Embedded Systems

Embedded RTOS System Startup

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Embedded applications

- Developing a "Hello World" application on an embedded system is not trivial
  - As compared with developing in a PC platform
- First, we must to understand *how to boot the target system*, i.e., the *booting process*
  - How to load the image onto the target system?
  - Where in memory to load the image?
  - How to initiate program execution?
  - How the program produces recognizable output?

Typical Cross-Platform Development Environment

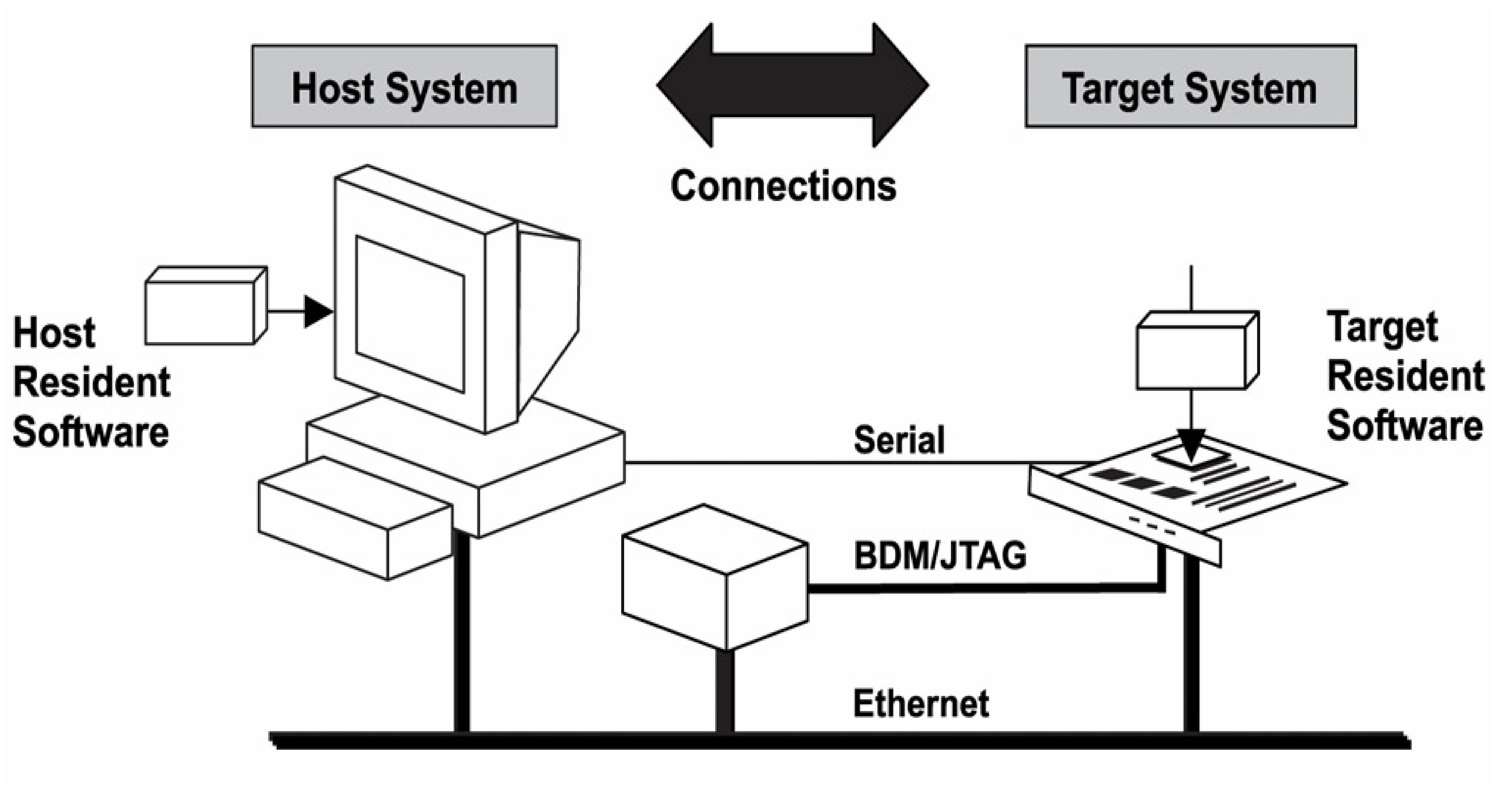

Image Transfer from the Host to the Target System (1/3)

- Loading process: transfer an executable image from the host onto the target
- Three approaches
  - Programming the image into EEPROM or flash
  - Downloading the image over a serial (RS-232) or network connection
    - Host: a data transfer utility
    - Target: a loader, a monitor or a debug agent
  - Download the image through either a JTAG or BDM interface

Image Transfer from the Host to the Target System (2/3)

- For the final product, the embedded software is stored in ROM or flash.
- If a system has both ROM and flash
  - Set *jumpers* to control which memory chip the processor uses to start its first set of instructions upon reboot
  - For example, if the image is stored in the flash
    - Set jumper to use the flash memory
    - The processors fetches its first instruction from *the starting address where the flash is mapped*

