

Part I Introduction

General Information

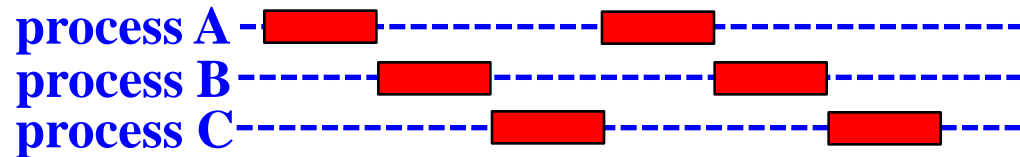
*Computer programming is an art form,
like the creation of poetry or music.*

1

Donald Ervin Knuth

Concurrent vs. Parallel: 1/3

- The execution of processes is said to be
❖ **interleaved**, if all processes are *in progress* but not all of them are *running*;



- ❖ **parallel**, if they are all *running* at the same time;



- ❖ **Concurrent**, if it is interleaved or parallel.

Concurrent vs. Parallel: 2/3

- A ***parallel*** program may have a number of processes or threads, each of which runs on a CPU/core. All execute at the same time.
- A parallel program needs multiple CPU/cores; but, a concurrent program may only need **ONE**.
- ***Concurrent*** is more general than ***Parallel***!
- ***Why?*** We may write a concurrent program with multiple processes or threads. If we have enough number of CPUs, all processes or threads can run in parallel. Otherwise, the OS assigns each process/thread some CPU time in turn so that they can finish their job bit-by-bit.³

Concurrent vs. Parallel: 3/3

- **This world is actually very concurrent.**
- **You are eating while watching TV.**
- **You listen to music, send e-mail, talk to your buddy at the same time.**
- **You text and drive at the same time. This is a dangerous concurrent system because due to interleaved execution you won't be able to pay attention to the traffic all the time.**
- **Think about some concurrent stuffs in a computer system.....**

Some Historical Remarks: 1/6

- It all started with operating systems design.
- If your program is doing input and output, it cannot run until the I/O completes. ***Why?***
- If there is only one program in the system, the CPU is idle when this program is doing I/O.
- Decades ago, I/O devices were very slow although CPUs were not fast either (but very expensive).
- Therefore, once the program starts doing I/O, we are wasting our money!

Some Historical Remarks: 2/6

- Then, why don't we run a second program while the first one is doing I/O?
- Thus, program 1 does I/O & program 2 computes, program 2 does I/O & program 1 computes, etc.
- The system has **TWO** programs running, each of which has some progress at any time. ***Isn't this the concept of concurrency?***
- If we could run two programs, why don't we run more? But, wait a minute! The power of a CPU is limited and is not able to run too many programs!

Some Historical Remarks: 3/6

- In the 1960's, operating systems could run multiple programs (i.e., multiprogramming).
- If a system could run several programs at the same time, why don't we split a program into multiple pieces (i.e., processes or threads) so that they run concurrently.
- So, systems can run multiple programs and programs can have multiple processes/threads.
- Concurrent programming is born.
- This is what we are going to talk about.

Some Historical Remarks: 4/6

- In the early 1960's, a number of higher-level programming languages supported concurrency.
- PL/I F and ALGOL 68 were among the first.
- Then, we had Modula 2, followed by Modula 3, Ada, Concurrent Euclid, Turing Plus, etc. No, I did not forget Java; but, it is a late comer. The new C++ standard also supports concurrency.
- Systems also provided system calls and libraries to support concurrent programming.
- Concurrent programming was booming in the 1990's.

Some Historical Remarks: 5/6

- Programmers may be excited about concurrency. But, the picture is not that rosy because splitting a program into multiple processes or threads is easily said than done.
- Processes and threads must communicate with each other to get the job done. Once there are communications there are troubles. (What if I missed your call asking for some data, to continue or not to continue becomes your big question.)
- This is ***synchronization***. I am sure many of you will hate me when we talk about it.

Some Historical Remarks: 6/6

- Not only synchronization is a headache, splitting a program improperly would just make the program more inefficient.
- This requires a new mindset to design good concurrent programs. ***So, be prepared.***
- The behavior of concurrent programs is ***dynamic***. A bug may not surface until our grader is grading your programs. Even if it appears at this time, it may not occur when you run the program again. Or, it may never occur!
- No debugger can catch dynamic bugs completely.

