Princeton University

Computer Science 217: Introduction to Programming Systems

Process Management

Goals of this Lecture

Help you learn about:

- Creating new processes
- Waiting for processes to terminate
- Executing new programs
- Shell structure

Why?

- Creating new processes and executing new programs are fundamental tasks of a Unix **shell**
  - See Assignment 7
- A power programmer knows about Unix shells

System-Level Functions

As noted in the ***Exceptions and Processes*** lecture…

Linux system-level functions for **process management**

Number	Function	Description
60	exit()	Terminate the process
57	fork()	Create a child process
7	wait()	Wait for child process termination
11	execvp()	Execute a program in current process
20	getpid()	Return the process id of the current process

Agenda

Creating new processes

Waiting for processes to terminate

Executing new programs

Shell structure

Why Create New Processes?

Why create a new process?

- Scenario 1: Program wants to run an additional instance of itself
  - E.g., **web server** receives request; creates additional instance of itself to handle the request; original instance continues listening for requests
- Scenario 2: Program wants to run a different program
  - E.g., **shell** receives a command; creates an additional instance of itself; additional instance overwrites itself with requested program to handle command; original instance continues listening for commands

How to create a new process?

- A "parent" process **forks** a "child" process
- (Optionally) child process overwrite itself with a new program

`fork` System-Level Function

```
pid_t fork(void);
```

- Create a new process by duplicating the calling process
- New (child) process is an exact duplicate of the calling (parent) process
- In the child, return 0
- In the parent, return the process id of the child

fork() is called once in parent process

fork() returns twice

- Once in parent process
- Once in child process

Creating New Processes

Parent process and child process run **concurrently**

- Two CPUs available ⇒
  - Parent process and child process run in **parallel**
- Fewer than two CPUs available ⇒
  - Parent process and child process run **serially**
  - OS provides the **illusion** of parallel execution
    - OS causes context switches between the two processes
    - (Recall ***Exceptions and Processes*** lecture)

Reality: Each CourseLab computer has 24 CPUs

Simplifying assumption: there is only one CPU

- We'll speak of "which process gets **the** CPU"

Simple `fork` Example

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

What is the output?

Simple `fork` Example Trace 1 (1)

Parent prints "one"

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple `fork` Example Trace 1 (2)

Parent forks child

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple `fork` Example Trace 1 (3)

OS gives CPU to child; child prints "two"

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple `fork` Example Trace 1 (4)

Child exits

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple fork Example Trace 1 (5)

OS gives CPU to parent; parent prints “two”

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple fork Example Trace 1 (6)

OS gives CPU to parent; parent prints “two”

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple fork Example Trace 1 Output

Output:

```
one    ← From parent
two    ← From child
two    ← From parent
```


Simple fork Example Trace 2 (1)

Parent prints “one”

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple fork Example Trace 2 (2)

Parent forks child

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple fork Example Trace 2 (3)

OS gives CPU to parent; parent prints “two”

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 2 (4)

Parent exits

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple `fork` Example Trace 2 (5)

OS gives CPU to child; child prints "two"

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple `fork` Example Trace 2 (6)

Child exits

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```


Simple `fork` Example Trace 2 Output

Output:

```
one
two
two
```

From parent

From parent

From child

Fact 1: `fork` and Process State

Immediately after **`fork()`**, parent and child have identical but distinct process states

- Contents of registers
- Contents of memory
- File descriptor tables
  - (Relevant later)
- Etc.
  - See Bryant & O'Hallaron book for details

Fact 2: `fork` and Process Ids

Any process has a unique nonnegative integer id

- Parent process and child processes have different process ids
- No process has process id 0

Fact 3: fork and Return Values

Return value of fork has meaning
- In child, **`fork()`** returns 0
- In parent, **`fork()`** returns process id of child

```
pid = fork();
if (pid == 0)
{
   /* in child */
   …
}
else
{
   /* in parent */
   …
}
```


fork Example

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

What is the output?

fork Example Trace 1 (1)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 1 (2)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 1 (3)

Assume OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

0

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 1 (4)

Child decrements its x, and prints “child: 0”

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

fork Example Trace 1 (5)