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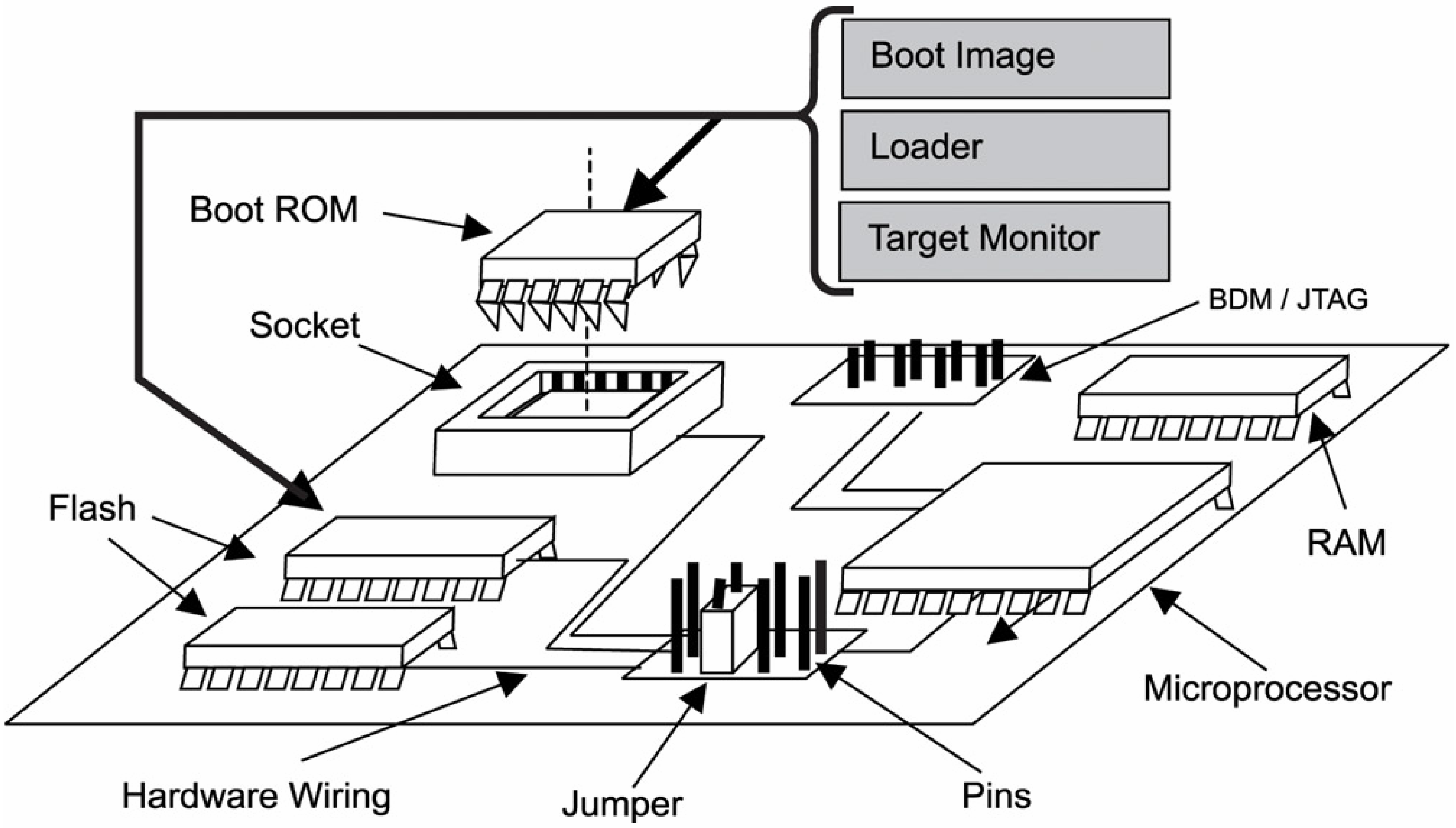
Image Transfer from the Host to the Target System (3/3)

- However, the final product method is impractical during the development stage
  - Reprogramming the *EEPROM* or the *flash memory* is time consuming
- Solution
  - Transfer the image directly into the target system's RAM memory
  - Achieved by
    - Serial or network connection
    - JTAG or BDM solution

Target System Tools

View of the Target Embedded System



Embedded Loader (1/3)

- At the early development phase, a common approach is write a *loader program* for the target and use it to download the image from the host system
- *Embedded loader*
  - Download the image from the host system to the target system
  - The loader is often programmed into ROM

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Embedded Loader (2/3)

- To communicate with the host system to download the image
  - Require a *data transfer protocol* and *communication parameters* between the *host utility* and the *embedded loader*
- Embedded loader may download the image
  - Either directly to the *RAM memory*
  - Or to the *flash memory* if the loader has the flash programming capability
    - After downloading to the flash, must set jumper to execute system from flash
- The downloading medium can be
  - Serial line
  - Network connection
    - For example, Ethernet and uses FTP or TFTP protocols

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Embedded Loader (3/3)

- However, before the loader can execute, there must be a *boot image* to initialize the target

- Boot image
  - Part of the ROM chip is occupied by the boot image
  - Consist of the code that executes when the system powers up
    - Initialize the required peripheral devices
    - Initialize the memory system for downloading the image
    - Initialize the interrupt controller and install default interrupt handler
  - Prepare the system to execute the loader

Embedded Monitor (1/2)

- An alternative to the *boot image* plus *embedded loader* approach is to use an *embedded monitor*
- Furthermore, embedded monitor enable developers to *examine and debug the target system at run time*
- Thus, an embedded monitor
  - *boot image* plus *embedded loader*
  - Add the *interactive debug capability*

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Embedded Monitor (2/2)

- How to provide developer to examine and debug the target system at run time?
- Solution:
  - Embedded monitor defines *a set of commands* that can be accessible through a terminal emulation program over the serial line
    - Download the image
    - Read from and write to system memory locations
    - Read and write system registers
    - Set and clear different types of breakpoints
    - Single-step instructions
    - Reset the system

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Target Debug Agent

- Target debug agent, or debug agent
  - *Embedded monitor* + *visual source-level debug capability for the host debugger*
- Thus, a target debug agent must provide enough information for the host debugger to provide visual source-level debug capability
- For example, a debug agent has built-in knowledge of the RTOS objects and services
  - Allow the developer to explore such object and services fully and visually