First Taste of Concurrency: 1/7

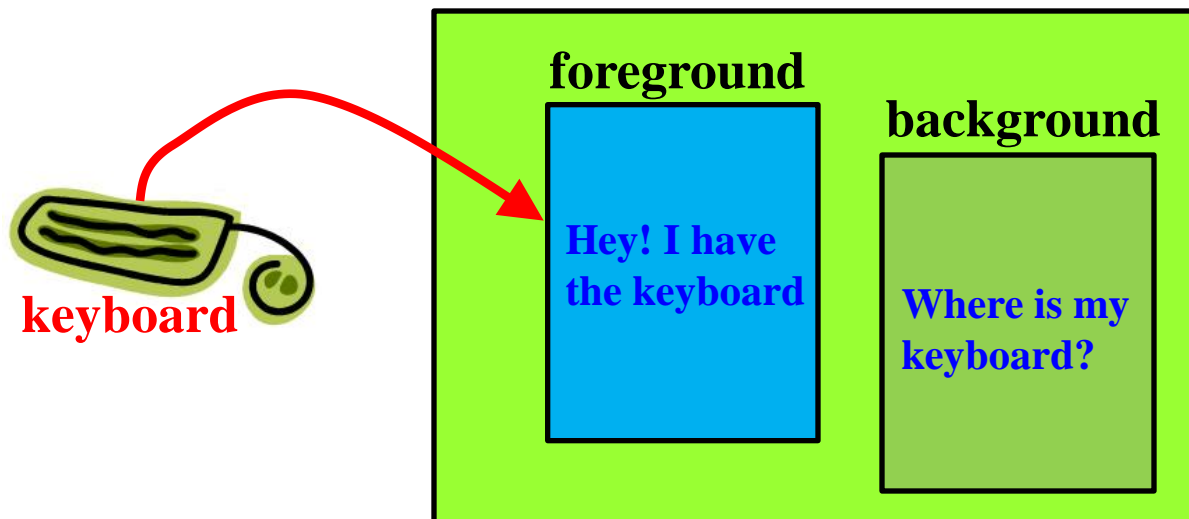
- **Actually, you know it and do it every day.**
- **You sit down in front of a computer and open multiple windows in each of which you run an application (i.e., web browser, editor, e-mail).**
- **This is concurrency!**
- **Let us look at a very simple example.**

First Taste of Concurrency: 2/7

- Consider the Unix command line operator `&`.
- Is `&` the **bit-wise and** operator? No, it is not! It runs a program in the background.
- When your program runs, it becomes a process. Don't worry about its actual meaning as we will explain it in great detail very soon.
- This process takes its input from the keyboard, and waits until the input becomes available.
- You won't be able to issue shell commands because the keyboard is now the `stdin` of your program.

First Taste of Concurrency: 3/7

- By running a process in the **background**, it means the window from which you run the program is detached from the process, and command line input becomes available.
- The process has the command line input is said to be in the **foreground**.



First Taste of Concurrency: 4/7

- Running a program with `&` puts that program in the background.

`a.out &`

- The above runs `a.out` in the background. The command line is available immediately.
- You may use `&` as many times as possible. The program before each `&` runs in the background.

`a.out & dumb-prog & smart`

- `a.out` and `dumb-prog` are in the background, while `smart` is in the foreground.
- So, ***they run concurrently!***

First Taste of Concurrency: 5/7

```
#include <stdio.h>
#include <stdlib.h>

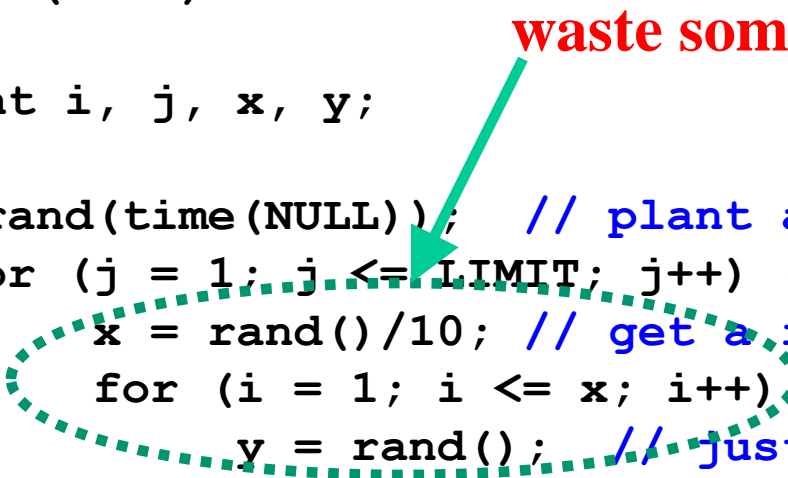
#define LIMIT (20) // run this number of iterations

int main(void)
{
    int i, j, x, y;

    srand(time(NULL)); // plant a random number seed
    for (j = 1; j <= LIMIT; j++) {
        x = rand()/10; // get a random number and scale
        for (i = 1; i <= x; i++)
            y = rand(); // just waste CPU time, :o)
        printf("Hi, A here! Random number = %d\n", x);
    }
    printf("A completes\n");
}
```

procA.c

waste some CPU time



First Taste of Concurrency: 6/7

```
#include <stdio.h>
#include <stdlib.h>

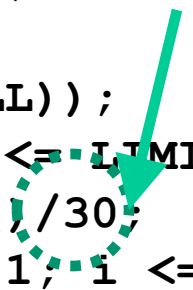
#define LIMIT (20)

int main(void)
{
    int i, j, x, y;

    srand(time(NULL));
    for (j = 1; j <= LIMIT; j++) {
        x = rand() / 30; // scaled differently
        for (i = 1; i <= x; i++)
            y = rand();
        printf("  Hi, B here!  Random number = %d\n", x);
    }
    printf("          B completes\n");
}
```

