Process Management

Process Abstraction

Lecture 2

Overview

- Program execution:
  - Hardware context
  - Memory context
    - Code & data
    - Function call
    - Dynamically allocated memory
- Introduction to process management
  - OS context
    - Process state
  - Process Control Block and Process Table
- OS interaction with process

Recap: C Sample Program and Assembly Code

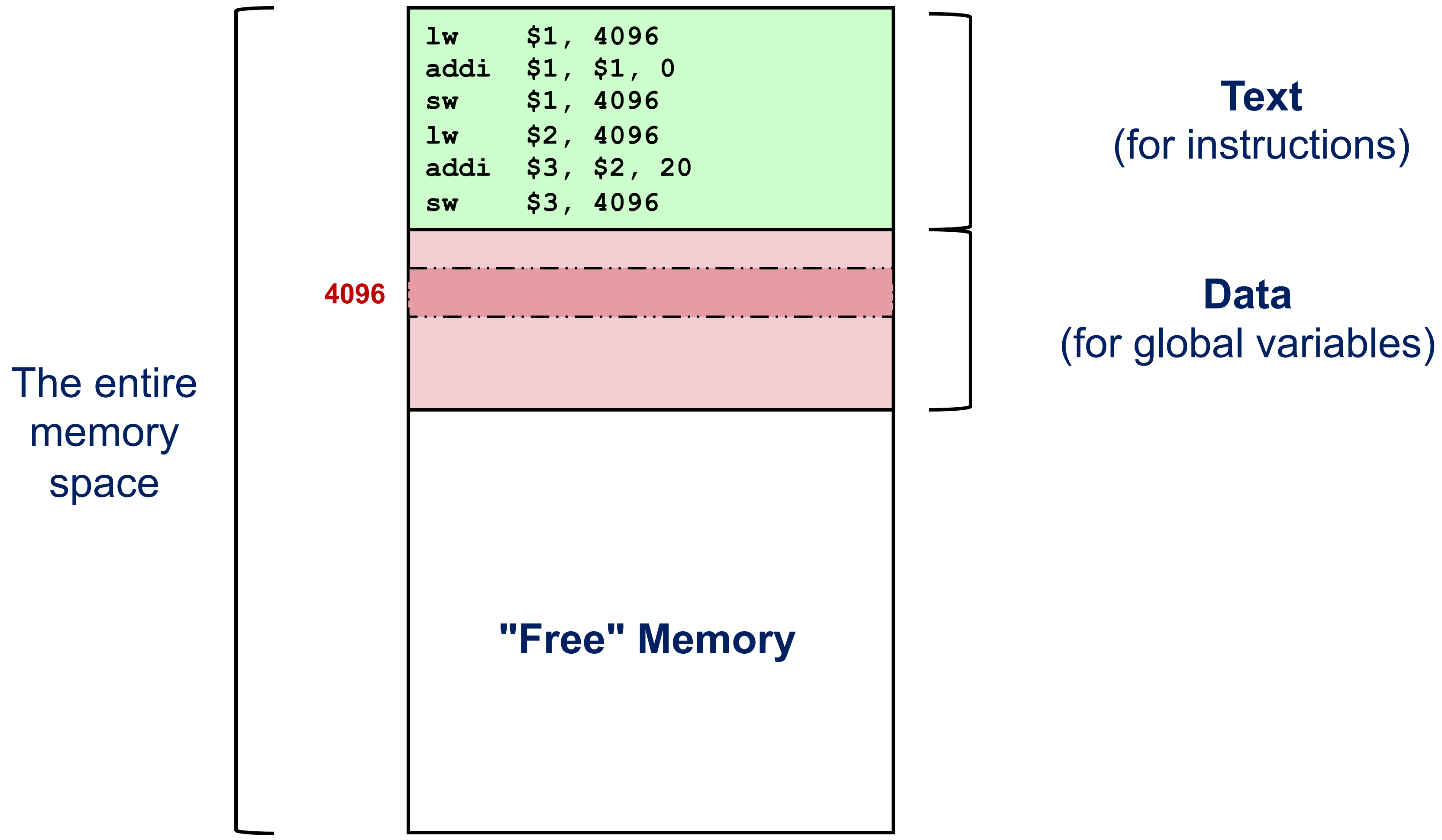
```c
int i = 0;

i = i + 20;
```

C Code Fragment

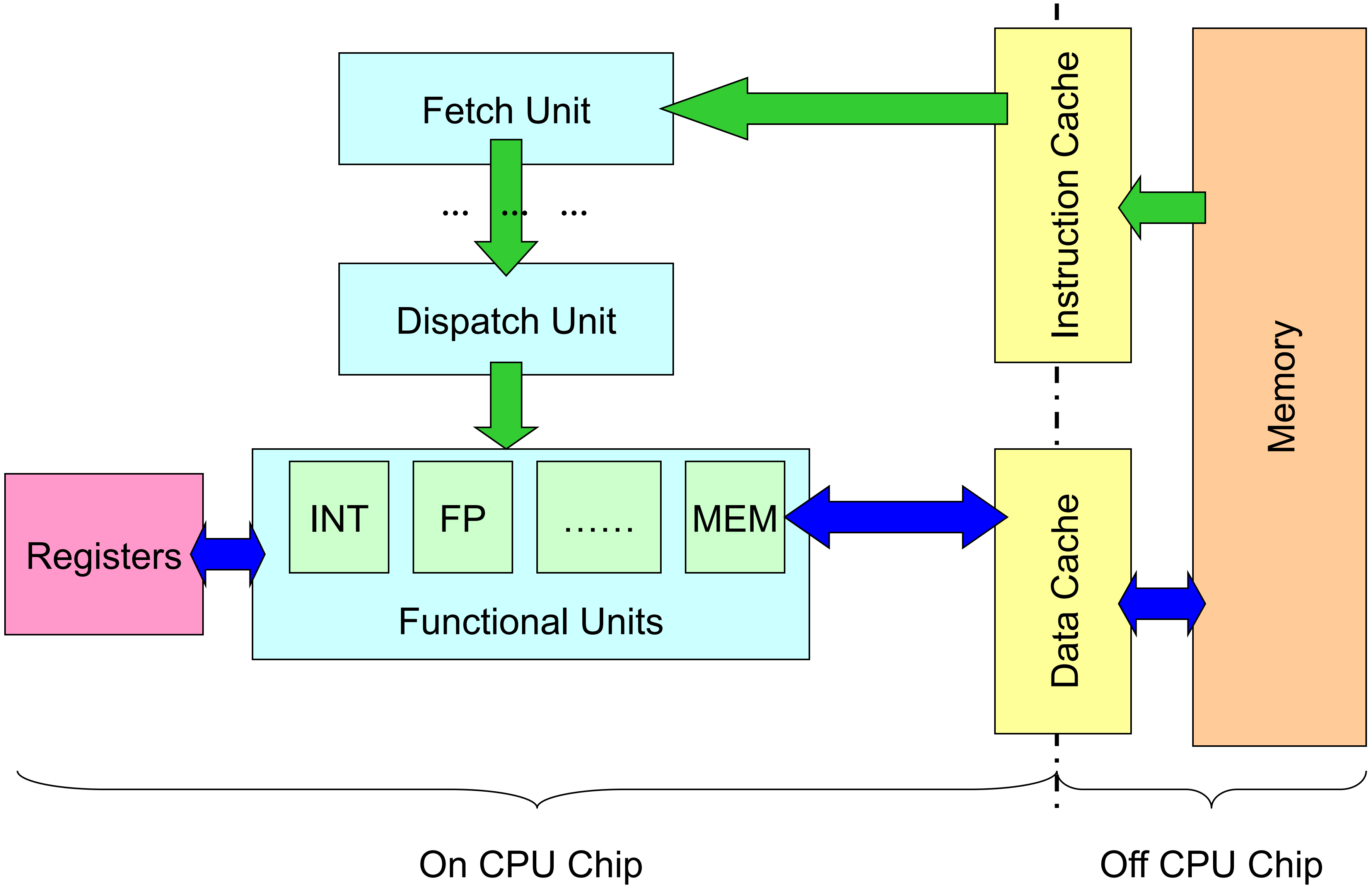
```
lw     $1, 4096            // Assume address of i = 4096
addi   $1, $0, 0           // register $1 = 0
sw     $1, 4096            // i = 0

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)



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
  - Special Register:
    - Program Counter (PC)
    - Stack Pointer (SP)
    - Frame Pointer (FP)
    - ...

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);      1
    ....
}                          2
                5
int g(int i, int j)
{
    int a;   3

    ......
    return ...;   4
}
```

