



Consortium des Equipements  
de Calcul Intensif  
en Fédération Wallonie-Bruxelles

# Introduction to Parallel Computing

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# Agenda

1. General concepts, definitions, challenges
2. Hardware for parallel computing
3. Programming models
4. User tools

1.

# General concepts

# Why parallel? (simplified)

Speed up – Solve a problem faster  
→ more processing power  
(a.k.a. strong scaling)

Scale up – Solve a larger problem  
→ more memory and network capacity  
(a.k.a. weak scaling)

Scale out – Solve many problems  
→ more storage capacity

# Parallelization involves:

- *decomposition* of the work
  - **distributing instructions** to processors
  - **distributing data** to memories
- *collaboration* of the workers
  - **synchronization** of the distributed work
  - **communication** of data

Parallelization involves:

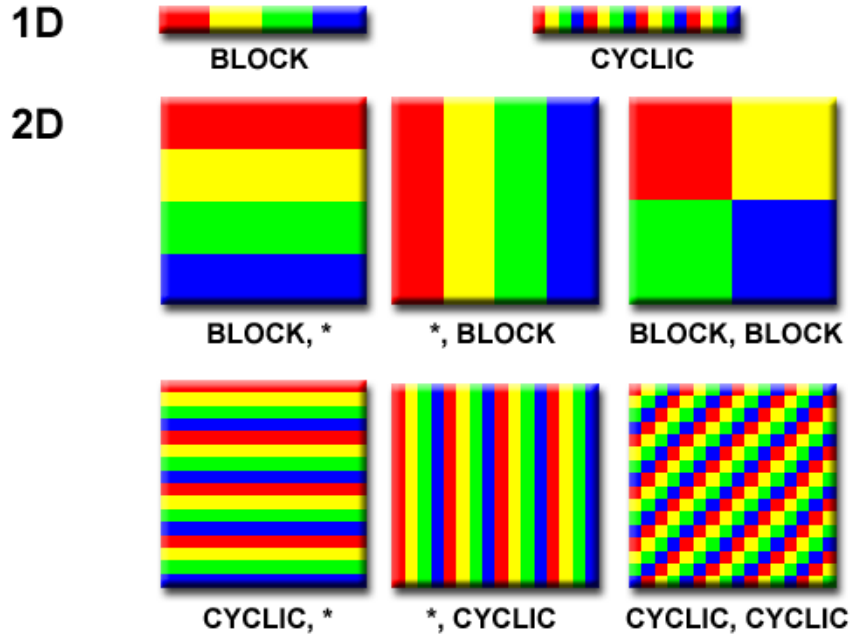
# Decomposition of the work

- **Operation decomposition** : task-level parallelism
  - Multiple programs (functional decomposition)
  - Multiple instances of the same program
- **Data decomposition** : data-level parallelism

Parallelization involves:

# Decomposition of the work

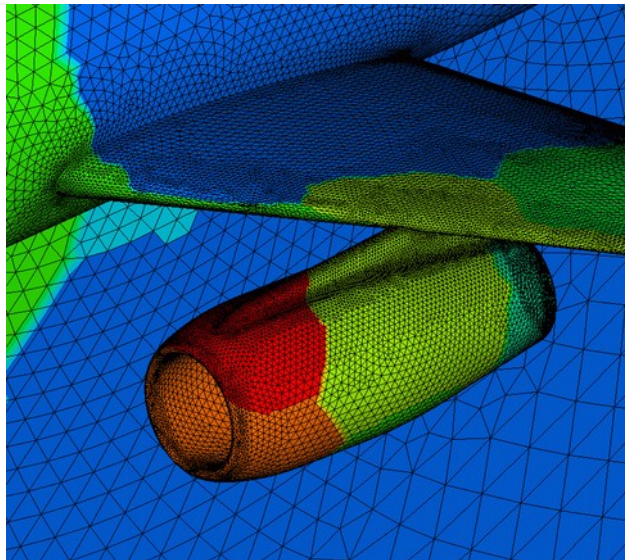
- **Operation decomposition** : task-level parallelism
- **Data decomposition** : data-level parallelism
  - **Block, cyclic**



