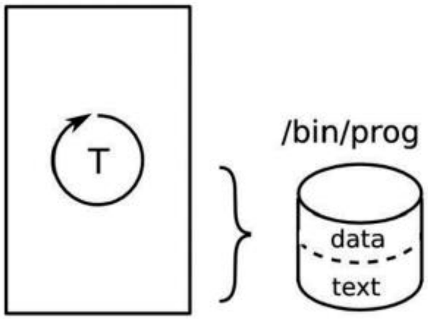
# EMBEDDED OPERATING SYSTEMS

Embedded Linux on Beaglebone Black

# Process

- A process is a combination of
  - Memory address space
  - Thread of execution
- Address space is private to the process
  - Other processes / threads cannot access it
  - Created by memory management subsystem in kernel



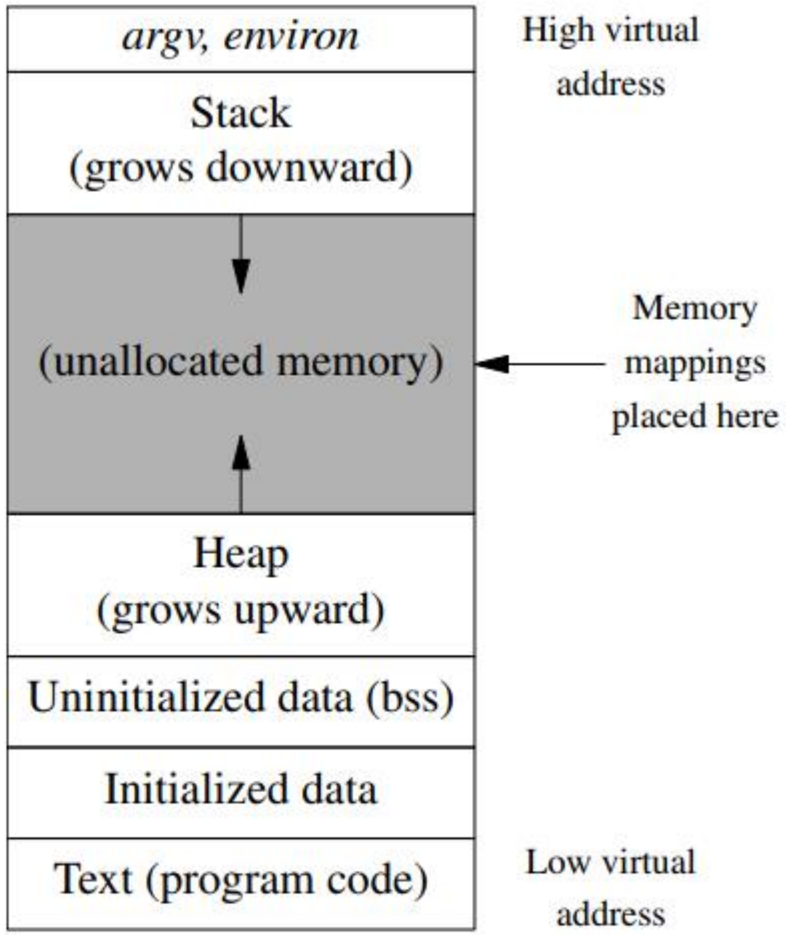

- Process has resources
  - Memory (stack, heap), file descriptors, etc.
- Kernel reclaims all resources when process ends

- Processes communicate among themselves using IPC
  - Inter-process communication

# Process memory space

- Divided into segments
  - **Text:**
    - Machine-language instructions
    - Marked read-only to prevent modifications
    - Multiple processes could share same code
  - **Initialized data**
    - Global and static variables explicitly initialized
    - Valued read from program when it is loaded
  - **Uninitialized data**
    - Global and static variables that are not explicitly initialized
    - Initialized to zero when process is created
  - **Stack**
    - Storage for function locals and linkage info
  - **Heap**
    - Area from which memory can be dynamically (de)allocated