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 for 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**

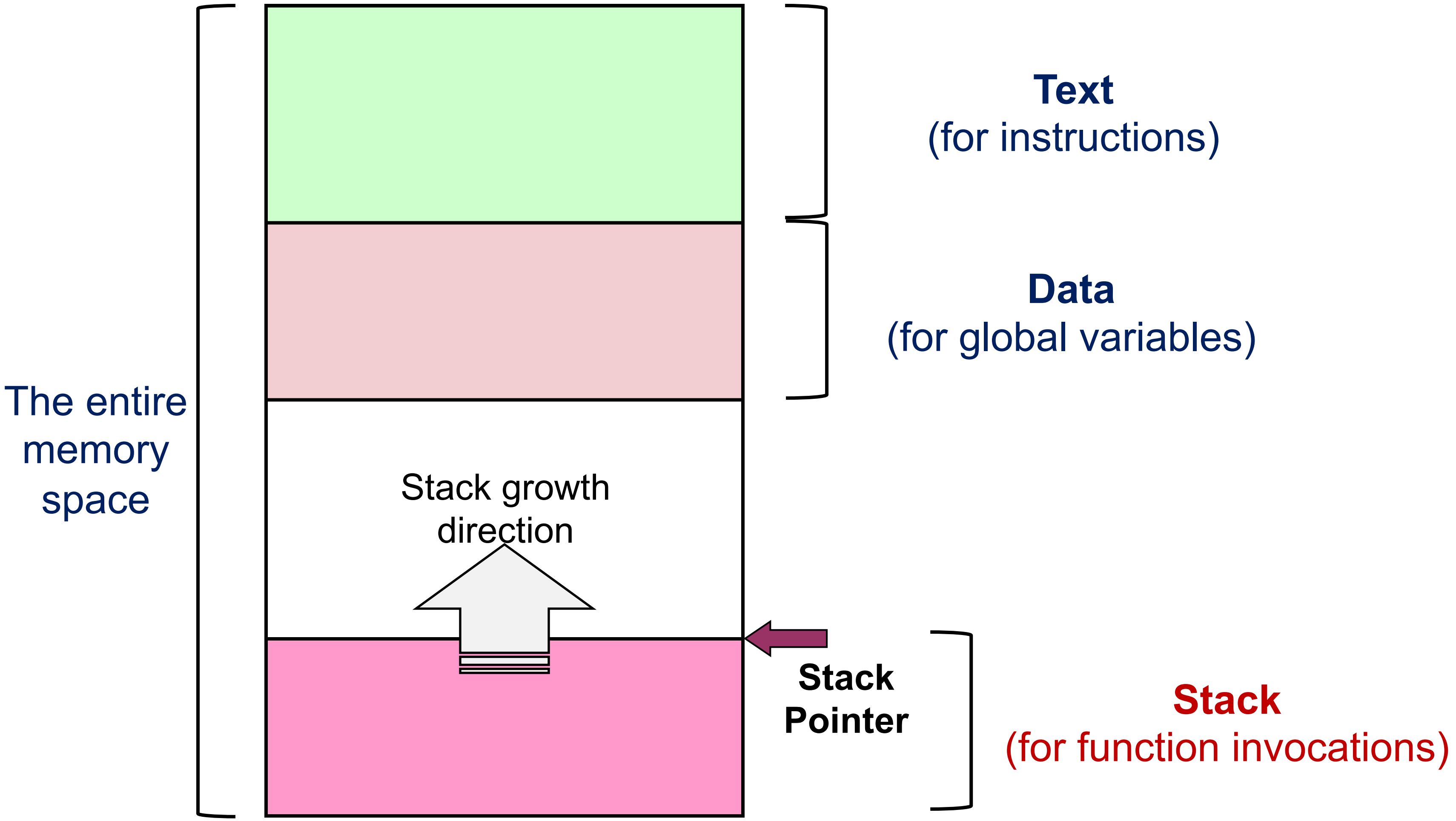


Illustration: **Stack Memory Usage** (1 / 5)

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

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

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

At this point

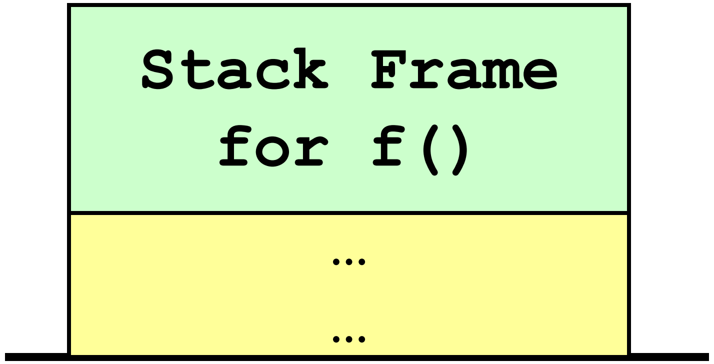


Illustration: **Stack Memory Usage** (2 / 5)

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

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

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

At this point

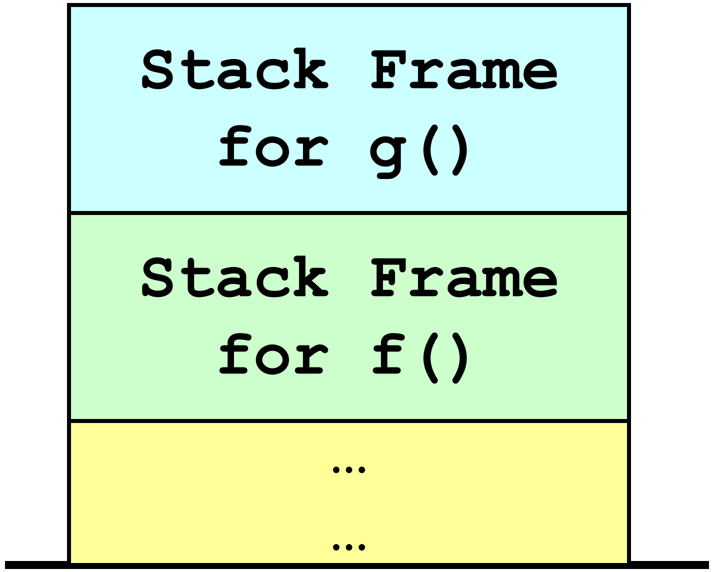


Illustration: **Stack Memory Usage** (3 / 5)