Target Boot Process

- We give an example to show a embedded system boot process
  - Note that, each embedded system may have its own booting scenario
- *Assume*
  - The *reset vector* is contained in ROM and mapped to *0x00000h*
    - The code executed when a embedded system powers on
    - Usually a jump into another part of memory space where the real initialization code is found
  - The *loader* is contained in flash and is mapped to *0x00040h*
  - A loader performs
    - System bootstrapping
    - Image downloading
    - Initialization

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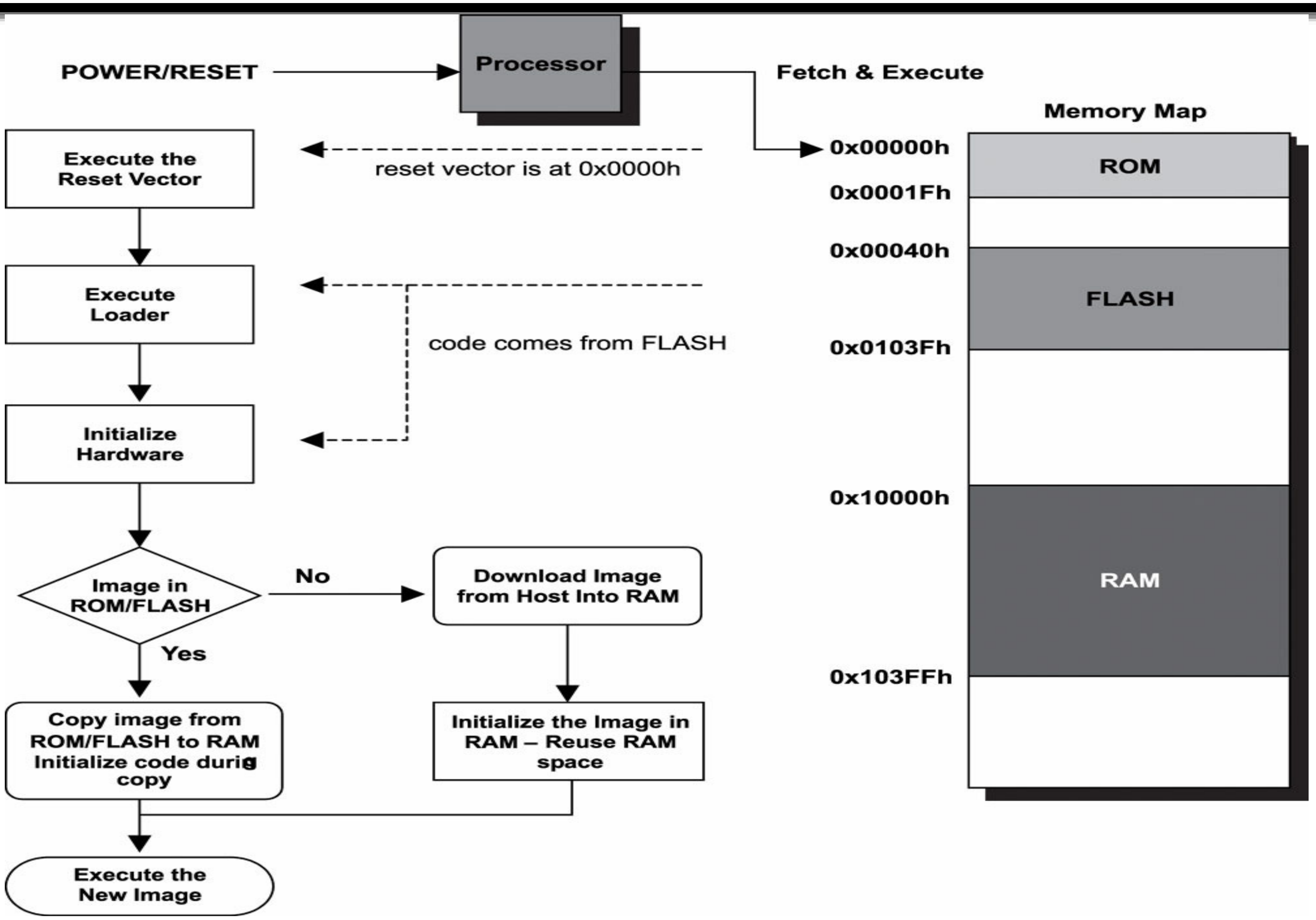
Reset Vector in ARM

```
Vector_Init_Block
                b       Reset_Addr
                b       Undefined_Addr
                b       SWI_Addr
                b       Prefetch_Addr
                b       Abort_Addr
                NOP                             ;Reserved vector
                b       IRQ_Addr
                b       FIQ_Addr

Reset_Addr      ...
Undefined_Addr  ...
SWI_Addr        ...
Prefetch_Addr   ...
Abort_Addr      ...
IRQ_Addr        ...
FIQ_Addr        ...
```

Example: Bootstrap Overview



Steps of the Example Bootstrap Process (1/3)

- Power on or reset
  - Processor fetch and executes code from *0x00000h*
    - Reset vector in ROM
  - The code in reset vector is a *jump instruction* to *0x00040h*
    - *Loader in flash*
  - The code in loader first initialize hardware to *put the system into a known state*
    - Processor registers are set with default value
    - Stack pointer is set with the value found in ROM
    - Disable interrupt
    - Initializes the RAM memory and the caches
    - Perform limited hardware diagnostics on those devices needed for its operation

Steps of the Example Bootstrap Process (2/3)

- Then, the loader optionally can copy itself from the flash memory into the RAM
  - Since RAM is faster than flash
- Besides, the loader must *copy* and *reserve* the *initialized* and *uninitialized data* sections of loader from flash to RAM
  - *Copy* the content of the *initialized* data section (.data and .sdata) to RAM
  - *Reserve* spaces for *unitialized* data section (.bss and .sbss) in RAM
  - Keep *.const* section in flash or RAM
- The next step is to *initialize the system devices*
  - Only the necessary devices that the loader requires are initialized
    - For example, network controller if loader uses network to download image
  - Fully initialization is left until the downloaded image perform its system initialization