# Process memory layout



# Process environment

- Each process has a list of environment variables
  - Strings of the form name=value
- New process (child) inherits parent’s environ
  - Simple 1-way IPC!
- Commonly used to control program behavior
- Examples:
  - USER: User’s name
  - HOME: User’s home directory
  - SHELL: User’s shell
  - PATH: User’s path

# The /proc file system

- Psuedo-file system
  - Exposes kernel information
  - Via file system metaphor
  - Structured as set of subdirectories and files

- Files don't really exist
  - Created on the fly in SDRAM
  - Many files are read-only
  - Some files are writable
    - Can update / change kernel settings

# Examples: /proc file system

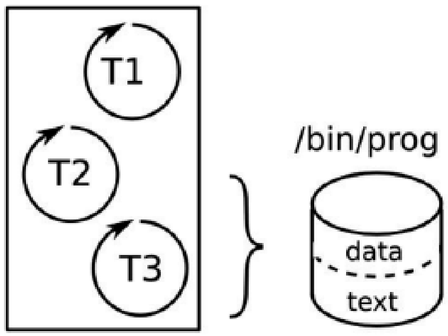
- `/proc/cmdline`: command line used to start kernel
- `/proc/cpuinfo`: info about CPUs on the system
- `/proc/meminfo`: info about memory and memory usage
- `/proc/modules`: info about loaded kernel modules
- `/proc/sys/fs/`: files and subdirectories with filesystem-related info
- `/proc/sys/kernel/`: files and subdirectories with various readable/settable kernel parameters
- `/proc/sys/net/`: files and subdirectories with various readable/settable networking parameters

# /proc/PID directories

- Each running process has a /proc/PID directory
  - Contains subdirectories and files
    - Exposing information about process with that PID
    - Examples:
      - cmdline: command line used to start the process
      - cwd: current working directory
      - environ: environment of current process
      - fd: info on open file descriptors
      - limits: resource limits
      - mounts: devices mounted by that process
      - status: info about the process

# Thread

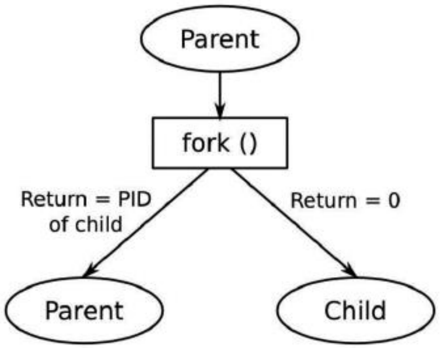
- A thread is an executional entity within a process
- All processes begin with *main()* thread
  - They may create more threads using **pthread** APIs
- Multiple threads in same process share
  - Same memory address space
  - Other resources like file descriptors
- Communication is easier
  - Needs to be properly synchronized



# Creating a process: fork()

- Processes are created using the ***fork()*** call

  *#include <sys/types.h>*
  *#include <unistd.h>*
  *pid_t **fork**(void);*
  - Here pid_t is the Process ID




- But fork() is a strange function
  - 2 returns on success
    - First return is 0 in the new process created (child)
    - Second return is a number in the original process (parent)

- Child is an exact copy of parent
  - But in separate address spaces!

# Terminating a process: exit()

- Process terminates when
  - It calls exit() function – ***voluntary***
  - It gets a signal (like SIGKILL) – *involuntary (is killed)*

- Return value of terminating process is either
  - Argument to exit() call
  - Signal value if killed

- Return value can be collected by parent
  - Using ***wait()*** or ***waitpid()*** calls
  - Kernel can notify parent using a SIGCHLD

- If parent is killed / not waiting
  - Child process becomes a **zombie**
  - Attached to init / kernel

# Forking exercise

- ***forking.c***
  - Notice how the code is written
    - Common codebase for child and parent
    - How child / parent process can be distinguished
      - Trapping the return value of the fork() call
    - How child process exits with an exit code
    - How parent can wait for child termination
      - And get access to exit code returned by child