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

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

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

At this point

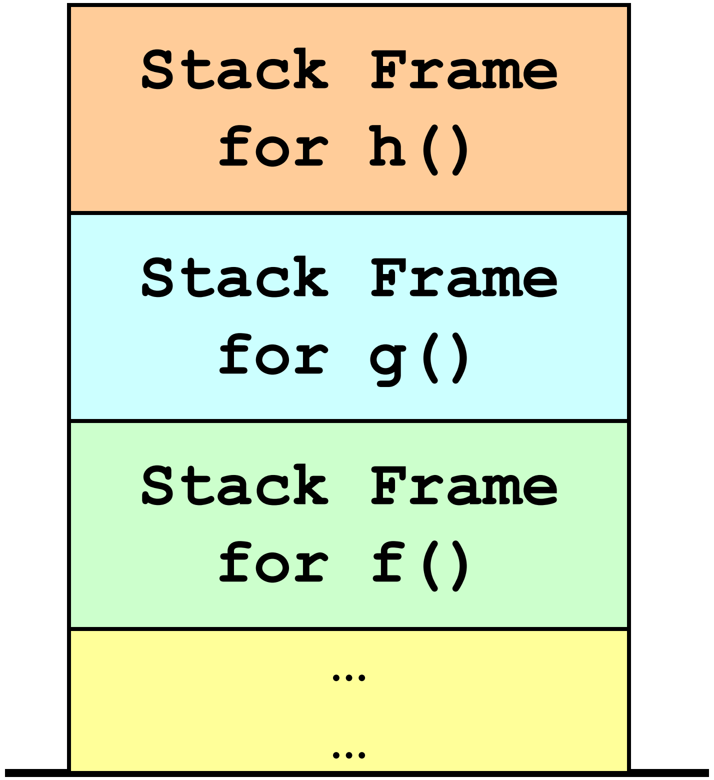


Illustration: **Stack Memory Usage** (4 / 5)

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

void g()
{
    h();
    ...      <- At this point
}

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

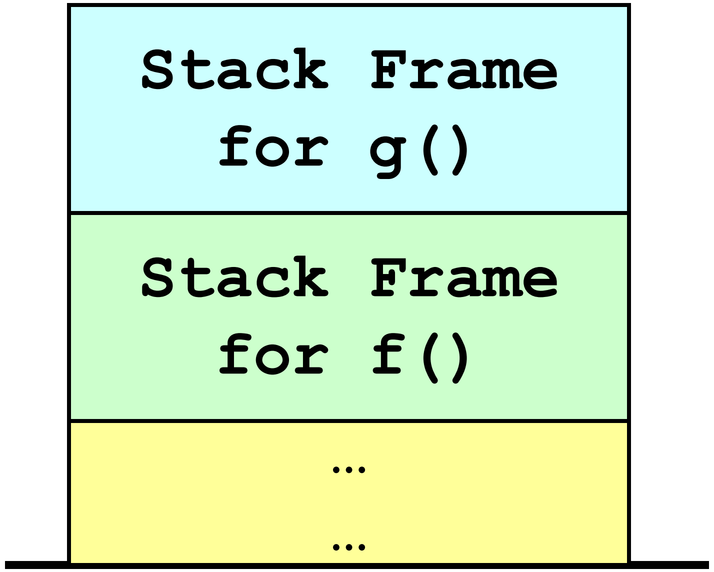


Illustration: **Stack Memory Usage** (5 / 5)

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

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

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

At this point

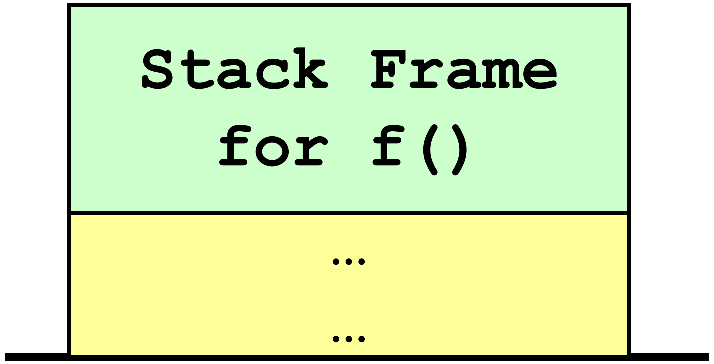
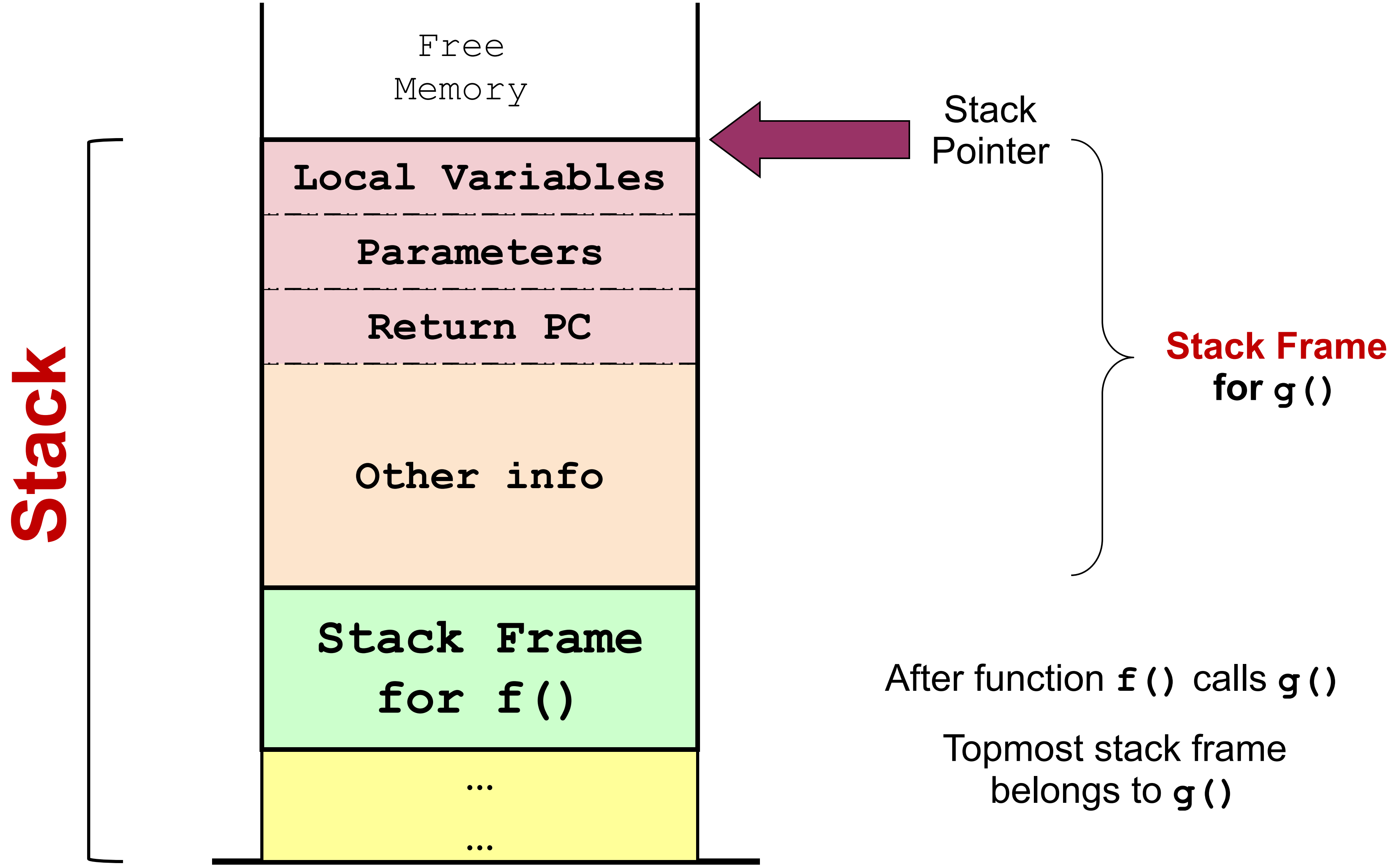