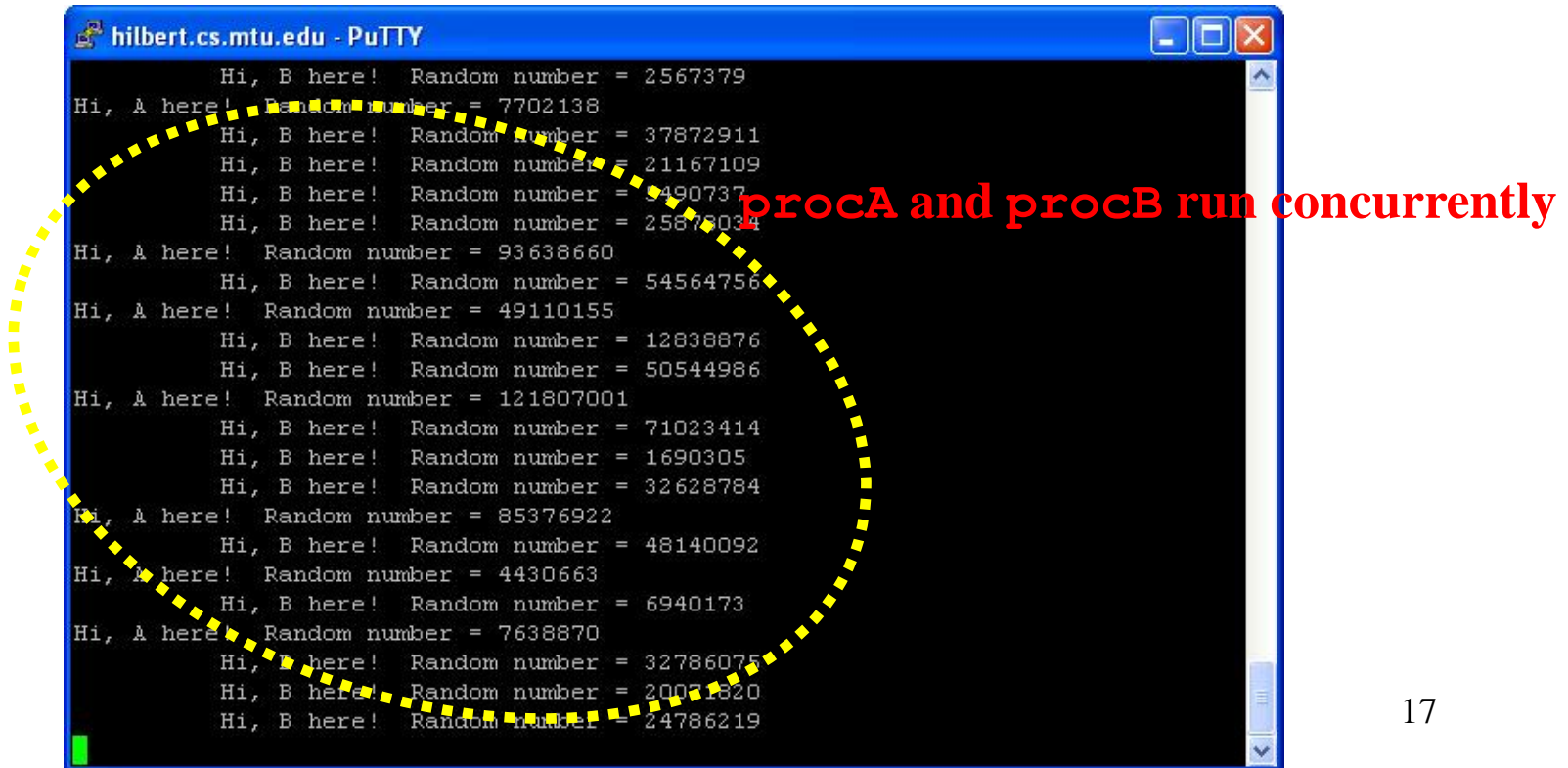
procB.c

Random number **x** is scaled differently
(only 1/3 of the one in **procA.c**)
Thus, **procB** prints faster



First Taste of Concurrency: 7/7

- Run them with **procA** & **procB**
- Which one is in the foreground/background?



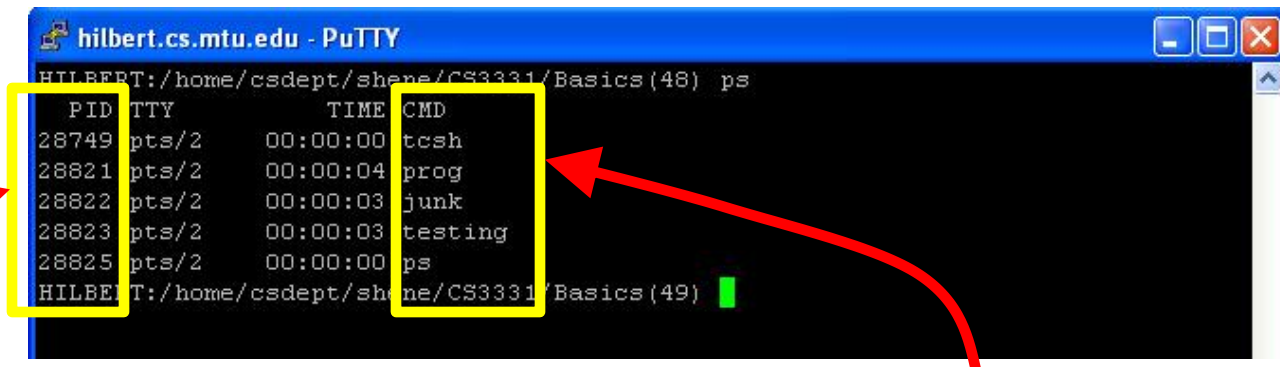
hilbert.cs.mtu.edu - PuTTY

```
Hi, B here! Random number = 2567379
Hi, A here! Random number = 7702138
Hi, B here! Random number = 37872911
Hi, B here! Random number = 21167109
Hi, B here! Random number = 3490737
Hi, B here! Random number = 25878034
Hi, A here! Random number = 93638660
Hi, B here! Random number = 54564756
Hi, A here! Random number = 49110155
Hi, B here! Random number = 12838876
Hi, B here! Random number = 50544986
Hi, A here! Random number = 121807001
Hi, B here! Random number = 71023414
Hi, B here! Random number = 1690305
Hi, B here! Random number = 32628784
Hi, A here! Random number = 85376922
Hi, B here! Random number = 48140092
Hi, A here! Random number = 4430663
Hi, B here! Random number = 6940173
Hi, A here! Random number = 7638870
Hi, B here! Random number = 32786075
Hi, B here! Random number = 20071820
Hi, B here! Random number = 24786219
```