# Forking different program: exec()

- What if we want a fork() but want to run something else, instead of parent code?
  - Use the exec() family of functions
    - Get ***location*** of the executable as argument
      - *execl()*
      - *execlp()*
      - *execle()*
    - Get a ***vector*** of arguments
      - *execv()*
      - *execvp()*
      - *execve()*

# The exec() family

- *int execl(const char *pathname, const char *arg, ..., NULL);*
- *int execlp(const char *file, const char *arg, ..., NULL);*
- *int execle(const char *pathname, const char *arg, ..., NULL, char *const envp[]);*

- *int execv(const char *pathname, char *const argv[]);*
- *int execvp(const char *file, char *const argv[]);*
- *int execve(const char *pathname, char *const argv[], char *const envp[]);*

# exec() exercise

- Use the shell script (run_all_execs.sh)
    - To run all types of exec() calls
- Note the different calls
    - Input parameters and usage!
- Terminology
    - *l* ➔ *location*
    - *v* ➔ *vector*
    - *p* ➔ *path*
    - *e* ➔ *environment (shell)*

# Inter-Process Communication

- Each process is an island of memory

- Inter-Process Communication (IPC) happens
  - By copying info from one address space to another
    - Using a queue / buffer to hold and pass messages
      - Examples: **sockets, pipes, message queues**
    - Using a **shared file** and **file locks**
  - By creating a memory area that all can access
    - Using shared memory; needs access synchronization
      - Examples: **shmem**

- Message and shared file based methods are easier to program and debug
  - But slow for large number of messages
- Shared memory based methods are more efficient
  - But need careful synchronization

# IPC using shared files, file locks

- Writer and reader process
  - Share a common file on file system (file.dat)

- Either operation needs a file lock (***flock***)

```
struct flock {
    ...
    short l_type;    /* Type of lock: F_RDLCK,
                        F_WRLCK, F_UNLCK */
    short l_whence;  /* How to interpret l_start:
                        SEEK_SET, SEEK_CUR, SEEK_END */
    off_t l_start;   /* Starting offset for lock */
    off_t l_len;     /* Number of bytes to lock */
    pid_t l_pid;     /* PID of process blocking our lock
                        (set by F_GETLK and F_OFD_GETLK) */
    ...
};
```

- Lock types:
  - Writer needs a F_WRLCK (exclusive)
  - Reader needs a F_RDLCK (shared / non-exclusive)
  - After the operation, process needs to F_UNLCK

# File locking using fcntl()

- Locks are obtained using ***fcntl()***

  *#include <unistd.h>*
  *#include <fcntl.h>*
  *int fcntl(int fd, int cmd, ... /* arg */ );*

- Commands for fcntl (*cmd*):
  - GETLK
    - Get the current lock; returns immediately
  - SETLK
    - Set the lock (3rd argument is &lock); no waiting
  - SETLKW
    - Set the lock (3rd argument is &lock), wait until you get the lock

# File lock exercise

- *flock-writer.c*
    - Implements the writer
    - Creates the file, and takes a write lock (F_WRLCK) – with wait
    - Writes data to file
    - Exits after releasing the file lock (F_UNLCK)

- *flock-reader.c*
    - Implements the reader
    - Takes a read lock (F_RDLCK) on the file
        - Waits till it gets it!
    - Reads data from file and displays on stdout
    - Exits after releasing the lock (F_UNLCK)

- Run *flock-writer.out* and *flock-reader.out* on different terminals at once
- Try running 2 writer processes (*flock-writer.out*) at once

# IPC using shared memory

- POSIX API for sharing memory
  - *shm_open()*
    - Create/open a new/existing shared memory object
  - *ftruncate()*
    - Set the size of the shared memory object (viewed as fd)
  - *mmap() / munmap()*
    - Map/unmap devices or files into process memory space
  - *shm_unlink()*
    - Unlink (delete) share memory object