Steps of the Example Bootstrap Process (3/3)

- Now, the loader can transfer the application image to the target system
  - Application image: *RTOS* + *kernel* + *application code*
  - Application image may come from
    - Read-only memory devices on the target
    - The host development system

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Target Image Execution Scenarios

- Three image execution scenarios
  - Execute from ROM while using RAM for data
  - Execute from RAM after being copied from ROM
  - Execute from RAM after being downloaded from a host system

Executing From ROM Using RAM for Data (1/2)

- *Execution in Place* (*XIP*)
- Program image executes directly out of ROM
  - Only act as a *boot image* optionally plus *application code*
  - No loader functionality
- However, the *data section* must still reside in *RAM*

Executing From ROM Using RAM for Data (2/2)

- Boot sequence
  1. The CPU's **IP** register is hardwired to execute the first instruction in memory, i.e., the reset vector
  2. The reset vector jump to the first instruction of the *.text* section of boot image
     1. Initialize the memory system
  3. The *.data* section is copied to RAM
  4. Reserve space if RAM for the .bss section
  5. Reserve stack space in RAM
  6. Set **SP** register to the beginning of the newly created stack

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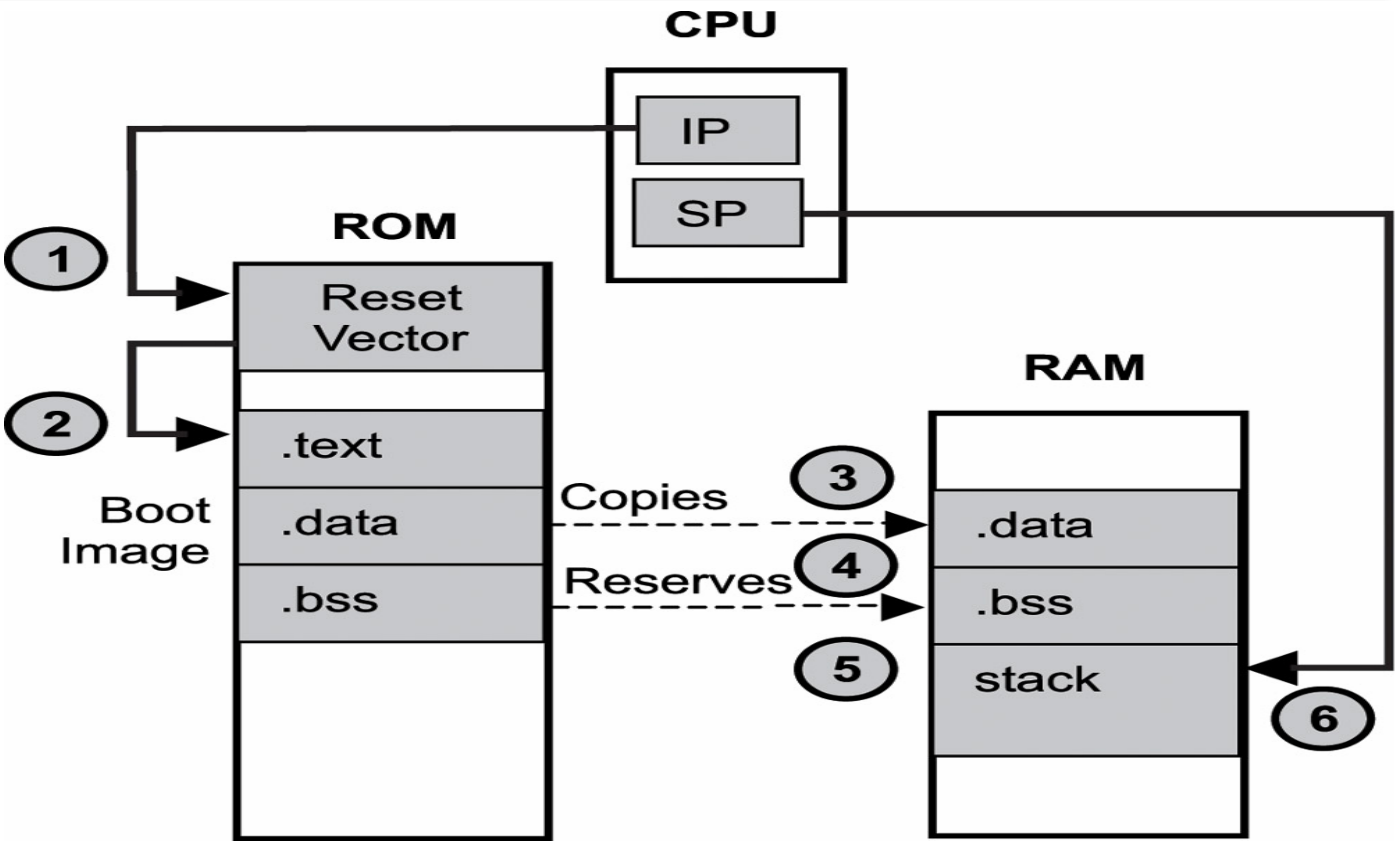
Boot Sequence For an Image Running From ROM



Executing from RAM After Image Transfer From ROM (1/2)

- The boot loader transfers an application image from ROM to RAM for execution
  - The application image is usually compressed in ROM to reduce the storage space required

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Executing from RAM After Image Transfer From ROM (2/2)

- Boot sequence
  7. Copy the Compressed application image from ROM to RAM in a work area
  8. Decompress and initialize the application image(1)
  9. Decompress and initialize the application image(2)
  10. Decompress and initialize the application image(3)
  11. The loader transfers control to the image using a processor-specific jump instruction
  12. Recycle the memory area occupied by the loader and the work area.
      - May also reinitialize the **SP** to point to the memory area occupied by the loader to use it as the stack space