Child exits; OS gives CPU to parent

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

fork Example Trace 1 (6)

In parent, fork() returns process id of child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Process id of child

fork Example Trace 1 (7)

Parent increments its x, and prints "parent: 2"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

fork Example Trace 1 (8)

Parent exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

fork Example Trace 1 Output

Example trace 1 output:

```
Child: 0
Parent: 2
```


fork Example Trace 2 (1)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (2)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (3)

Assume OS gives CPU to parent

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Process ID of child

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (4)

Parent increments its x and prints "parent: 2"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (5)

Parent exits; OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (6)

In child, fork() returns 0

0

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (7)

Child decrements its x and prints "child: 0"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

fork Example Trace 2 (8)

Child exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

fork Example Trace 2 Output

Example trace 2 output:

```
Parent: 2
Child: 0
```


Agenda

Creating new processes

Waiting for processes to terminate

Executing new programs

Shell structure

wait System-Level Function

Problem:
- How to control execution order?

Solution:
- Parent should call **wait()**
- (child is a "zombie" until parent does the **wait()**, so the parent should **harvest** (or **reap**) its children... more later)

pid_t wait(int *status);
- Suspends execution of the calling process until one of its children terminates
- If status is not NULL, stores status information in the int to which it points; this integer can be inspected with macros [see man page for details].
- On success, returns the process ID of the terminated child
- On error, returns -1

Paraphrasing man page

wait Example

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

What is the output?

wait Example Trace 1 (1)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

wait Example Trace 1 (2)

OS gives CPU to parent

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 1 (3)

Parent calls **wait()**

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 1 (4)

OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 1 (5)

Child prints “child” and exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 1 (6)

Parent returns from call of wait(), prints “parent”, exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 1 Output

Example trace 1 output

```
child
parent
```

wait Example Trace 2 (1)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 2 (2)

OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 2 (3)

Child prints "child" and exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 2 (4)

OS gives CPU to parent

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 2 (5)

Parent calls **wait()**; returns immediately

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```


wait Example Trace 2 (6)

Parent prints "parent" and exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

`wait` Example Trace 2 Output

Example trace 2 output

```
child
parent
```

Same as trace 1 output!

Aside: Orphans and Zombies

Question:

- What happens if parent process does not wait for (reap/harvest) child process?

Answer 1:

- In shell, could cause sequencing problems
- E.g, parent process running shell writes prompt for next command before current command is finished executing

Answer 2:

- In general, child process becomes **zombie** and/or **orphan**

Aside: Orphans and Zombies

Orphan

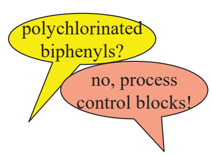
- A process that has no parent

Zombie

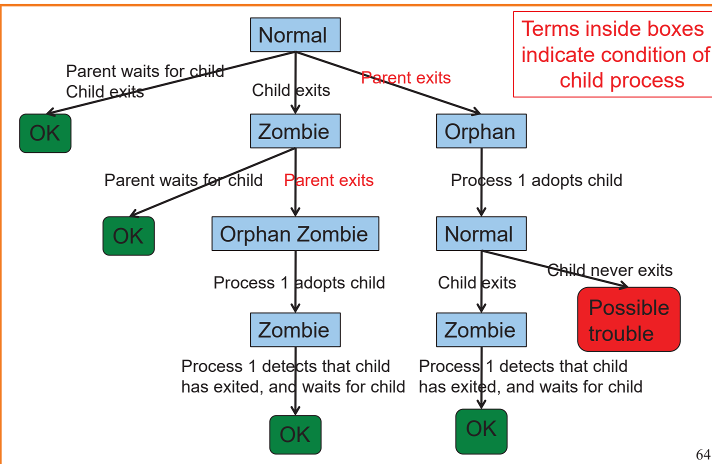
- A process that has terminated but has not been waited for (reaped)

Orphans and zombies

- Clutter Unix data structures unnecessarily
  - OS maintains unnecessary PCBs
- Can become long-running processes
  - Consume CPU time unnecessarily



Aside: Orphans and Zombies



Agenda

Creating new processes

Waiting for processes to terminate

Executing new programs

Shell structure

execvp System-Level Function

Problem: How to execute a new program?