procA and procB run concurrently

Let Us Investigate Further

- Since programs become processes when they run, how many processes do I have?
- The Unix **ps** command reports process status.
- **ps** without arguments reports **your** processes.
- **ps** may use other arguments to get a full report that includes **all** processes running concurrently.



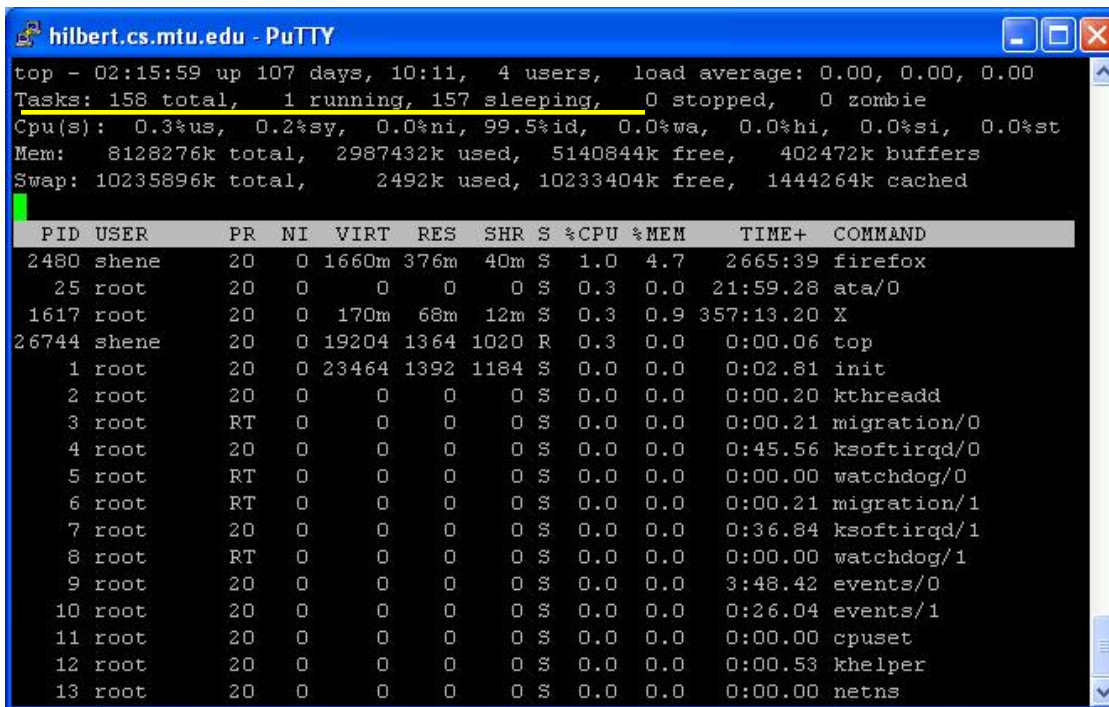
```
hilbert.cs.mtu.edu - PuTTY
HILBERT:/home/csdept/shane/CS3331/Basics(48) ps
  PID TTY          TIME CMD
 28749 pts/2        00:00:00 tcsh
 28821 pts/2        00:00:04 prog
 28822 pts/2        00:00:03 junk
 28823 pts/2        00:00:03 testing
 28825 pts/2        00:00:00 ps
HILBERT:/home/csdept/shane/CS3331/Basics(49) █
```

These are the assigned process IDs

These are the program names

Who Is the Top CPU Hog?

- The **top** command is a system monitor tool, which shows and frequently updates system resource usage, usually sorted by percentage of CPU usage.