- POSIX maintains a backing file for shared memory
  - Located in /dev/shm/…

- We need to use primitives like *semaphore/mutex*
  - For controlling exclusive access to memory object

- Linking flags: ***-lrt -lpthread***

# POSIX shared memory API

- Open/create and close

```
#include <sys/mman.h>
#include <sys/stat.h>        /* For mode constants */
#include <fcntl.h>           /* For O_* constants */
int shm_open(const char *name, int oflag, mode_t mode);
int shm_unlink(const char *name);
```

- Set size

```
#include <unistd.h>
#include <sys/types.h>
int ftruncate(int fd, off_t length);
```

- Memory map/unmap

```
void *mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset);
int munmap(void *addr, size_t length);
```

# POSIX semaphore API

- Open/create

  *#include <fcntl.h>            /* For O_* constants */*
  *#include <sys/stat.h>        /* For mode constants */*
  *#include <semaphore.h>*
  *sem_t ****sem_open***(const char *name, int oflag, mode_t mode, unsigned int value);*
  - Semaphore mode
    - **O_CREAT | O_RDWR** for writer
    - **O_RDWR** for reader

- Wait on / Post a semaphore

  *int* ***sem_wait****(sem_t *sem);*
  *int* ***sem_post****(sem_t *sem);*

- Close/unlink

  *int* ***sem_close****(sem_t *sem);*
  *int* ***sem_unlink****(const char *name);*

# Shared memory exercise

- *shmem-writer.c*
  - Implements the writer
  - Opens/creates and mmaps the shared mem segment
    - Sets the size
  - Creates the semaphore
    - Writes to mem segment while holding it
  - Releases (posts) the semaphore
  - Cleans up (semaphore deletion, unlinking backing file, etc.)

- *shmem-reader.c*
  - Implements the reader
  - Opens and mmaps the shared mem segment
  - Tries to take the semaphore
    - Waits till it gets the semaphore
  - Reads from the segment and outputs to stdout
  - Unmaps the mem segment and exits

# Threads on Linux

- Linux uses the POSIX threads library
  - Commonly called ***pthread***

- Threads are called ‘light-weight processes’ (LWP)
  - Share same resources (memory space, file descriptors) as the parent process

- A process starts by creating a single thread
  - Called main thread (from the C ***main()*** entrypoint)

- Inter-thread communication
  - Is simpler and has less overhead
  - But needs to be synchronized and controlled!

- Linking: ***-lpthread***

# What threads share (& don't!)

- Threads in a process share:
  - Process ID (PID)
  - Parent Process ID (PPID)
  - User ID (UID) and Group ID (GID)
  - Controlling terminal
  - File descriptors and locks

- Distinct for each thread:
  - Thread ID (TID)
  - Signal mask
  - ***errno*** variable
  - RT scheduling policy and priority

# POSIX thread API

- Open/create

  *#include <pthread.h>*

  *int **pthread_create**(pthread_t *thread, const pthread_attr_t *attr, void *(*start_routine) (void *), void *arg);*

- Termination options

  *void **pthread_exit**(void *retval);*

  *int **pthread_cancel**(pthread_t thread);*

  *int **pthread_join**(pthread_t thread, void **retval);*

  - Return from start_routine()