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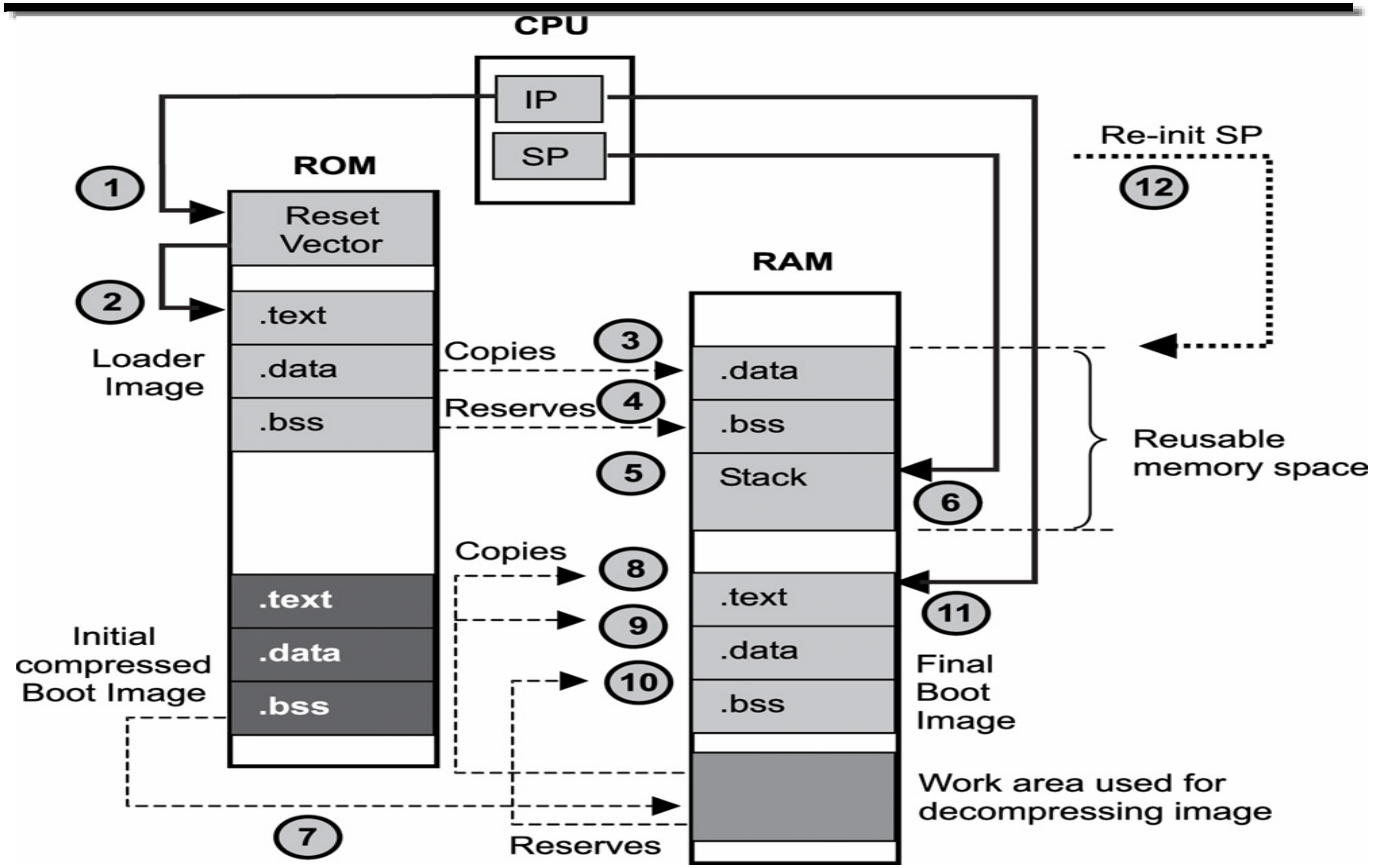
Boot Sequence For an Image Executing From RAM after Transfer From ROM



Executing from RAM After Image Transfer From Host

- Boot sequence
  7. The application image is downloaded from the host development system
  8. The image integrity is verified
  9. The image is decompressed if necessary

  10-12. The debug agent loads the image section into their respective *run address* in RAM