- Usually, in the newly-created child process

Solution: **`execvp()`**

```
int execvp(const char *file, char *const argv[]);
```

- Replaces the current process image with a new process image
- Provides an array of pointers to null-terminated strings that represent the argument list available to the new program
  - The first argument, by convention, should point to the filename associated with the file being executed
  - The array of pointers must be terminated by a NULL pointer

Paraphrasing man page

execvp System-Level Function

Example: Execute "cat readme"

```
char *newCmd;
char *newArgv[3];
newCmd = "cat";
newArgv[0] = "cat";
newArgv[1] = "readme";
newArgv[2] = NULL;
execvp(newCmd, newArgv);
```

- First argument: name of program to be executed
- Second argument: argv to be passed to main() of new program
  - Must begin with program name, end with NULL

execvp Failure

fork()

- If successful, returns **two** times
  - Once in parent
  - Once in child

```
char *newCmd;
char *newArgv[3];
newCmd = "cat";
newArgv[0] = "cat";
newArgv[1] = "readme";
newArgv[2] = NULL;
execvp(newCmd, newArgv);
fprintf(stderr, "exec failed\n");
exit(EXIT_FAILURE);
```

execvp()

- If successful, returns **zero** times
  - Calling program is overwritten with new program
- Corollary:
  - If **execvp()** returns, then it must have failed

execvp Example

```
$ cat readme
This is my
readme file.
```


execvp Example

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
int main(void)
{  char *newCmd;
   char *newArgv[3];
   newCmd = "cat";
   newArgv[0] = "cat";
   newArgv[1] = "readme";
   newArgv[2] = NULL;
   execvp(newCmd, newArgv);
   fprintf(stderr, "exec failed\n");
   return EXIT_FAILURE;
}
```

What is the output?

execvp Example Trace (1)

Process creates arguments to be passed to **execvp()**

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
int main(void)
{  char *newCmd;
   char *newArgv[3];
   newCmd = "cat";
   newArgv[0] = "cat";
   newArgv[1] = "readme";
   newArgv[2] = NULL;
   execvp(newCmd, newArgv);
   fprintf(stderr, "exec failed\n");
   return EXIT_FAILURE;
}
```


execvp Example Trace (2)

Process executes **execvp()**

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
int main(void)
{  char *newCmd;
   char *newArgv[3];
   newCmd = "cat";
   newArgv[0] = "cat";
   newArgv[1] = "readme";
   newArgv[2] = NULL;
   execvp(newCmd, newArgv);
   fprintf(stderr, "exec failed\n");
   return EXIT_FAILURE;
}
```

execvp Example Trace (3)

`cat` program executes in same process

```
cat program

with argv array:
   argv[0] = "cat"
   argv[1] = "readme"
   argv[2] = NULL
```


execvp Example Trace (4)

`cat` program writes "This is my\nreadme file."

```
cat program

with argv array:
   argv[0] = "cat"
   argv[1] = "readme"
   argv[2] = NULL
```


execvp Example Trace (5)

`cat` program terminates

```
cat program

with argv array:
   argv[0] = "cat"
   argv[1] = "readme"
   argv[2] = NULL
```


execvp Example Trace (6)

Output

```
This is my
readme file.
```


Agenda

Creating new processes

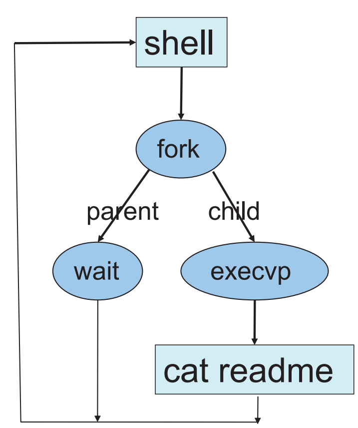
Waiting for processes to terminate

Executing new programs

Shell structure

Shell Structure

- Parent (shell) reads & parses the command line
  - E.g., "cat readme"
- Parent forks child
- Parent waits
- Child calls execvp to execute command
- Child exits
- Parent returns from wait
- Parent repeats



Simple Shell Code

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```


Simple Shell Trace (1)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

Parent reads and parses command line
Parent assigns values to **somepgm** and **someargv**

Simple Shell Trace (2)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

executing concurrently

Child Process