Illustration: **Stack Frame v1.0**



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 vs. in 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

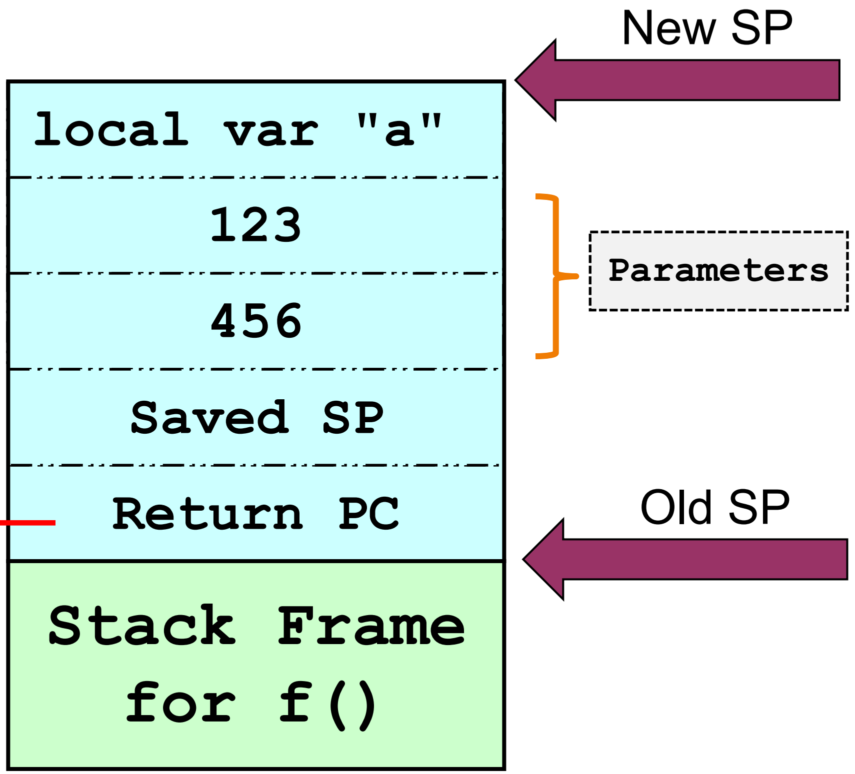
Stack Frame Setup

`Local Variable`
`Parameters`
`Saved SP`
`Return PC`

- Prepare to make a function call:
  - **Caller**: Pass parameters using 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

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;
}
```



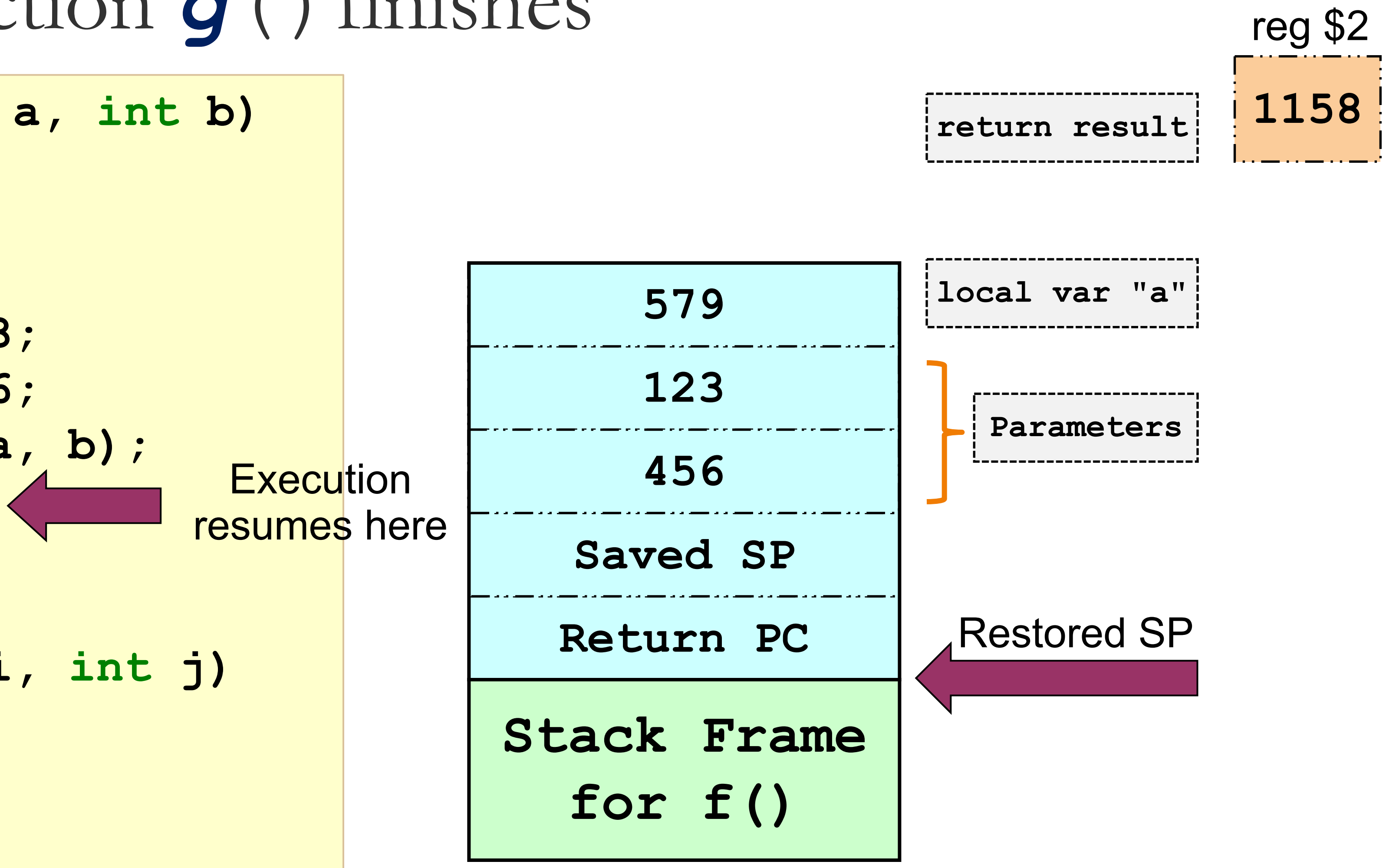
Stack Frame Teardown

Local Variable
Parameters
Saved SP
Return PC

- On returning from function call:
  - **Callee:** Place return result in register (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;
}
```