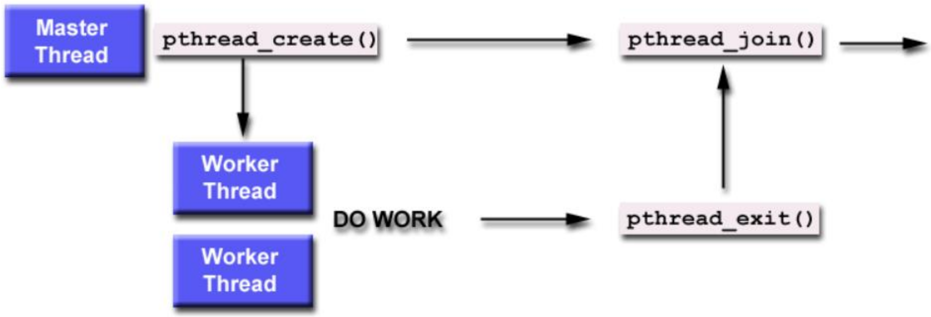
- Thread attributes

  *int **pthread_attr_init**(pthread_attr_t *attr);*

  *int **pthread_attr_destroy**(pthread_attr_t *attr);*

# Joinable vs. Detachable threads

- Usual lifecycle of threads




- By default, threads are joinable
  - ***Master*** waits for ***worker*** using ***pthread_join()***
  - ***Worker*** resources not freed up till ***master*** joins, even if ***worker*** exits

- But what if we want to free ***worker*** resources early on?
  - Then ***worker*** can be created ***detachable***

# Creating detachable threads

- Create a ***pthread_attr_t attr;***
- Set/get detach state using these APIs:

  *int **pthread_attr_setdetachstate**(pthread_attr_t *attr, int detachstate);*
  *int **pthread_attr_getdetachstate**(const pthread_attr_t *attr, int *detachstate);*

- Detach states:
  - *PTHREAD_CREATE_DETACHED*
  - *PTHREAD_CREATE_JOINABLE*

- Create the thread using this ***attr***

  *int **pthread_create**(pthread_t *thread, const pthread_attr_t *attr, void *(*start_routine) (void *), void *arg);*

- A joinable thread can be changed to detached using the API

  *int **pthread_detach**(pthread_t thread);*

# Joinable/detached exercise

- Run ***join-detach.out***

- Observe the output
  - When threads are created
  - As threads execute
  - When main tries to join the threads

- Notice that
  - Joinable thread can be joined
  - Detached threads cannot be joined any more

# Mutex

- Mutex is an exclusive lock
  - Used for controlling / serializing access
  - To a common (shared) resource
  - Between multiple threads

- Only the thread holding the lock
  - Can access the shared resource
  - It then releases (unlocks) the mutex

- The other thread has to wait till the mutex is free

# Conditional variable (condvar)

- Threads need to be able to alert other threads
  - Something has changed / needs attention
  - This is called a condition
  - The alert is sent through a ***conditional variable (condvar)***

- One thread (alerter) signals the other (alertee)
  - By signaling using the ***condvar***

- The other thread sleep-waits on the ***condvar***
  - Waiting for the signal from the 1$^{st}$ thread

- Since both threads use/access the ***condvar*** at one time
  - We need a ***mutex*** to serialize access to the ***condvar***

# POSIX mutex and condvar API

- Mutex API
  - Creation

    ***pthread_mutex_t*** *mutex = PTHREAD_MUTEX_INITIALIZER;*
  - Lock/unlock

    *int* ***pthread_mutex_lock****(pthread_mutex_t *mutex);*

    *int* ***pthread_mutex_unlock****(pthread_mutex_t *mutex);*

- Conditional variable (condvar) API
  - Creation

    ***pthread_cond_t*** *cond = PTHREAD_COND_INITIALIZER;*
  - Wait/signal

    *int* ***pthread_cond_wait****(pthread_cond_t *cond, pthread_mutex_t *mutex);*

    *int* ***pthread_cond_signal****(pthread_cond_t *cond);*

# Mutex-Condvar exercise

- Run ***mutex-condvar.out***

- Observe
  - Producer and Consumer share a global char buffer
  - Producer enters data into the buffer
    - Signals this to Consumer
  - Consumer waits for signal from Producer
    - Retrieves data from buffer; resets it to “empty”
  - They use a *condvar* and a *mutex*
    - For serialized and controlled access to the *condvar*

# THANK YOU!