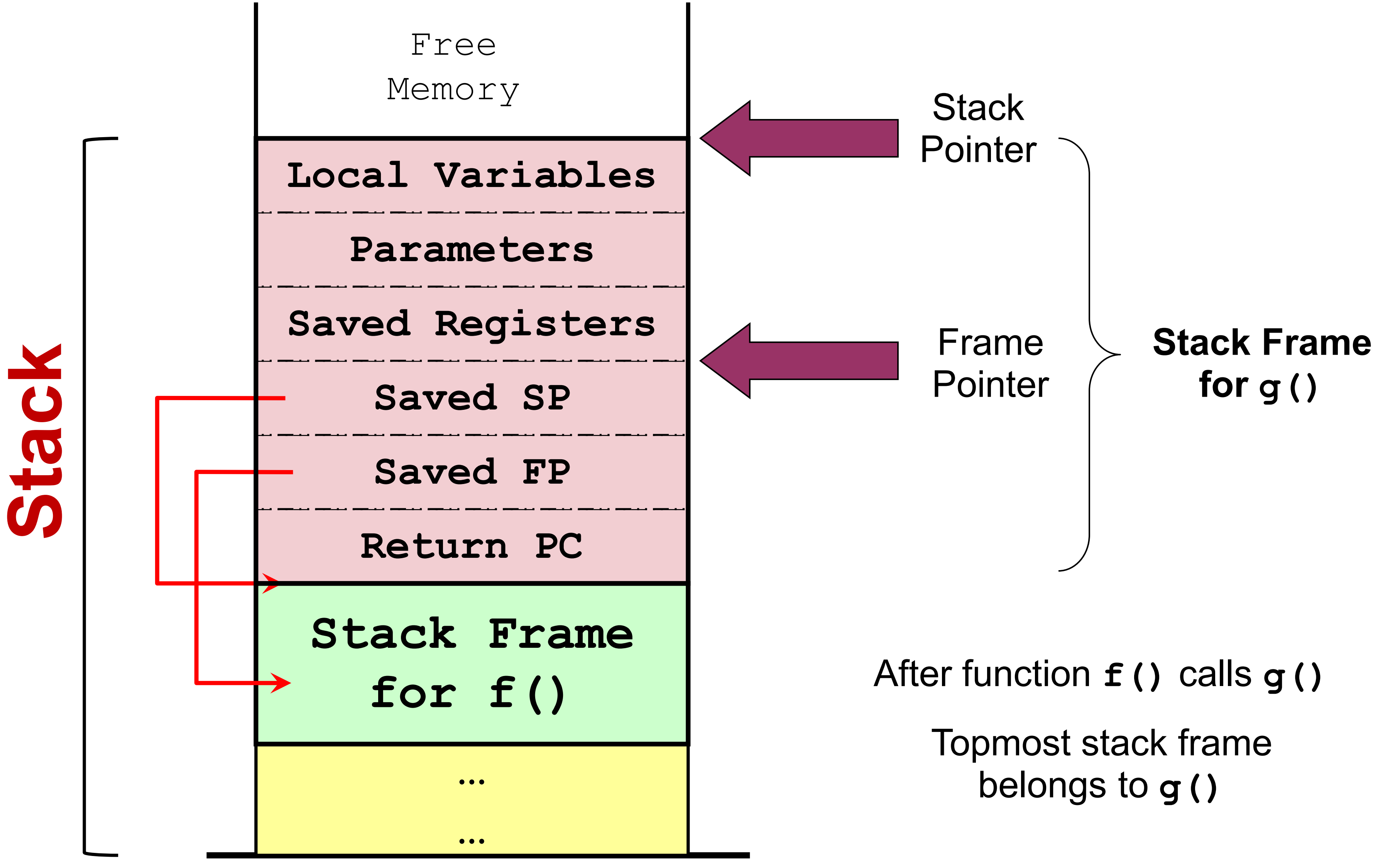
- The frame pointer points to a fixed location in a stack frame
  - Other items are accessed as a displacement from the frame pointer

- The usage of FP is platform dependent

Saved Registers

- The number of general purpose register (GPR) on most processors are very limited:
  - E.g. MIPS has 32 GPRs, x86 has 16 GPRs
- When GPRs are exhausted:
  - Use memory to temporary hold the GPR value
  - That GPR can then be reused for other purpose
  - The GPR value can be restored afterwards
  - known as **register spilling**
- Similarly, a function can spill the registers it intend to use before the function starts
  - Restore those registers at the end of function

Illustration: **Stack Frame v2.0**



After function `f()` calls `g()`

Topmost stack frame belongs to `g()`

Stack Frame Setup / Teardown [Updated]

- On executing function call:
  - **Caller**: Pass arguments with registers and/or stack
  - **Caller**: Save Return PC on stack
  - **Transfer control from caller to callee**
  - **Callee**: Save registers used by callee. Save old FP, SP
  - **Callee**: Allocate space for local variables of callee on stack
  - **Callee**: Adjust SP to point to new stack top

- On returning from function call:
  - **Callee**: Restore saved registers, FP, SP
  - Transfer control from callee to caller using saved PC
  - **Caller**: Continues execution in caller

- Remember, just an example!