Other Information in Stack Frame

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

- A few common additional information in the stack frame:
  - Frame Pointer
  - Saved Registers

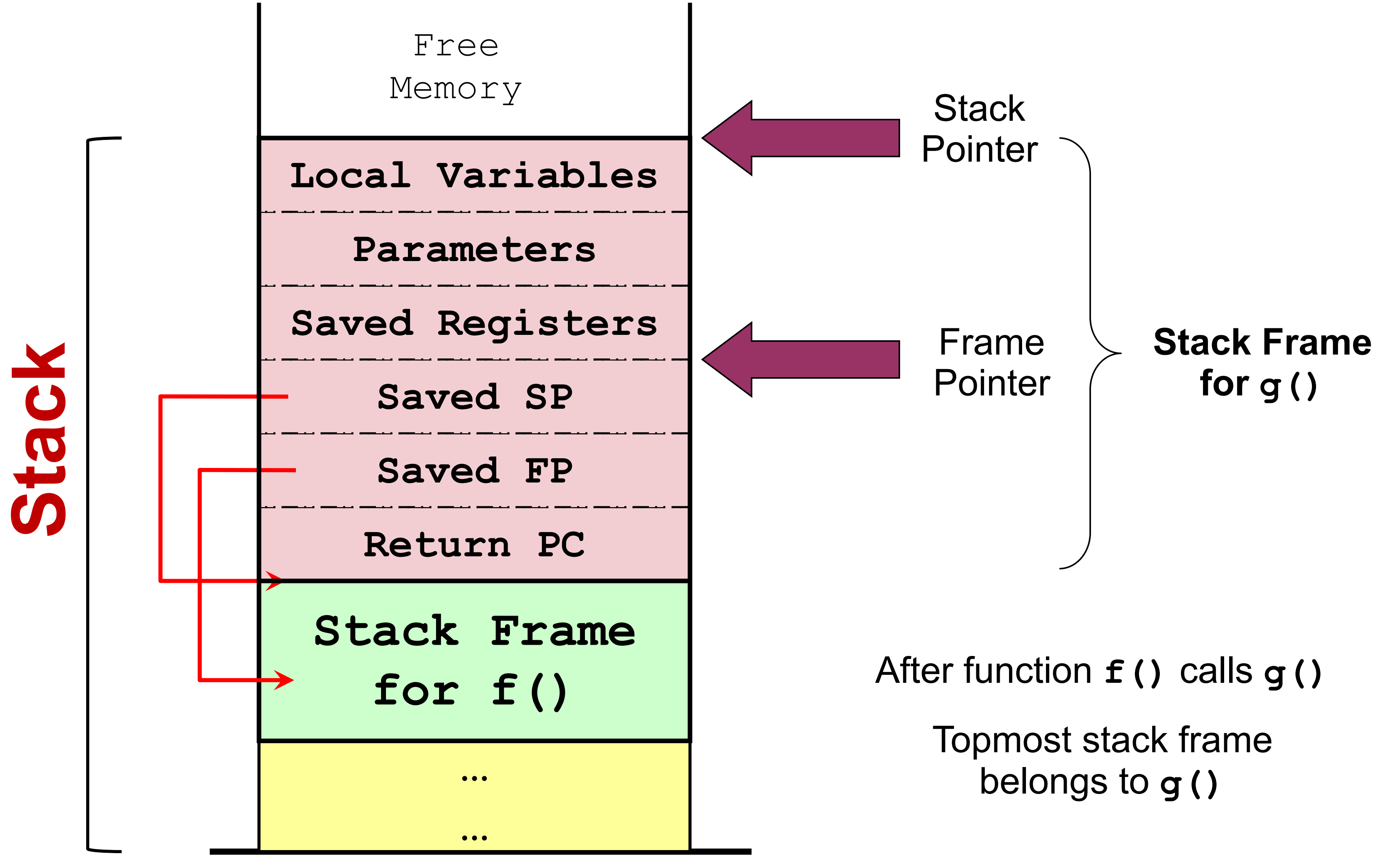
Frame Pointer

- 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
  - GPR can then be reused for other purposes
  - 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 (callee-saved)
  - 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; adjust FP

- 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

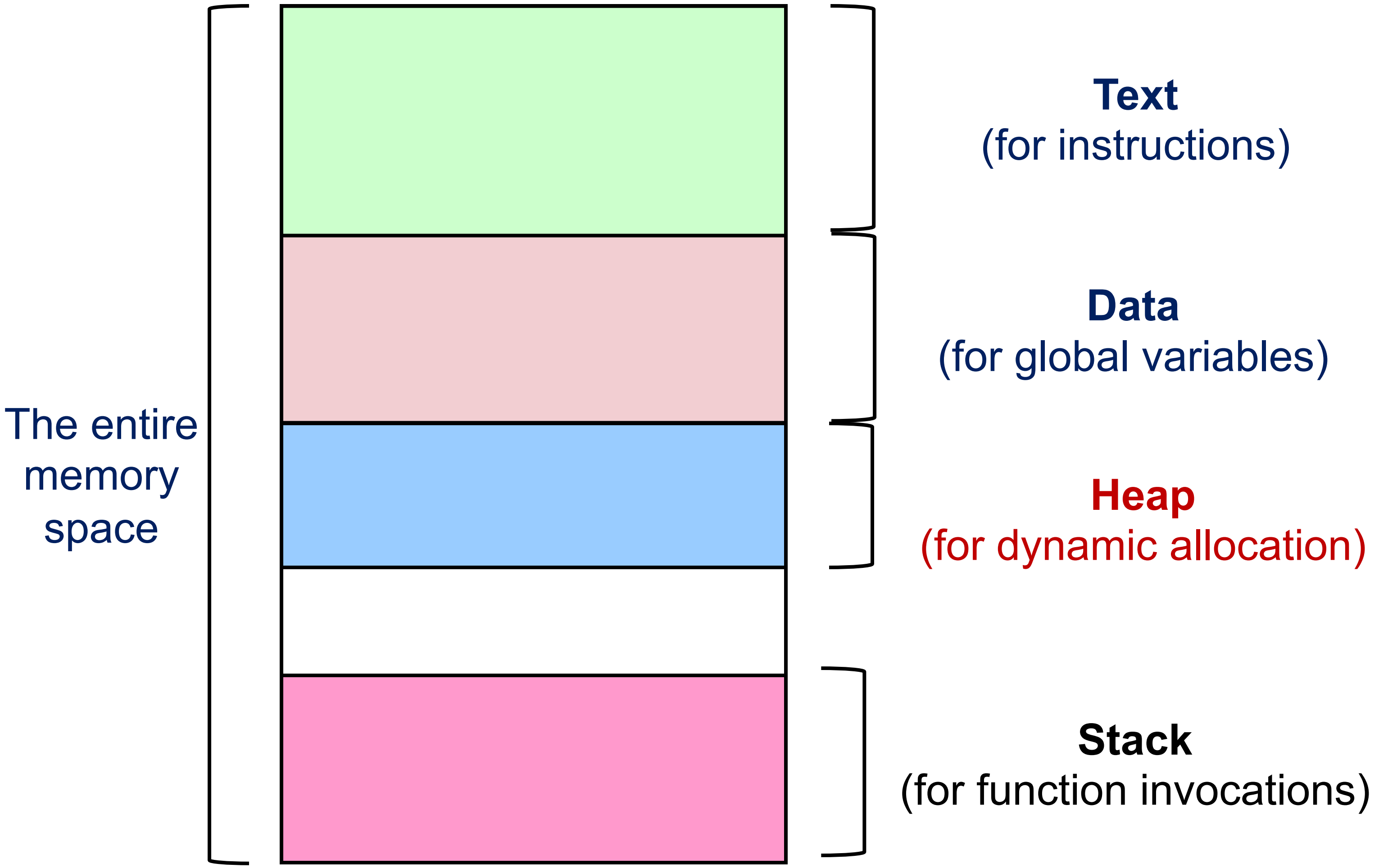
- Question:
  - Can we use the existing "Data" or "Stack" memory regions?