  13. The debug agent transfers control to the download image

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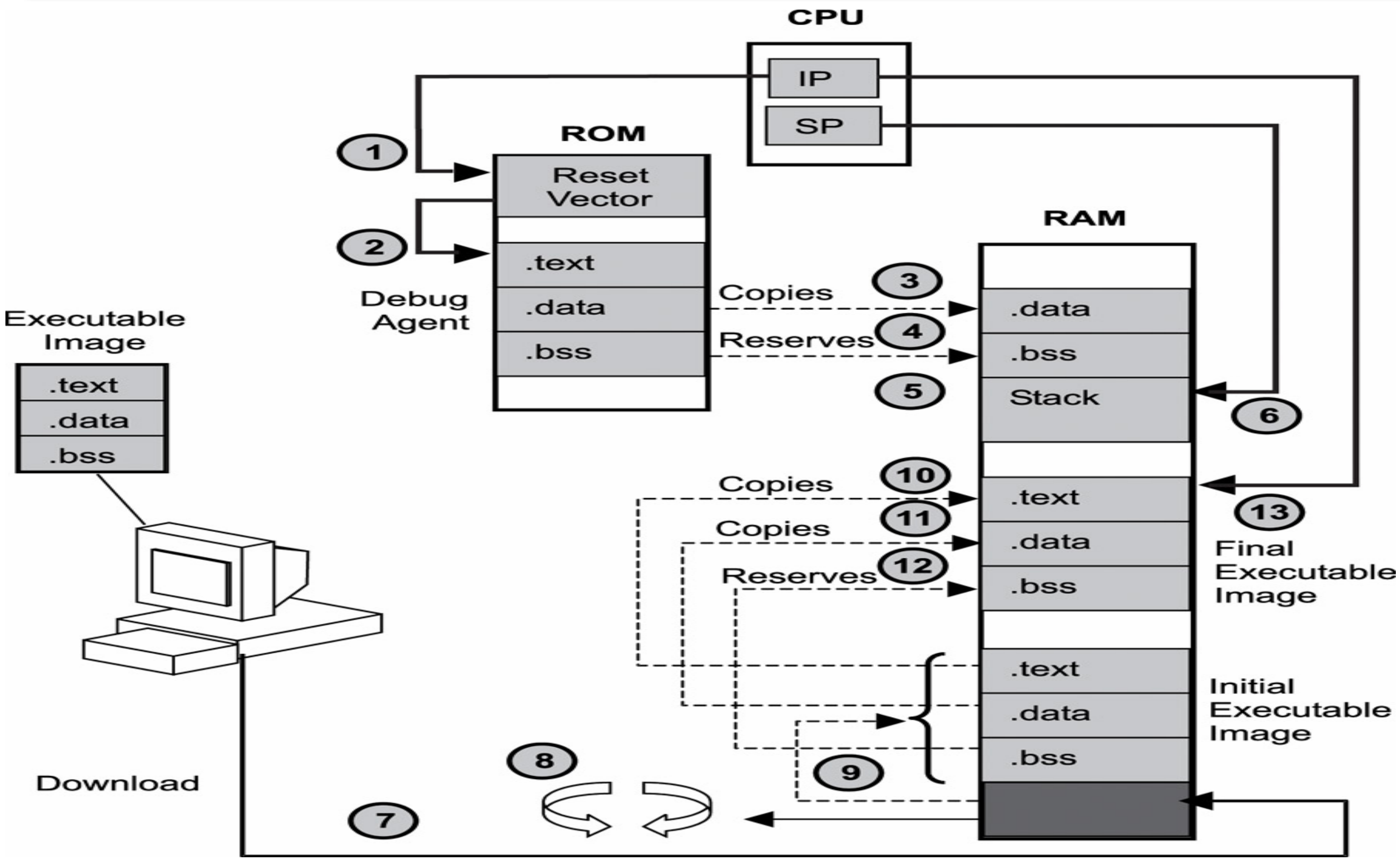
Boot Sequence For an Image Executing From RAM after Transfer From Host System



Target System Software Initialization Sequence (1/2)

- Target image may consists
  - Board support package (BSP)
    - A full spectrum of drivers for the hardware components/devices
  - RTOS
  - Other embedded modules
    - File system, networking…
  - Application

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Target System Software Initialization Sequence (2/2)

- Example: a target image structured in the following slide
- Then, the main steps to initialize the system
  - Hardware initialization
  - RTOS initialization
  - Application initialization

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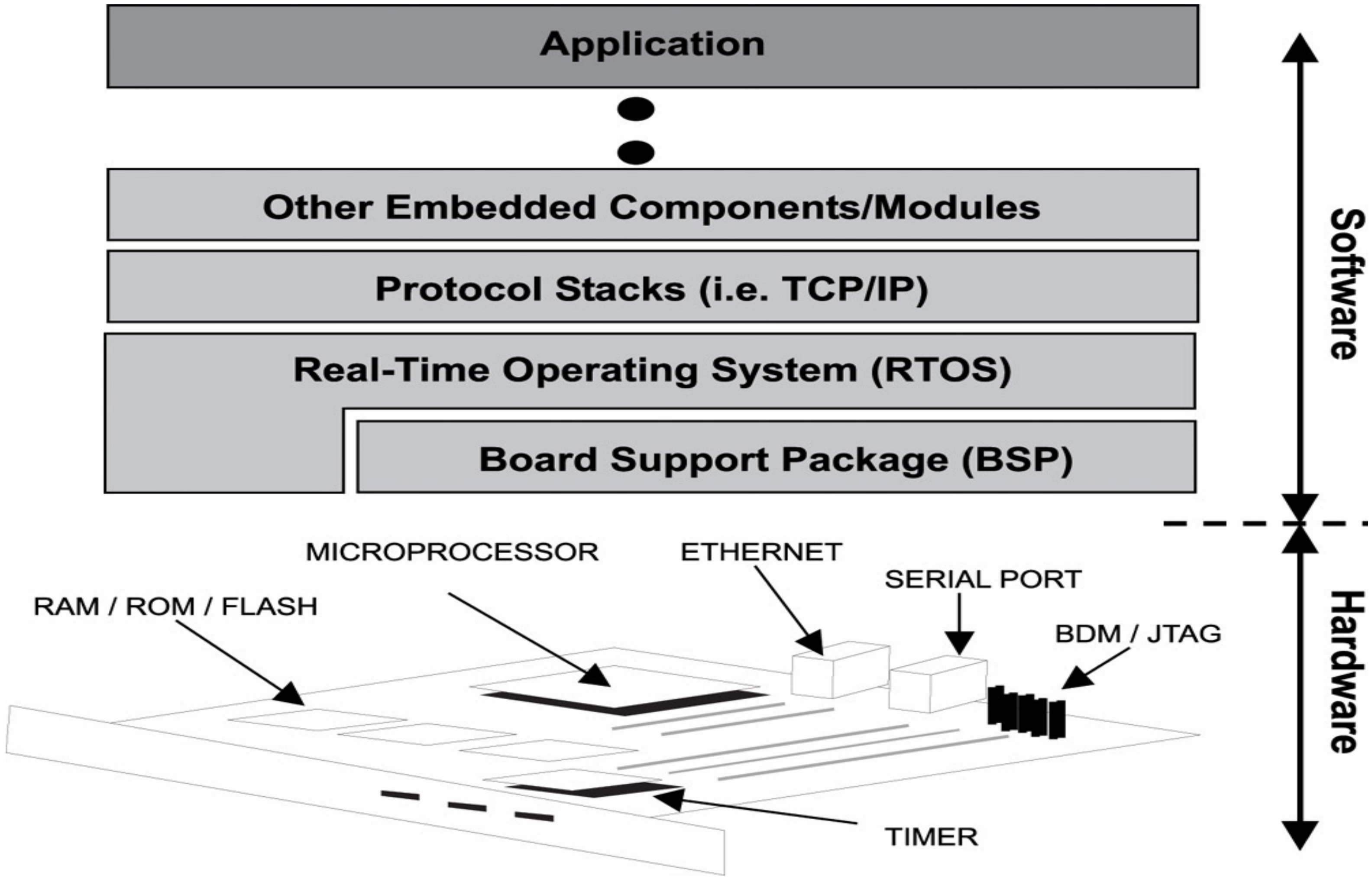
Software Components of a Target Image