Function Call Summary

- In this part, we learned:
  - Another portion of memory space is used as a **Stack Memory**
  - Stack Memory stores the executing function using **Stack Frame**
    - Typical information stored on a stack frame
    - Typical scheme of setting up and tearing down a stack frame
  - The usage of Stack Pointer and Frame Pointer

Memory Context

Dynamically Allocated Memory

Hmm… I need more memory

Dynamically Allocated Memory

- Most programming languages allow dynamically allocated memory:
  - i.e. acquire memory space during **execution time**

- Examples:
  - In C, the ***`malloc()`*** function call
  - In C++, the ***`new`*** keyword
  - In Java, the ***`new`*** keyword

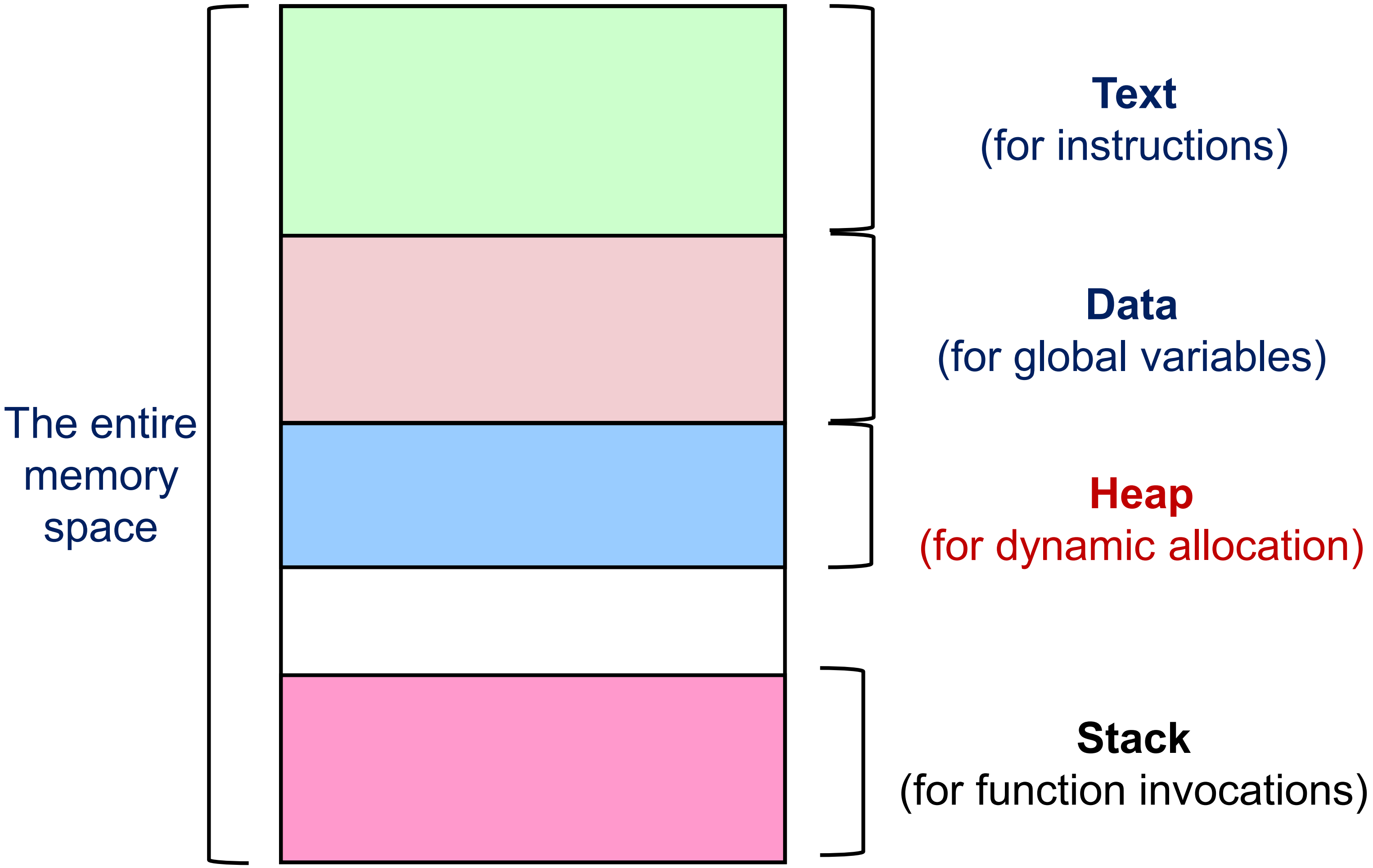
- Question:
  - Can we use the existing "Data" or "Stack" memory regions?