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 **program execution**:

  - Memory context:
    - Text, Data, **Stack** and **Heap**

  - Hardware context:
    - General purpose registers, Program Counter, **Stack pointer, Stack frame pointer,** ….

Overview

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

Recap: **Efficient Hardware Utilization**

- OS should provide efficient use of hardware resources:
  - 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?
    - Batch processing?
- Solution:
  - Allow **multiple programs to share the hardware**
    - e.g., multiprogramming, time-sharing

Introduction to Process Management

- As the OS, 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
- **Stack**
- **Heap**

Hardware Context
- Registers
- PC
- **Stack pointer**
- **Stack frame pointer**
- ….

OS Context
- Process Properties
- Resources used
- ...

OS Context

Process Id & Process State

Your ID? Give me a status report!

Process Identification

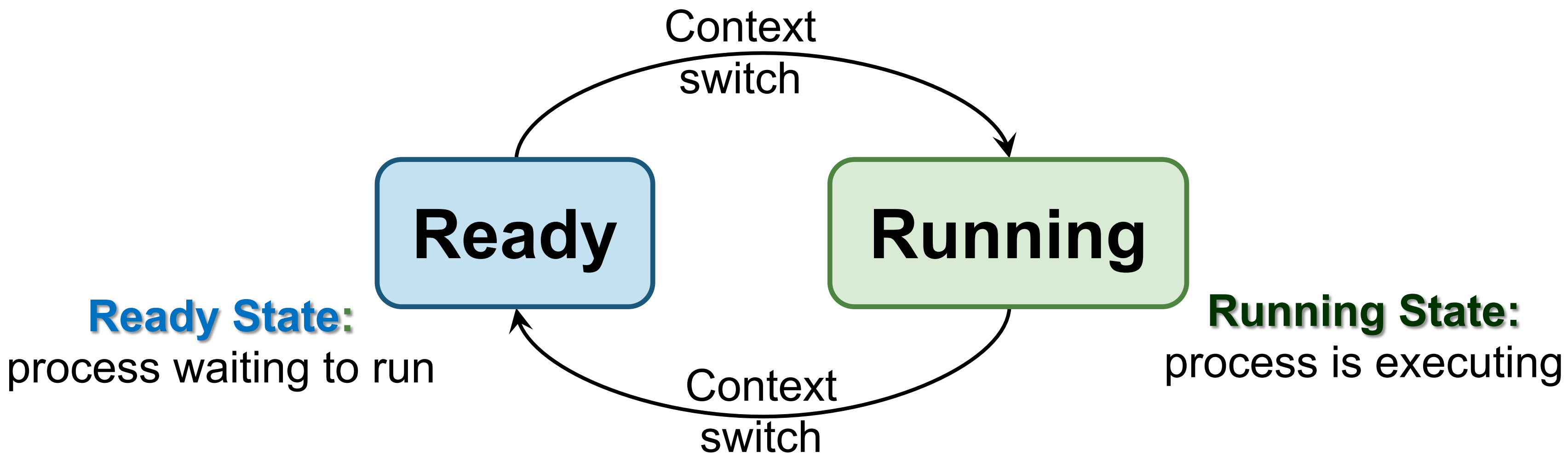
- To distinguish processes from each other
  - Common approach is to use process ID (**PID**)
    - Just a number
  - Unique among processes

- 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

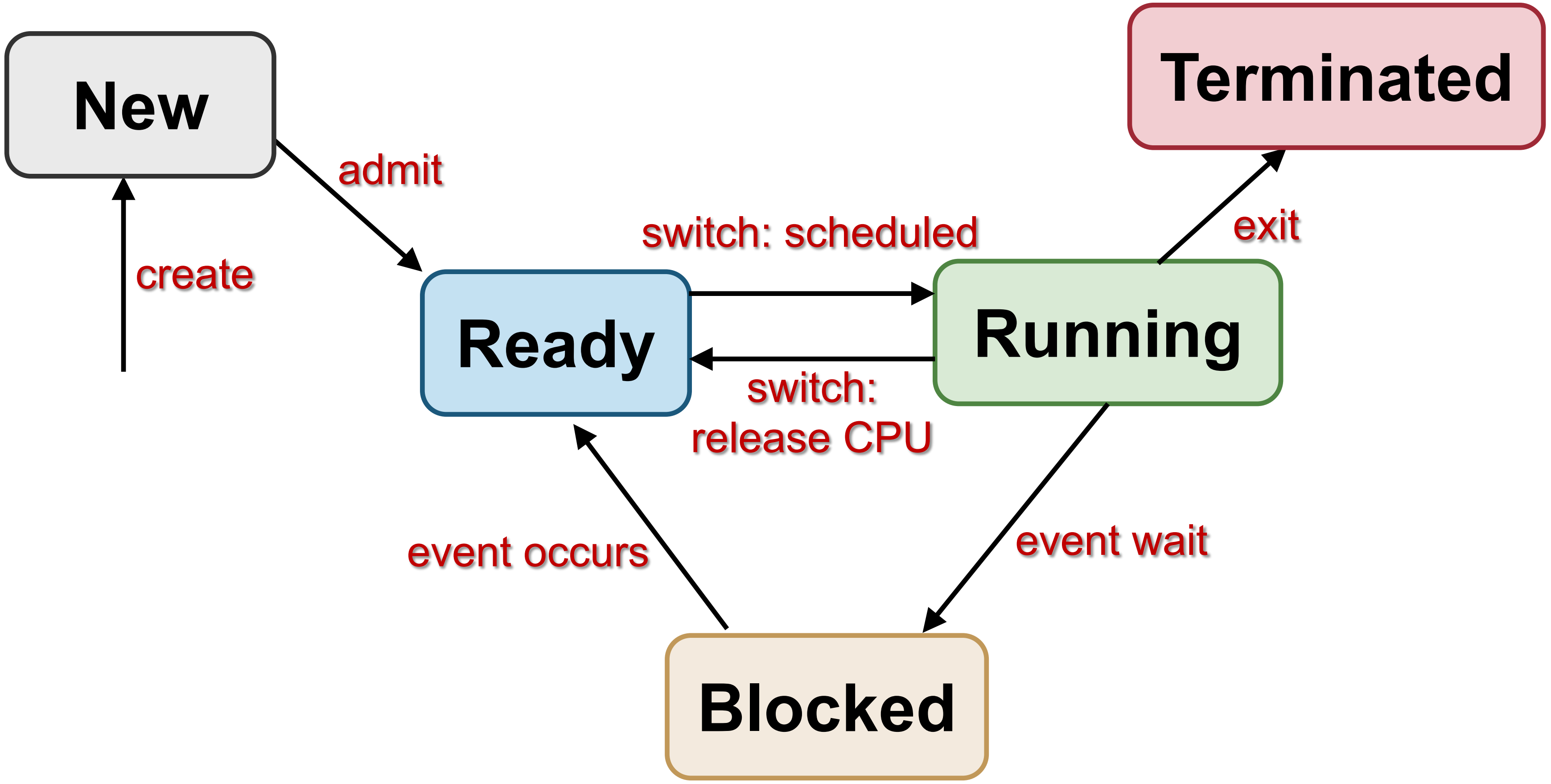
- In the multitasking scenario:
  - A process can be:
    - Running OR
    - Not-running, e.g., another process running
- A process can be ready to run
  - But not actually executing
  - E.g., waiting for its turn to use the CPU
- Hence, each process should have a **process state**:
  - As an indication of the execution status