```
Parse command line
Assign values to somefile, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

fork() creates child process
Which process gets the CPU first? Let's assume the parent…

Simple Shell Trace (3)

Parent Process

child's pid

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

executing concurrently

Child Process

```
Parse command line
Assign values to somefile, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

In parent, pid != 0; parent waits; OS gives CPU to child

Simple Shell Trace (4)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

executing concurrently

0

Child Process

```
Parse command line
Assign values to somefile, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

In child, pid == 0; child calls **execvp()**

Simple Shell Trace (5)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

executing concurrently

Child Process

```
somepgm
With someargv
as argv param
```

In child, somepgm overwrites shell program;
main() is called with **someargv** as **argv** parameter

Simple Shell Trace (6)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

executing concurrently

Child Process

```
somepgm
With someargv
as argv param
```

Somepgm executes in child, and eventually exits

Simple Shell Trace (7)

Parent Process

```
Parse command line
Assign values to somepgm, someargv
pid = fork();
if (pid == 0) {
   /* in child */
   execvp(somepgm, someargv);
   fprintf(stderr, "exec failed\n");
   exit(EXIT_FAILURE);
}
/* in parent */
wait(NULL);
Repeat the previous
```

Parent returns from **`wait()`** and repeats

Background processes

Unix shell lets you run a process "in the background"

`$  compute <my-input >my-output &`

How it's implemented in the shell:

Don't wait() after the fork!

But: must clean up zombie processes

`waitpid(0, &status, WNOHANG)` (more info: "man 2 wait")

When to do it?

Every time around the main loop, or

When parent receives the SIGCHLD signal.

One or the other, don't need both!

Aside: `system` Function

Common combination of operations
- **`fork()`** to create a new child process
- **`execvp()`** to execute new program in child process
- **`wait()`** in the parent process for the child to complete

Single call that combines all three
- **`int system(const char *cmd);`**

Example

```
#include <stdlib.h>
int main(void)
{  system("cat readme");
   return 0;
}
```


Aside: `system` Function

Question:
- Why not use **`system()`** instead of **`fork()/execvp()/wait()`** in Assignment 7 shell?

Shallow answer:
- Assignment requirements!

Deeper answer:
- Using **`system()`**, shell could not handle **signals** as specified
- See ***Signals*** reference notes

Aside: `fork` Efficiency

Question:
- **`fork()`** duplicates an entire process (text, bss, data, rodata, stack, heap sections)
- Isn't that *very* inefficient???!!!

Answer:
- Using virtual memory, not really!
- Upon **`fork()`**, OS creates virtual pages for child process
- Each child virtual page maps to physical page (in memory or on disk) of parent
- OS duplicates physical pages incrementally, and only if/when "write" occurs ("copy-on-write")

Aside: exec Efficiency

Question:

- **`execvp()`** loads a new program from disk into memory
- Isn't that somewhat inefficient?

Answer:

- Using virtual memory, not really!
- Upon **`execvp()`**, OS changes process's virtual page table to point to pages on disk containing the new program
- As page faults occur, OS swaps pages of new program into memory incrementally as needed

Aside: `fork/exec` Efficiency

The bottom line…

`fork()` and **`execvp()`** are efficient

- Because they were designed with virtual memory in mind!

Commentary: A **beautiful** intersection of three **beautiful** abstractions

Assignment 7 Suggestion

A shell is mostly a big loop

- **Read char array** from **`stdin`**
- **Lexically** analyze char array to create **token array**
- **Parse** token array to create **command**
- **Execute** command
  - Fork child process
  - Parent:
    - Wait for child to terminate
  - Child:
    - Exec new program

Start with code from earlier slides and from precepts

- And edit until it becomes a Unix shell!

Summary

Creating new processes

- **`fork()`**

Executing new programs

- **`execvp()`**

Waiting for processes to terminate

- **`wait()`**

Shell structure

- Combination of **`fork()`**, **`execvp()`**, **`wait()`**