A screenshot of a PuTTY terminal window titled 'hilbert.cs.mtu.edu - PuTTY'. The window displays the output of the 'top' command. The first section shows system statistics: 'top - 02:15:59 up 107 days, 10:11, 4 users, load average: 0.00, 0.00, 0.00', 'Tasks: 158 total, 1 running, 157 sleeping, 0 stopped, 0 zombie', 'Cpu(s): 0.3%us, 0.2%sy, 0.0%ni, 99.5%id, 0.0%wa, 0.0%hi, 0.0%si, 0.0%st', and 'Mem: 8128276k total, 2987432k used, 5140844k free, 402472k buffers'. The second section is a table of processes. The first row is the header: 'PID USER PR NI VIRT RES SHR S %CPU %MEM TIME+ COMMAND'. The second row shows '2480 shene 20 0 1660m 376m 40m S 1.0 4.7 2665:39 firefox'. The third row shows '25 root 20 0 0 0 0 S 0.3 0.0 21:59.28 ata/0'. The fourth row shows '1617 root 20 0 170m 68m 12m S 0.3 0.9 357:13.20 X'. The fifth row shows '26744 shene 20 0 19204 1364 1020 R 0.3 0.0 0:00.06 top'. The sixth row shows '1 root 20 0 23464 1392 1184 S 0.0 0.0 0:02.81 init'. The seventh row shows '2 root 20 0 0 0 0 S 0.0 0.0 0:00.20 kthreadd'. The eighth row shows '3 root RT 0 0 0 0 S 0.0 0.0 0:00.21 migration/0'. The ninth row shows '4 root 20 0 0 0 0 S 0.0 0.0 0:45.56 ksoftirqd/0'. The tenth row shows '5 root RT 0 0 0 0 S 0.0 0.0 0:00.00 watchdog/0'. The eleventh row shows '6 root RT 0 0 0 0 S 0.0 0.0 0:00.21 migration/1'. The twelfth row shows '7 root 20 0 0 0 0 S 0.0 0.0 0:36.84 ksoftirqd/1'. The thirteenth row shows '8 root RT 0 0 0 0 S 0.0 0.0 0:00.00 watchdog/1'. The fourteenth row shows '9 root 20 0 0 0 0 S 0.0 0.0 3:48.42 events/0'. The fifteenth row shows '10 root 20 0 0 0 0 S 0.0 0.0 0:26.04 events/1'. The sixteenth row shows '11 root 20 0 0 0 0 S 0.0 0.0 0:00.00 cpuset'. The seventeenth row shows '12 root 20 0 0 0 0 S 0.0 0.0 0:00.53 khelper'. The eighteenth row shows '13 root 20 0 0 0 0 S 0.0 0.0 0:00.00 netns'.

```
hilbert.cs.mtu.edu - PuTTY
top - 02:15:59 up 107 days, 10:11, 4 users, load average: 0.00, 0.00, 0.00
Tasks: 158 total, 1 running, 157 sleeping, 0 stopped, 0 zombie
Cpu(s): 0.3%us, 0.2%sy, 0.0%ni, 99.5%id, 0.0%wa, 0.0%hi, 0.0%si, 0.0%st
Mem: 8128276k total, 2987432k used, 5140844k free, 402472k buffers
Swap: 10235896k total, 2492k used, 10233404k free, 1444264k cached

  PID USER      PR  NI  VIRT  RES  SHR  S  %CPU  %MEM    TIME+  COMMAND
 2480 shene    20   0 1660m 376m 40m   S   1.0   4.7   2665:39  firefox
    25 root       20   0     0     0     0   S   0.3   0.0   21:59.28  ata/0
 1617 root       20   0 170m   68m 12m   S   0.3   0.9   357:13.20  X
26744 shene    20   0 19204 1364 1020  R   0.3   0.0    0:00.06  top
     1 root       20   0 23464 1392 1184  S   0.0   0.0    0:02.81  init
     2 root       20   0     0     0     0   S   0.0   0.0    0:00.20  kthreadd
     3 root      RT   0     0     0     0   S   0.0   0.0    0:00.21  migration/0
     4 root       20   0     0     0     0   S   0.0   0.0    0:45.56  ksoftirqd/0
     5 root      RT   0     0     0     0   S   0.0   0.0    0:00.00  watchdog/0
     6 root      RT   0     0     0     0   S   0.0   0.0    0:00.21  migration/1
     7 root       20   0     0     0     0   S   0.0   0.0    0:36.84  ksoftirqd/1
     8 root      RT   0     0     0     0   S   0.0   0.0    0:00.00  watchdog/1
     9 root       20   0     0     0     0   S   0.0   0.0    3:48.42  events/0
    10 root       20   0     0     0     0   S   0.0   0.0    0:26.04  events/1
    11 root       20   0     0     0     0   S   0.0   0.0    0:00.00  cpuset
    12 root       20   0     0     0     0   S   0.0   0.0    0:00.53  khelper
    13 root       20   0     0     0     0   S   0.0   0.0    0:00.00  netns
```