(Simple) Process Model State Diagram



- 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:
    - Acquiring lock, waiting for I/O, *(more later)*

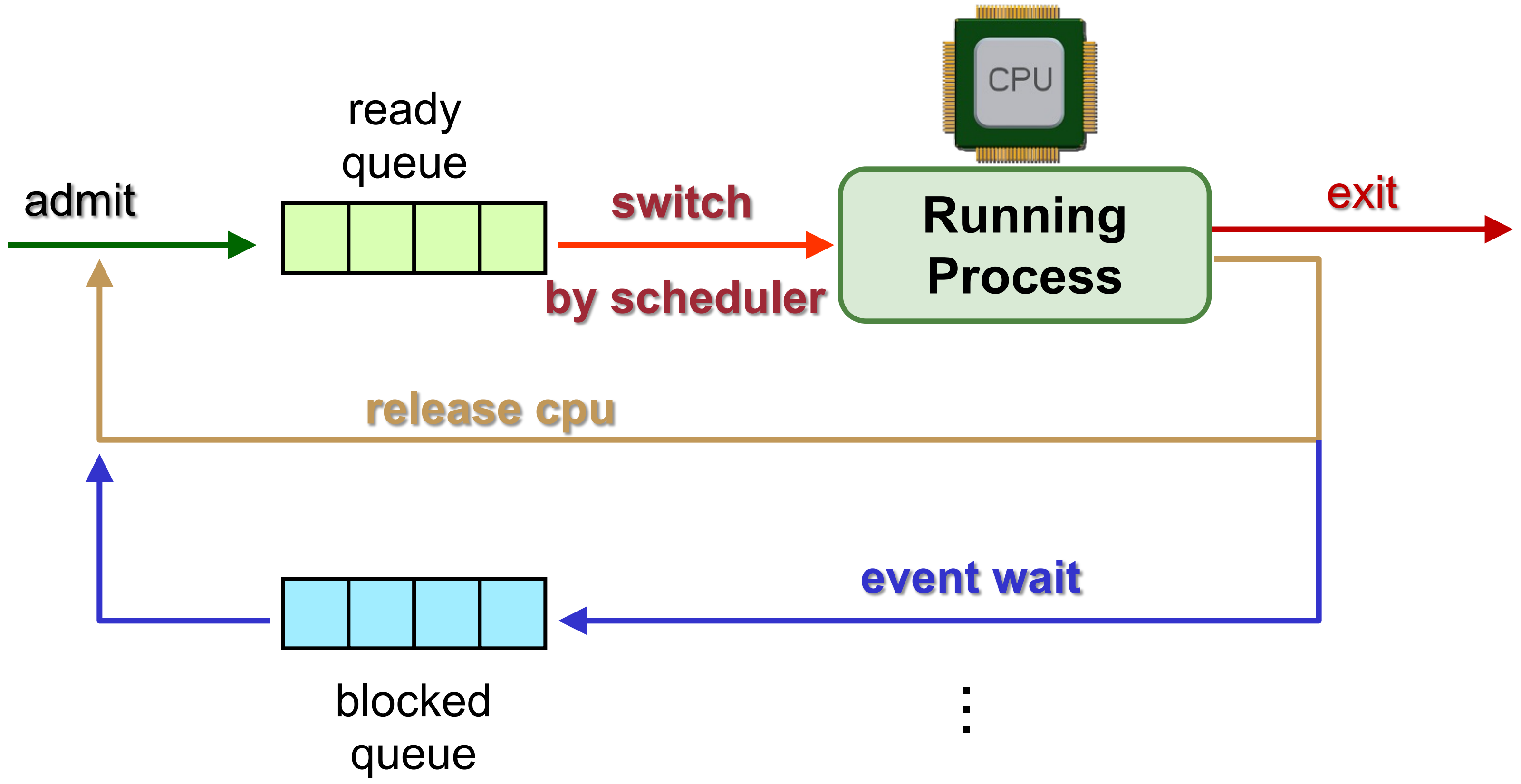
- Event occurs (Blocked → Ready):
  - Event occurs ➔ process can continue

Global View of Process States

- Given n processes:
  - With 1 CPU (core):
    - $\leq$ 1 process in running state
    - conceptually 1 transition at a time
  - With m CPUs (cores):
    - $\leq$ 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
- **Assumption in CS2106: Our CPU has 1 core!**