Dynamically Allocated Memory

- Observations:
  - These memory blocks have different behaviors:
    1. Allocated only at runtime, i.e. size is not known during compilation time ➔ Cannot place in **Data** region
    2. No definite deallocation timing, e.g. can be explicitly freed by programmer in C/C++, can be implicitly freed by garbage collector in Java ➔ Cannot place in **Stack** region

- Solution:
  - Setup a separate **heap memory region**

Illustration for **Heap Memory**



Managing Heap Memory

- Heap memory is a lot trickier to manage due to its nature:
  - Variable size
  - Variable allocation / deallocation timing
- You can easily construct a scenario where heap memory are allocated /deallocated in such a way to create "holes" in the memory
  - Free memory block squeezed in between of occupied memory block
- We will learn more in the memory management (much) later in the course

Checkpoint: Contexts updated

- Information describing a **process**:
  - Memory context:
    - Text, Data, **Stack** and **Heap**
  - Hardware context:
    - General purpose registers, Program Counter, **Stack pointer, Stack frame pointer,** ….

OS Context

Process Id & Process State

Your ID? Give me a status report!

Process Identification

- To distinguish processes from each other
  - Common approach is to use process ID (**PID**)
    - Just a number
  - Unique among processes

- There are a couple of OS dependent issues:
  - Are PIDs reused?
  - Does it limit the maximum no. of processes?
  - Are there reserved PIDs?

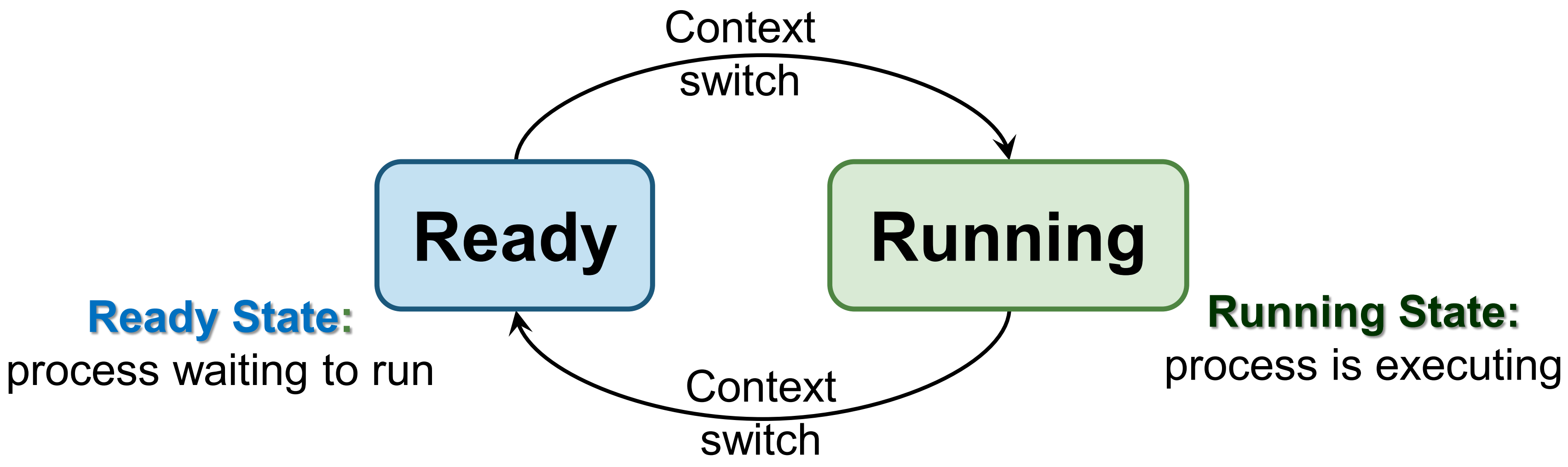
Introducing Process State

- With the multi-process scenario:
  - A process can be:
    - Running OR
    - Not-running, eg. another process running

- A process can be ready to run
  - But not actually executing
  - E.g. waiting for its turn to use the CPU

- Hence, each process should have a **process state**:
  - As an indication of the execution status