158 processes
1 running
157 sleeping
Top CPU usage: firefox, 1%

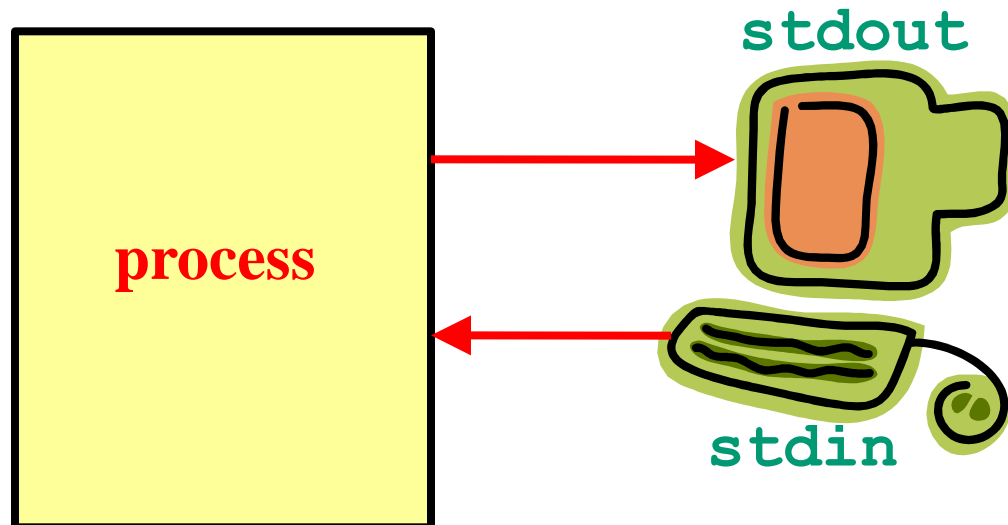
These processes are run
concurrently

Some Cooperation: 1/10

- Previous examples have processes running ***independent of each other*** (i.e., they do not need any help from each other).
- They are ***independent processes***.
- If processes must communicate with each other to complete a task, they become cooperative (i.e., ***cooperating processes***).
- Independent processes are easy to handle; however, cooperating processes require a careful planning for ***synchronization***.

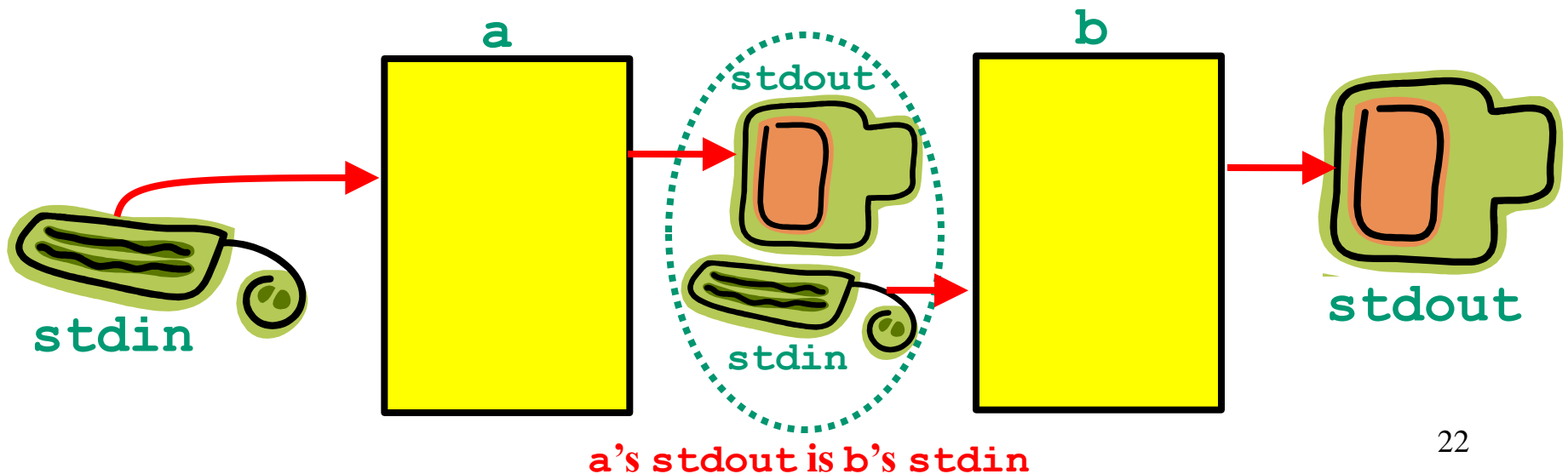
Some Cooperation: 2/10

- Here is a very simple cooperating processes example.
- This is the Unix pipe operator `|`.
- A program has its default I/O: `stdin` (keyboard), `stdout` (screen), and `stderr`.



Some Cooperation: 3/10

- If you use **a | b**, where **a** and **b** are two programs, the **stdout** of **a** becomes the **stdin** of **b**.
- In this way, **a** takes input from its **stdin**, sends output to **b**, and **b** prints to **b**'s **stdout**.



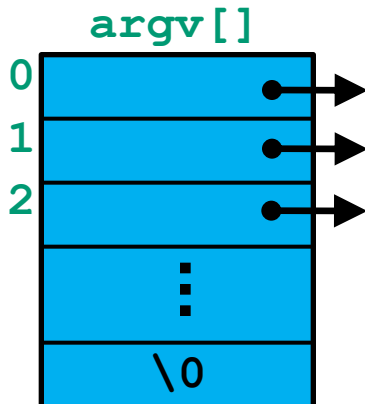
Some Cooperation: 4/10

pA.c

```
#include <stdio.h>

int main(int argc, char **argv[])
{
    int    i, LIMIT;
    char   output[100];

    LIMIT = atoi(argv[1]); // read command line argument
    printf("%d\n", LIMIT); // print # of lines
    for (i = 1; i <= LIMIT; i++) { // print the lines
        sprintf(output, "Printing %d from A", i);
        printf("%s\n", output);
    }
}
```