Application
Other Embedded Components/Modules
Protocol Stacks (i.e. TCP/IP)
Real-Time Operating System (RTOS)
Board Support Package (BSP)
Software
Hardware
MICROPROCESSOR
ETHERNET
SERIAL PORT
RAM / ROM / FLASH
BDM / JTAG
TIMER

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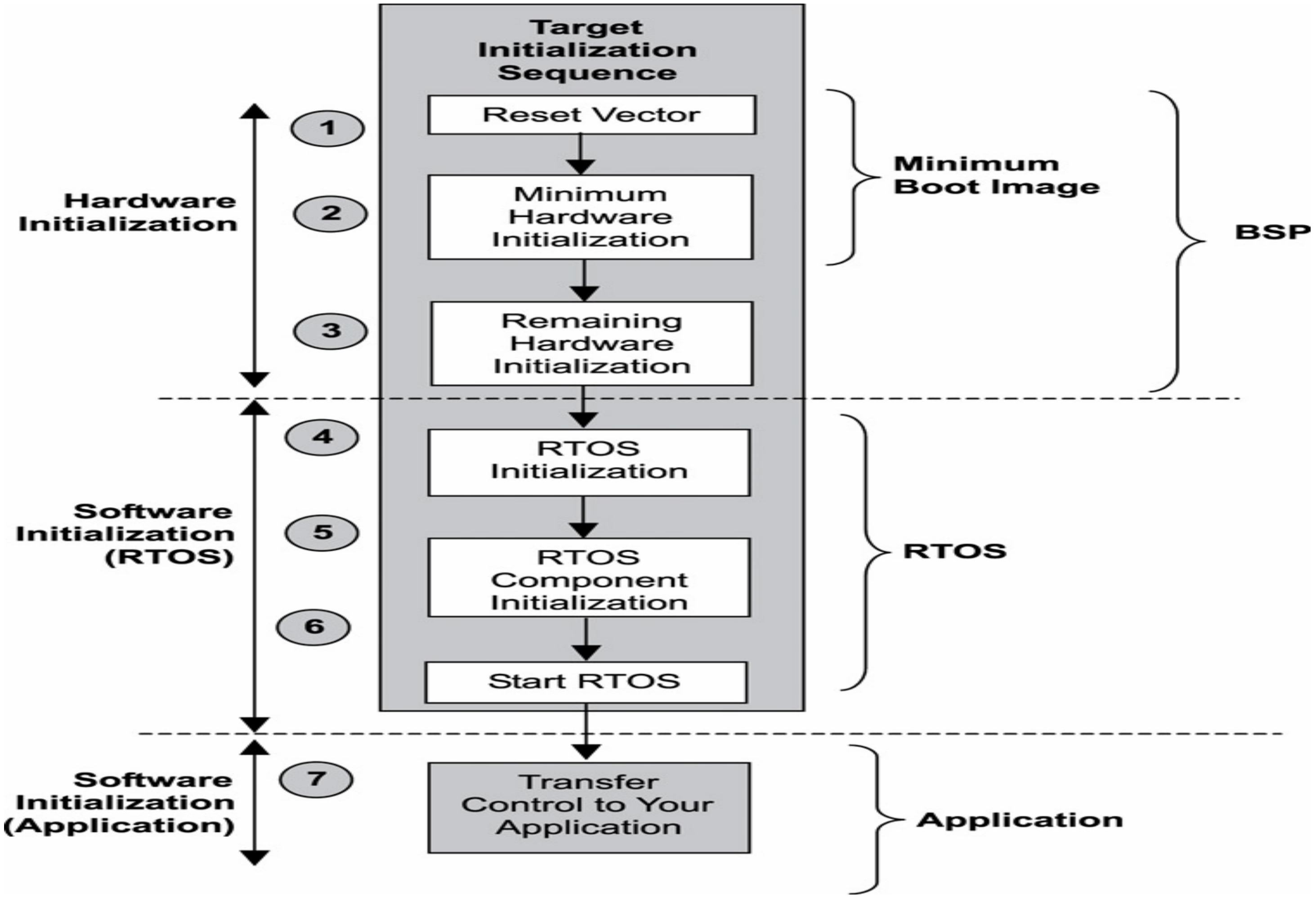
The Software Initialization Process


Target Initialization Sequence
Hardware Initialization
Software Initialization (RTOS)
Software Initialization (Application)
1
2
3
4
5
6
7
Reset Vector
Minimum Hardware Initialization
Remaining Hardware Initialization
RTOS Initialization
RTOS Component Initialization
Start RTOS
Transfer Control to Your Application
Minimum Boot Image
BSP
RTOS
Application

Hardware Initialization (1/3)