(Simple) Process Model State Diagram

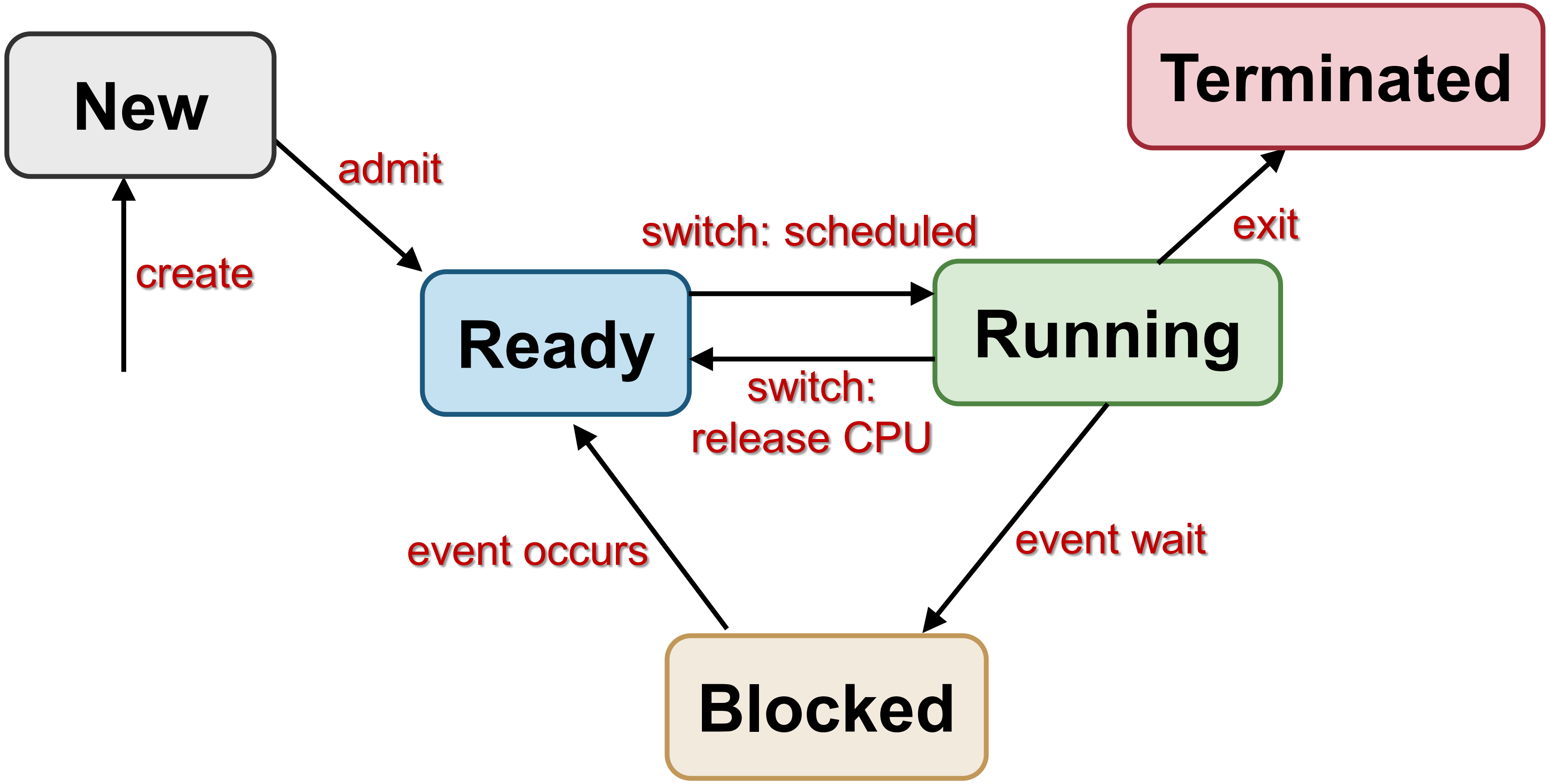


Ready State: process waiting to run

Running State: process is executing

- The set of states and transitions are known as **process model**
  - Describes the behaviors of a process

Generic 5-State Process Model



Notes: generic process states, details vary in actual OS

Process States for 5-Stage Model

- **New**:
  - New process created
  - May still be under initialization ➔ not yet ready
- **Ready**:
  - process is waiting to run
- **Running**:
  - Process being executed on CPU
- **Blocked**:
  - Process waiting (sleeping) for event
  - Cannot execute until event is available
- **Terminated**:
  - Process has finished execution, may require OS cleanup

Process State Transitions in 5-Stage Model

- Create (nil → New):
  - New process is created
- Admit (New → Ready):
  - Process ready to be scheduled for running
- Switch (Ready → Running):
  - Process selected to run
- Switch (Running → Ready):
  - Process gives up CPU voluntarily or *preempted* by scheduler

Process State Transitions

- Event wait (Running → Blocked):
  - Process requests event/resource/service which is not available/in progress
  - Example events:
    - System call, waiting for I/O, *(more later)*