The diagram shows an array named `argv[]` with indices 0, 1, 2, and a final cell containing `\0`. Arrows point from the first three cells to the right. A red dotted arrow points from the `argv[1]` in the code to the first cell of the array. Another red dotted arrow points from the `output` variable in the code to the `sprintf` function call.

print to a character string

read an **int** from command line and print that number of lines

Some Cooperation: 5/10

pB.c

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

```
int main(void)
{
    int i, LIMIT;
    char input[100];

    gets(input); // read a complete input line
    LIMIT = atoi(input); // convert to integer
    for (i = 1; i <= LIMIT; i++) { // repeat
        gets(input); // read a complete input line
        printf("    From B: %s\n", input);
    }
}
```

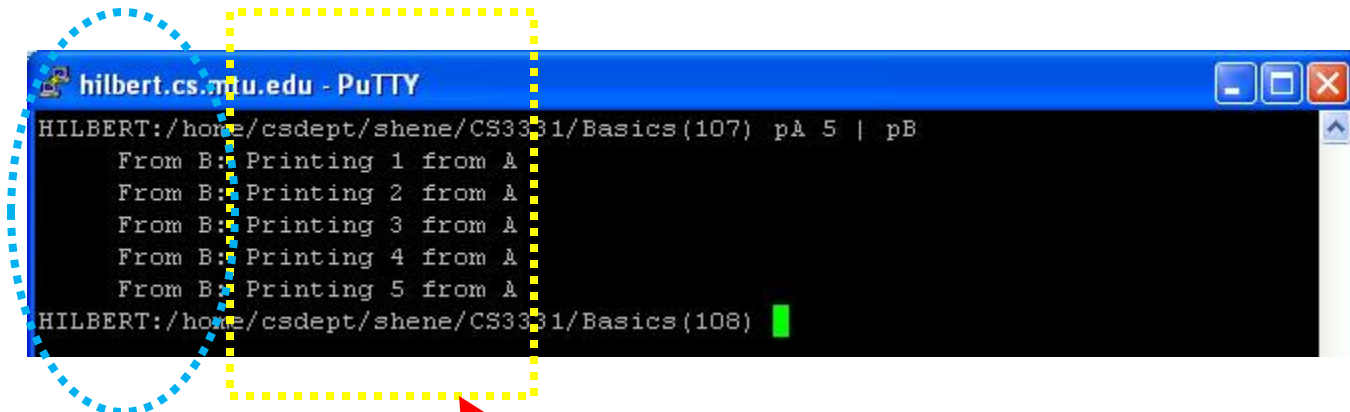
The first `int` gives the number of lines to be read

`gets(input);` is a bit risky as it does not have a bound.

Some Cooperation: 6/10

The following shows the result of

pA 5 | pB
print 5 lines from pA



```
hilbert.cs.mtu.edu - PuTTY
HILBERT:/home/csdept/shene/CS3331/Basics(107) pA 5 | pB
  From B: Printing 1 from A
  From B: Printing 2 from A
  From B: Printing 3 from A
  From B: Printing 4 from A
  From B: Printing 5 from A
HILBERT:/home/csdept/shene/CS3331/Basics(108) █
```

pB adds this portion

pB receives this portion from pA

Some Cooperation: 7/10

pC.c

```
#include <stdio.h>

int main(void)
{
    int i, LIMIT = 100;
    char input[100];

    // now we use a better way: fgets()
    // keep reading until EOF
    while (fgets(input, LIMIT, stdin) != NULL)
        printf("From C: %s", input);
}
```

fgets() is safer than **gets()**

input char []

max length including \0

NULL means EOF

Some Cooperation: 8/10

The following shows the result of

pA 7 | pB | pC
print 7 lines from pA

```
hilbert.cs.mtu.edu - PuTTY
HILBERT:/home/csdept/shene/CS331/Basics(116) pA 7 | pB | pC
  From C:      From B: Printing 1 from A
  From C:      From B: Printing 2 from A
  From C:      From B: Printing 3 from A
  From C:      From B: Printing 4 from A
  From C:      From B: Printing 5 from A
  From C:      From B: Printing 6 from A
  From C:      From B: Printing 7 from A
HILBERT:/home/csdept/shene/CS331/Basics(117)
```

pC adds this portion

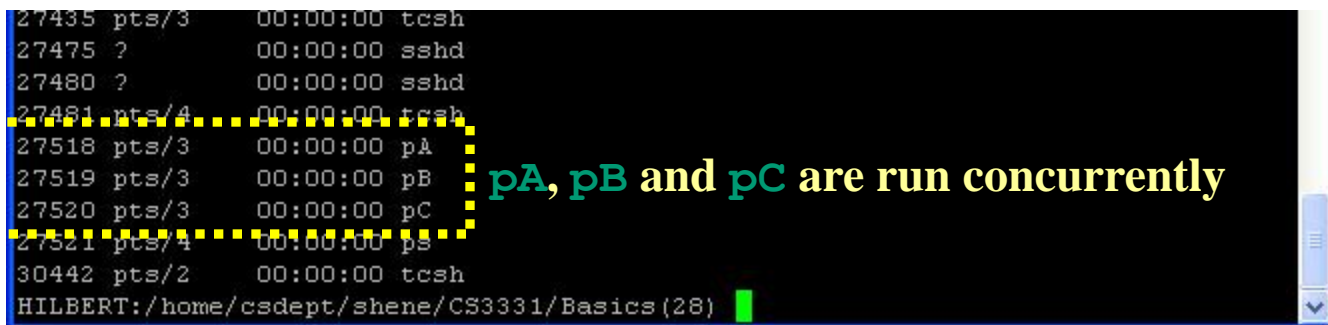
pB adds this portion

pB receives this portion from pA

Some Cooperation: 9/10

- Processes **pA**, **pB** and **pC** run concurrently.
- The following is a screenshot of the **ps** command **ps -A** while **pA 10000 | pB | pC** is in execution.