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, Frame Pointer, …

  - **OS context:**
    - **Process ID, Process State, …**

Process Table & Process Control Block

Putting it together

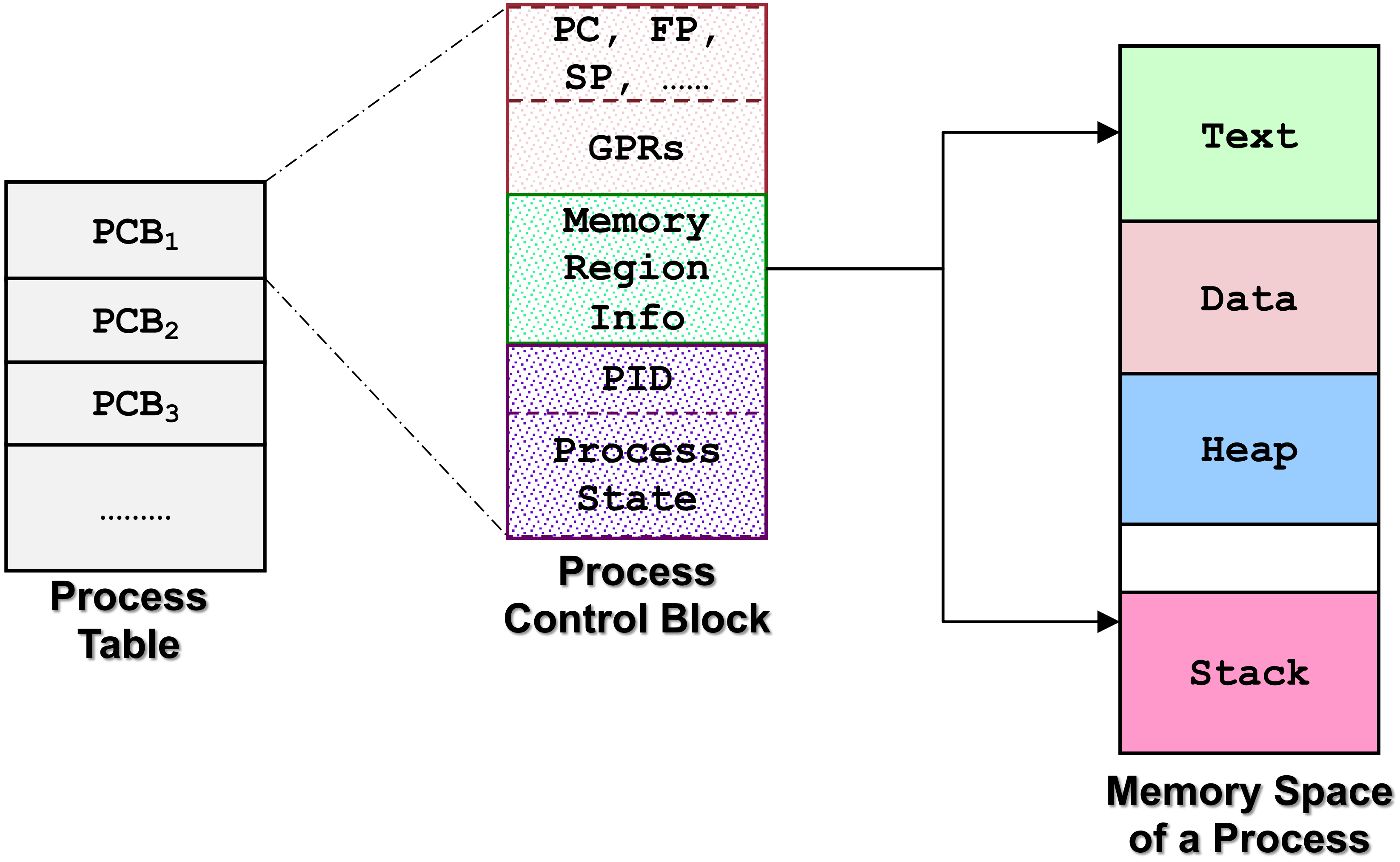
Process Control Block & Table

- 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 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

```
#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

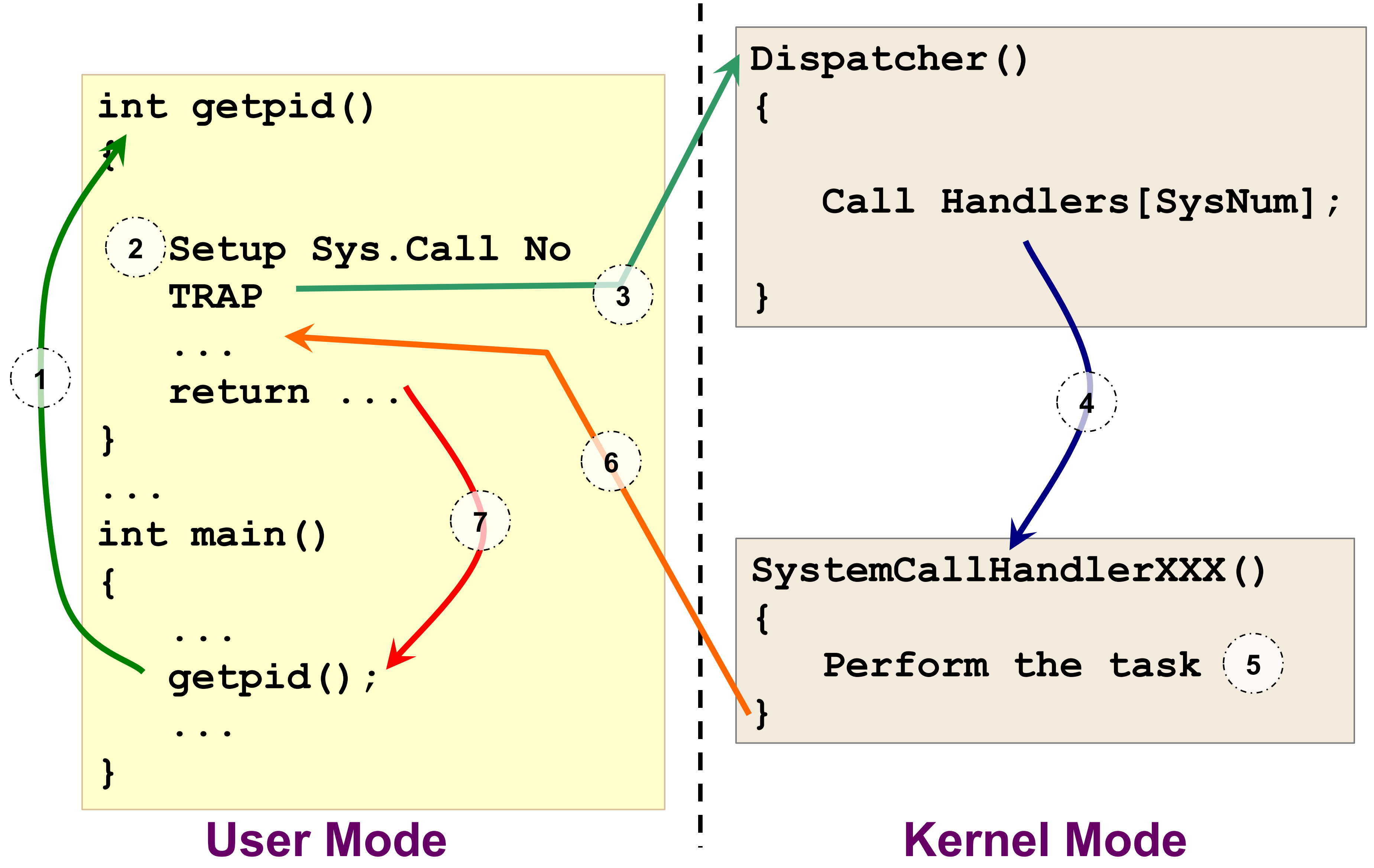
General System Call Mechanism

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., a register
3. Library call executes a special instruction to switch from user mode to kernel mode
   - That instruction is commonly known as **TRAP**
   - Saves CPU state

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:
   - Restore CPU state, and 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**



Process interaction with OS

Exception and Interrupt

Ops!

Exception

- Executing a **machine level instruction** can cause exception
- For example:
  - Arithmetic Errors
    - Overflow, Division by Zero
  - Memory Accessing Errors
    - Illegal memory address, Misaligned memory access
  - ...
- Exception is **Synchronous**
  - occur due to program execution
- Effect of exception:
  - Have to execute an **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;          1
    ...
}

void handler()
{
    1. Save Register/CPU state
    2. Perform the handler routine
    3. Restore Register/CPU
2   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