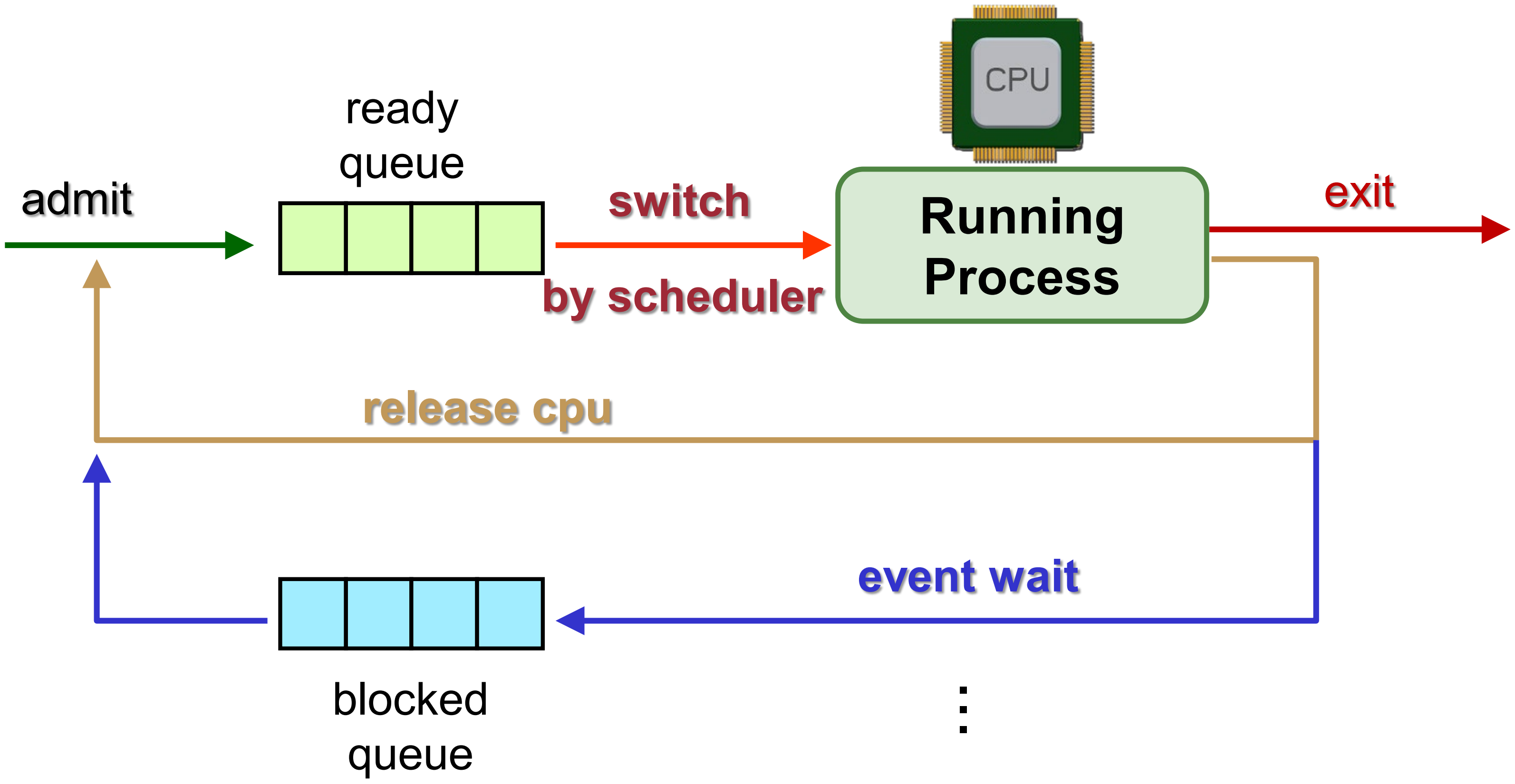
- Event occurs (Blocked → Ready):
  - Event occurs ➔ process can continue

Global View of Process States

- Given n processes:
  - With 1 CPU:
    - $\leq$ 1 process in running state
    - conceptually 1 transition at a time
  - With m CPUs:
    - $\leq$ m process in running state
    - possibly parallel transitions

- Different processes may be in different states
  - each process may be in different part of its state diagram

Queuing Model of 5 state transition



Notes:

- More than 1 process can be in ready + blocked queues
- May have separate event queues
- Queuing model gives global view of the processes, i.e. how the OS views them

Checkpoint: Contexts updated

- When a program is **under execution**, there are **more information**:
  - Memory context:
    - Text and Data, Stack and Heap
  - Hardware context:
    - General purpose registers, Program Counter, Stack pointer, Stack frame pointer, …
  - **OS context:**
    - **Process ID, Process State, …**