- Power on-> reset vector -> boot image
  - Initialize the minimum hardware required to get the boot image to execute
  - *Steps 1 and 2* in previous slide
    - Starting execution at the reset vector
    - Putting the *processor* into a known state by setting the appropriate registers
      - Getting the processor type
      - Getting or setting the CPU's clock speed
    - Disabling interrupts and caches
    - Initializing *memory* controller, memory chips, and cache units
      - Getting the start address for memory
      - Getting the size of memory
      - Performing preliminary memory tests, if required

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Hardware Initialization (2/3)

- Then
  - Boot sequence *may* copy and decompress the sections of code to RAM
  - It *must* copy and decompress its data to RAM
- Finally, initialize other hardware components
  - Step 3 in previous slide
    - Setting up execution handlers
    - Initializing interrupt handlers
    - Initializing bus interfaces, such as PCI, USB…
    - Initializing board peripherals such as serial, LAN and SCSI

Hardware Initialization (3/3)

- *Initial boot sequence*
  - Steps 1 and 2
  - Mainly initialize the *CPU* and *memory subsystem*
- *BSP initialization phase*
  - Also called *hardware initialization*
  - Steps 1 to 3

Example: Hardware Initialization in an ARM-Based Embedded System

- After reset or power on, the instruction located at address *0x0* must transfer control to the initialization code
  - Set up *exception vectors*
  - Initialize the *memory* system
  - Initialize the *stack pointer* registers
  - Change *processor mode* if necessary
  - Change *processor state* if necessary
- Note, the state of ARM processor cores after reset is
  - SVC mode
  - interrupts disabled
  - ARM state.

Set Up Exception Vector

```
Vector_Init_Block
                 b        Reset_Addr
                 b        Undefined_Addr
                 b        SWI_Addr
                 b        Prefetch_Addr
                 b        Abort_Addr
                 NOP                          ;Reserved vector
                 b        IRQ_Addr
                 b        FIQ_Addr

Reset_Addr       ...
Undefined_Addr   ...
SWI_Addr         ...
Prefetch_Addr    ...
Abort_Addr       ...
IRQ_Addr         ...
FIQ_Addr         ...
```

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Initialize the Memory System

- --- Perform ROM/RAM remapping, if required

```
IF :DEF: ROM_RAM_REMAP
```

- --- Initialize memory system

```
IF :DEF: CACHE
        IMPORT Clock_Speed
        IMPORT Cache_Init
        BL Clock_Speed
        BL Cache_Init
ENDIF
```

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Initialize the Stack Pointer

- In ARM, you might have to initialize some or all of the following stack pointers, depending on the interrupts and exceptions you use
  - sp_SVC: this must always be initialized.
  - sp_IRQ: this must be initialized if IRQ interrupts are used.
    - It must be initialized before interrupts are enabled.
  - sp_FIQ: this must be initialized if FIQ interrupts are used.
    - It must be initialized before interrupts are enabled.
  - sp_ABT: This must be initialized for Data and Prefetch Abort handling.
  - sp_UND: This must be initialized for Undefined Instruction handling.

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Initialize the Stack Pointer

- --- Initialize stack pointer registers
- --- Enter each mode in turn and set up the stack pointer

```
LDR r0, =top_of_stacks
MSR CPSR_c, #Mode_IRQ:OR:I_Bit:OR:F_Bit          ; No interrupts
SUB sp, r0, #Offset_IRQ_Stack

MSR CPSR_c, #Mode_FIQ:OR:I_Bit:OR:F_Bit          ; No interrupts
SUB sp, r0, #Offset_FIQ_Stack

MSR CPSR_c, #Mode_ABT:OR:I_Bit:OR:F_Bit          ; No interrupts
SUB sp, r0, #Offset_ABT_Stack

MSR CPSR_c, #Mode_UND:OR:I_Bit:OR:F_Bit          ; No interrupts
SUB sp, r0, #Offset_UND_Stack

MSR CPSR_c, #Mode_SVC:OR:I_Bit:OR:F_Bit          ; No interrupts
SUB sp, r0, #Offset_SVC_Stack
```

Change the Processor Mode

- The processor is in *Supervisor mode* upon reset
- If the application runs in *User mode*
  - Change to *User mode* and initialize the User mode *sp (stack pointer)* register

- --- Now change to *User mode* and set up *User mode stack.*

```
MSR CPSR_c, #Mode_USR:OR:F_Bit          ; IRQs now
    enabled
SUB sp, r0, #Offset_USR_Stack
```

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Change the Processor State

- ARM cores start up in ARM state on reset.
  - The initialization code, at least the reset handler, must be ARM code.
- If the application is compiled for Thumb
  - Changing processor state from ARM to Thumb

Jump to the RTOS

- After the initialization, now we can jump to the RTOS initialization code
- --- Now enter the C code
  - IMPORT __main
  - B __main ; note use B not BL, because an ; application will never return this way

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RTOS Initialization

- Steps 4 to 6
  - Initializing the RTOS
  - Initializing different RTOS objects and services
    - Task objects
    - Semaphore objects
    - Message-queue objects
    - Timer services
    - Interrupt services
    - Memory-management services
  - Creating necessary stack for RTOS
  - Initializing additional RTOS extensions
    - TCP/IP stack or file system
  - Starting the RTOS and its initial tasks

Example: LyraOS Initialization

```
void __main(caddr_t addr, size_t npg)
{
    pthread_t thread_id;

    addr = (void *)((int)(addr + MM_PAGE_SIZE - 1) &
    ~(MM_PAGE_SIZE - 1));
    page_init(addr, npg);
    init_timer();
    pthread_init();
     irq_enable();

    msginit();

    start_application();
}
```

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Application Software Initialization

- Finally, transfer control to the application
  - RTOS calls a predefined function implemented by the application
  - Then, the application software goes through its initialization
    - Declared and implemented necessary objects, services, data structures, variables, and other constructs

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References

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- Steve B. Furber, "ARM System-on-Chip Architecture," Addison-Wesley, 2000