show all processes



```
27435 pts/3    00:00:00 tcsh
27475 ?        00:00:00 sshd
27480 ?        00:00:00 sshd
27481 pts/4    00:00:00 tcsh
27518 pts/3    00:00:00 pA
27519 pts/3    00:00:00 pB
27520 pts/3    00:00:00 pC
27521 pts/4    00:00:00 ps
30442 pts/2    00:00:00 tcsh
HILBERT:/home/csdept/shene/CS3331/Basics (28)
```

pA, pB and pC are run concurrently

Some Cooperation: 10/10

- Since **pB** depends on **pA**'s output, and **pC** depends on **pB**'s output, **pA**, **pB** and **pC** are cooperating processes, and they communicate via their “hooked” **stdins** and **stdouts**, even though this type of communication is very simple.
- We will see more complex communication techniques among processes and threads soon.

Few Extra Unix Commands: 1/2

- ***Ctrl-Z***: Suspend the foreground process and return to the shell (i.e., command line)
- **bg**: Run the most recently suspended process in the background.

prog // run program **prog**

Ctrl-Z // suspend **prog**

bg // resume **prog** in the background

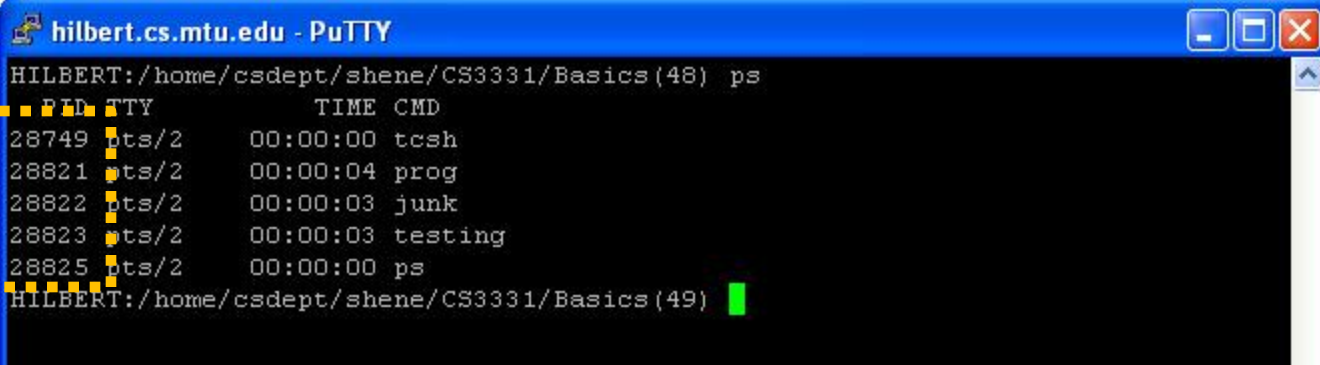
- **fg**: Bring the most recent background process to foreground.

fg // **prog** in the foreground

Few Extra Unix Commands: 2/2

- Each process has a process ID assigned by the OS.

process ID



```
hilbert.cs.mtu.edu - PuTTY
HILBERT:/home/csdept/shene/CS3331/Basics(48) ps
  PID TTY          TIME CMD
 28749 pts/2        00:00:00 tcsh
 28821 pts/2        00:00:04 prog
 28822 pts/2        00:00:03 junk
 28823 pts/2        00:00:03 testing
 28825 pts/2        00:00:00 ps
HILBERT:/home/csdept/shene/CS3331/Basics(49)
```

- To terminate processes, use
`kill -KILL pid1 pid2 ... pidi`
- `kill -KILL 28821 28823` terminates `prog` and `testing`.
- Note that `KILL` is actually `9`. I prefer `KILL`.

I/O Redirection: 1/3

- A program may read input from a text file instead of `stdin` (i.e., redirecting input).
- Similarly, a program may print output to a text file instead of `stdout` (i.e., redirecting output).
- `prog < data`: program `prog` reads input from file `data`. File `data` must exist before `prog` is run.
- `prog > report`: program `prog` prints output to file `report`.

I/O Redirection: 2/3

- What is the difference between the following:

`pA | pB`

and

`pA > temp-file`

`pB < temp-file`

- The first version has `pA` and `pB` running concurrently, while the second is not.
- Since input file `temp-file` of `pB` must exist before `pB` runs, `pB` must wait until `pA` finishes its work.

I/O Redirection: 3/3

- Both `stdin` and `stdout` may be redirected.
- In the following, `prog` reads input from file `data` and prints output to file `report`:

```
prog < data > report
```

The End