Process Table & Process Control Block

Putting it together

Process Control Block & Table

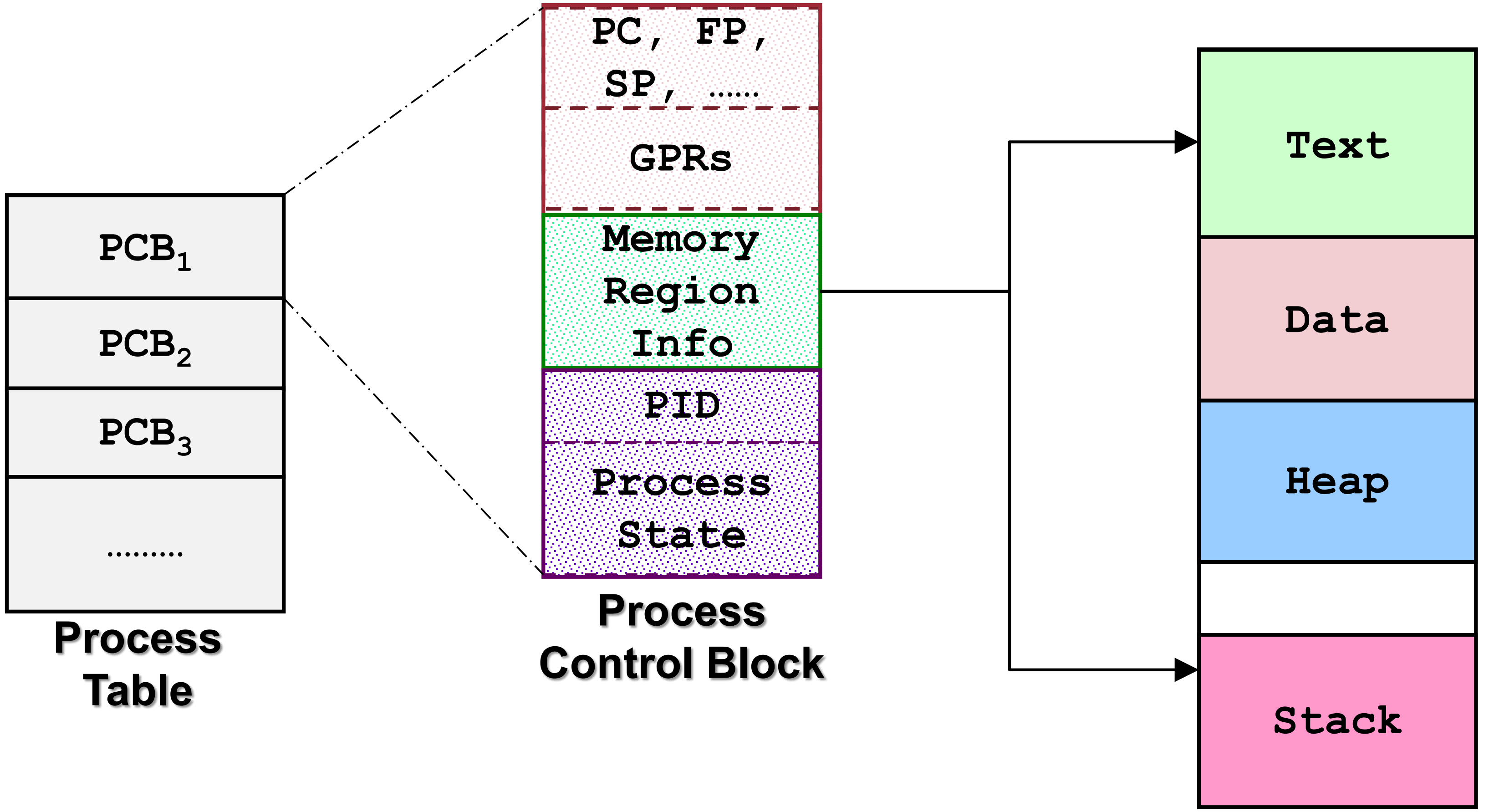
- The entire execution context for a process
  - Traditionally called **P**rocess **C**ontrol **B**lock (PCB) or **P**rocess **T**able **E**ntry

- Kernel maintains PCB for all processes
  - Conceptually stored as one table representing all processes

Interesting Issues:

- Scalability
  - How many concurrent processes can you have?
- Efficiency
  - Should provide efficient access with minimum space wastage

Illustration of a Process Table



Process Table

Process Control Block

Memory Space of a Process

Process interaction with OS

System Calls

Can you please do this for me?

System Calls

- Application Program Interface (API) to OS
  - Provides way of calling facilities/services in kernel
  - **NOT** the same as normal function call
    - have to change from user mode to kernel mode

- Different OS have different APIs:
  - Unix Variants:
    - Most follows **POSIX** standards
    - Small number of calls: ~100
  - Windows Family:
    - Uses **Win API** across different Windows versions
    - New version of windows usually adds more calls
    - Huge number of calls:~1000

Unix System Calls in C/C++ program

- In C/C++ program, system call can be invoked *almost directly*
  - Majority of the system calls have a library version with the **same name** and the same parameters
    - The library version act as a **function wrapper**
  - Other than that, a few library functions present a more user friendly version to the programmer
    - E.g. lesser number of parameters, more flexible parameter values etc
    - The library version acts as a **function adapter**

Example

```c
#include <unistd.h>
#include <stdio.h>

int main()
{
      int pid;

      /* get Process ID */
      pid = getpid();

      printf("process id = %d\n", pid);

      return 0;
}
```

Library call that has the same name as a system call

Library call that make a system call

- System Calls invoked in this example:
  - **`getpid()`**
  - **`write()`** – made by **`printf()`** library call

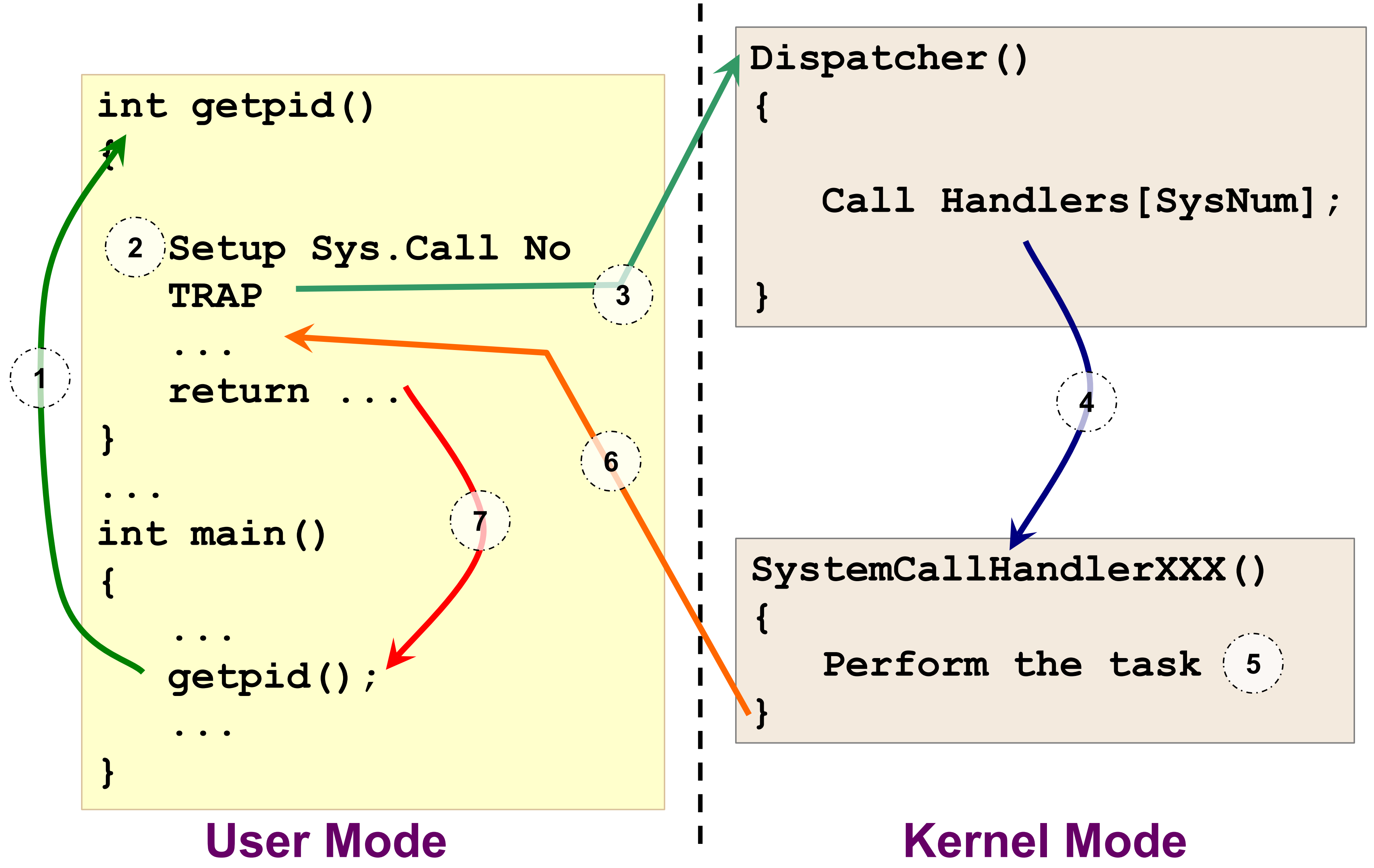
General System Call Mechanism

1. User program invokes the library call
   - Using the normal function call mechanism as discussed
2. Library call (usually in assembly code) places the **system call number** in a designated location
   - E.g. Register
3. Library call executes a special instruction to switch from user mode to kernel mode
   - That instruction is commonly known as **TRAP**

General System Call Mechanism (cont)

4. Now in kernel mode, the appropriate system call handler is determined:
   - Using the system call number as index
   - This step is usually handled by a **dispatcher**
5. System call handler is executed:
   - Carry out the actual request
6. System call handler ended:
   - Control return to the library call
   - Switch from kernel mode to user mode
7. Library call return to the user program:
   - via normal function return mechanism

Illustration: **System Call Mechanism**



```
int getpid()
{

    Setup Sys.Call No
    TRAP
    ...
    return ...
}
...
int main()
{
    ...
    getpid();
    ...
}
```

```
Dispatcher()
{

    Call Handlers[SysNum];

}
```

```
SystemCallHandlerXXX()
{
    Perform the task
}
```

Process interaction with OS

Exception and Interrupt

Ops!

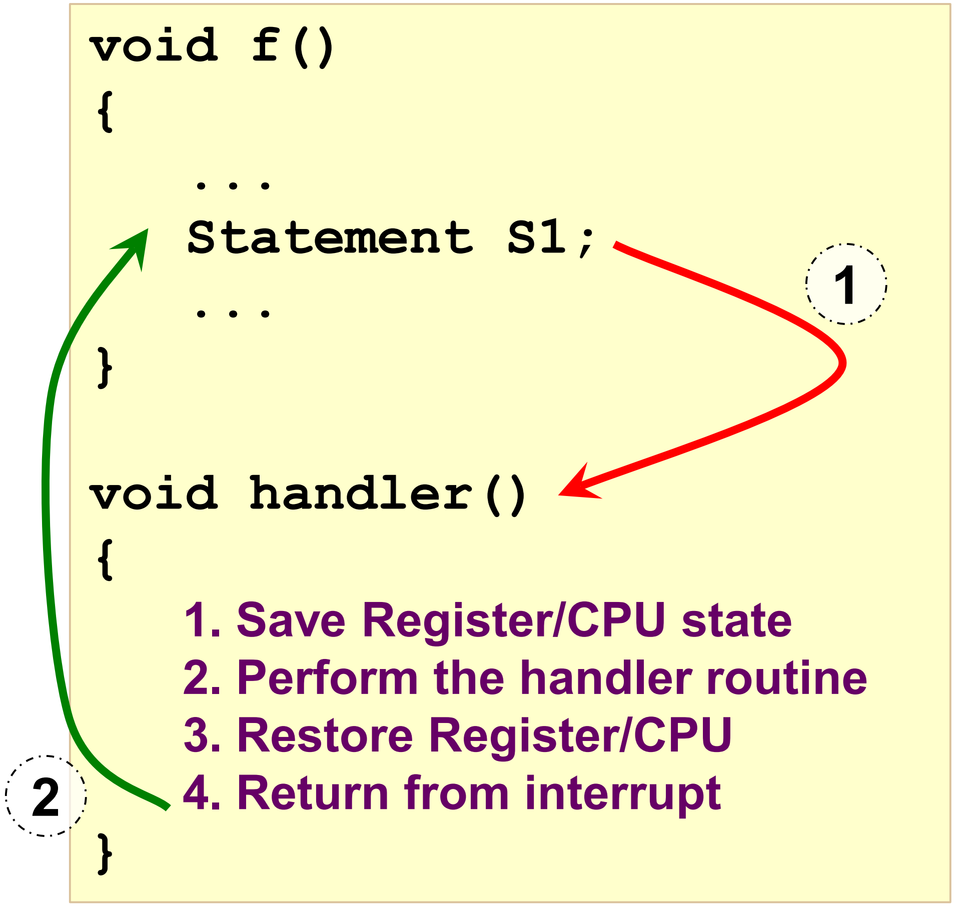
Exception

- Executing a **machine level instruction** can cause exception
- For example:
  - Arithmetic Errors
    - Overflow, Underflow, Division by Zero
  - Memory Accessing Errors
    - Illegal memory address, Mis-aligned memory access
  - Etc
- Exception is **Synchronous**
  - occur due to program execution
- Effect of exception:
  - Have to execute a **exception handler**
  - Similar to a **forced function call**

Interrupt

- External events can interrupt the execution of a program
- Usually hardware related, e.g.:
  - Timer, Mouse Movement, Keyboard Pressed etc
- Interrupt is **asynchronous**
  - Events that occurs **independent** of program execution
- Effect of interrupt:
  - Program execution is suspended
  - Have to execute an **interrupt handler**

Exception/Interrupt Handler: Illustration



```
void f()
{
    ...
    Statement S1;
    ...
}

void handler()
{
    1. Save Register/CPU state
    2. Perform the handler routine
    3. Restore Register/CPU
    4. Return from interrupt
}
```

1. Exception/Interrupt occurs:
   - Control transfer to a handler routine **automatically**
2. Return from handler routine:
   - Program execution resume
   - **May** behave as if nothing happened

Summary

- Using process as an abstraction of running program:
  - Necessary information (environment) of execution
  - Memory, Hardware and OS contexts

- Process from OS perspective:
  - PCB and process table

- OS ← → Process interactions
  - System calls
  - Exception / Interrupt

References

- Modern Operating System (3rd Edition)
  - Section 2.1
- Operating System Concepts (8th Edition)
  - Section 3.1