Parallelization involves:

# Decomposition of the work

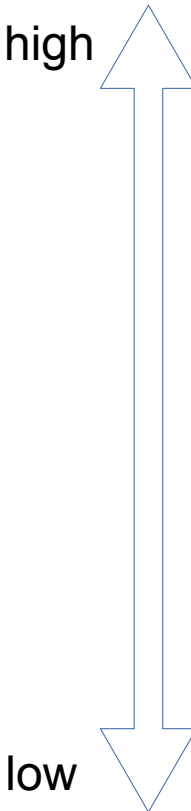
- **Operation decomposition** : task-level parallelism
- **Data decomposition** : data-level parallelism
  - **Domain decomposition** : decomposition of work and data is done in a higher model, e.g. in the reality





# Collaboration of the workers

- **Synchronization of the workers**

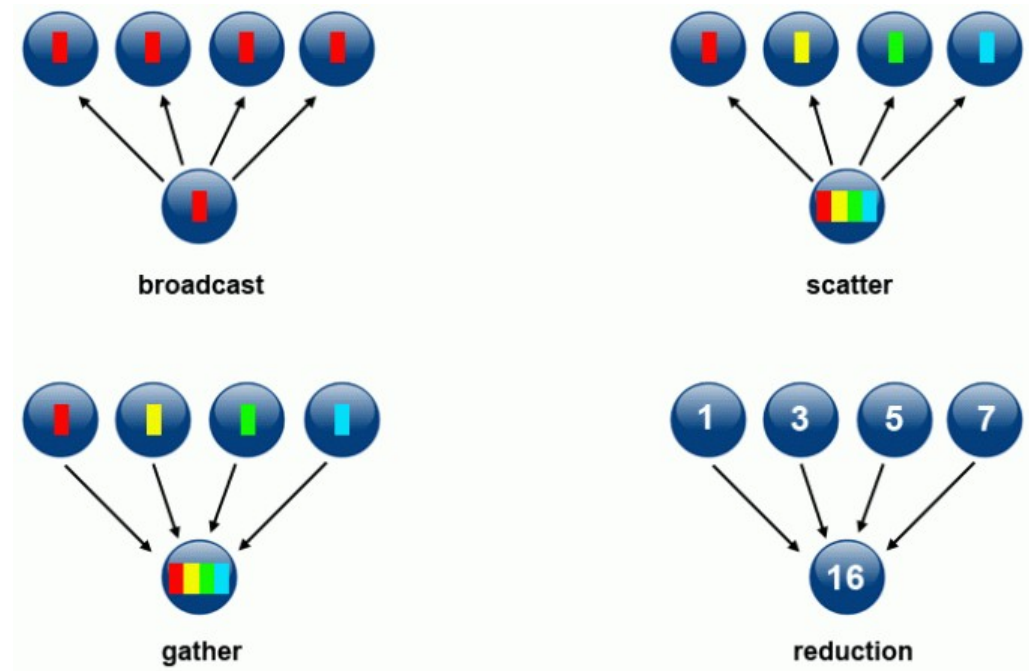
- 
- **Synchronous** (SIMD) at the processor level ; the same processor instruction for each worker at any time ; (instruction level)
  - **Fine-grained** parallelism : subtasks communicate many times per second (typically at the loop level)
  - **Coarse-grained** parallelism : they do not communicate many times per second (typically function-call level)
  - **Embarrassingly parallel** : they rarely or never have to communicate (asynchronous)

Parallelization involves:

# Collaboration of the workers

- **Communication between workers**

- Point to point
- Broadcast
- Scatter
- Gather
- Reduction



# Does it work?

## Speedup, Efficiency, Scalability

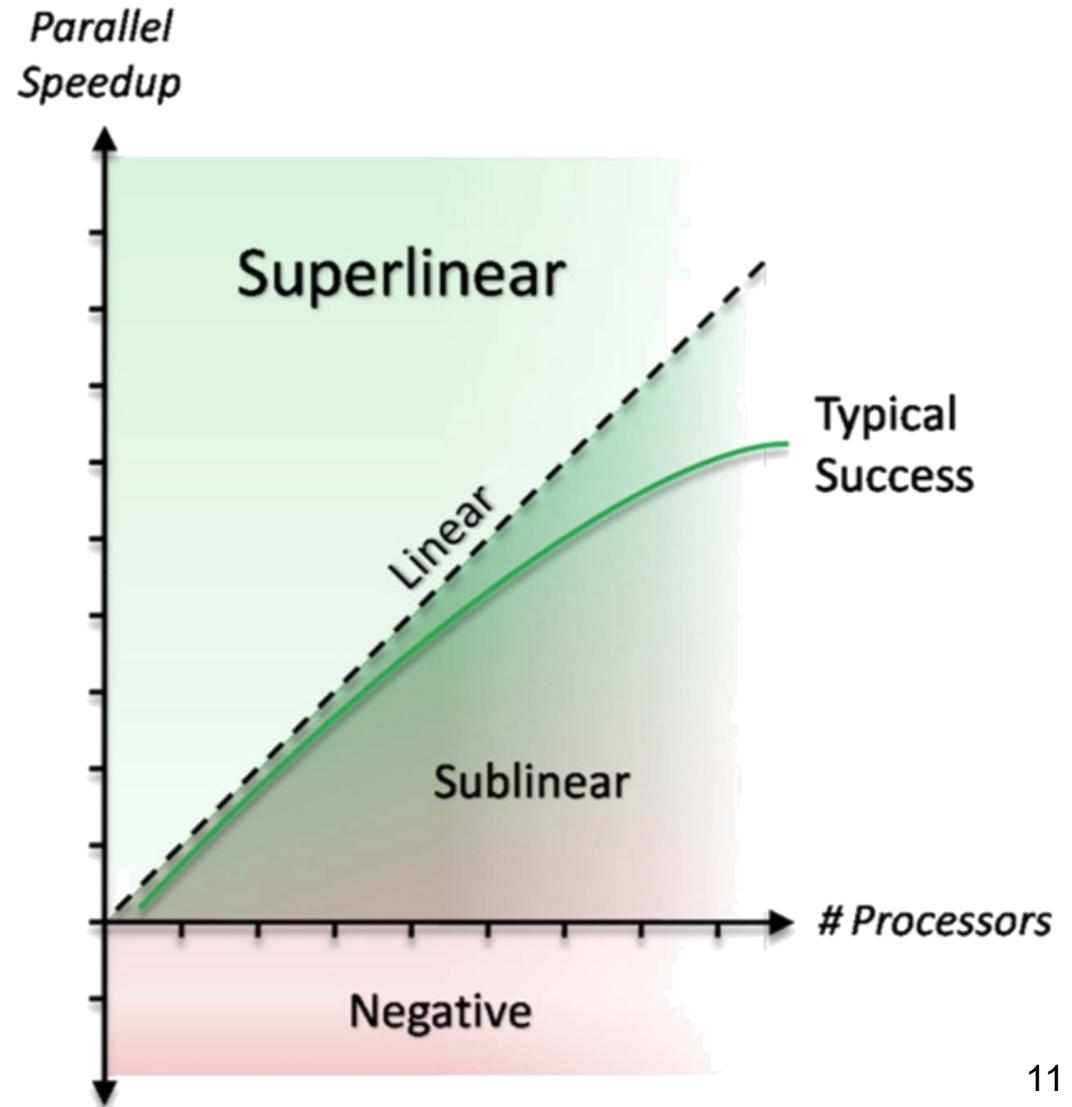
Time for serial operations

Speedup  $S = \frac{T_S}{T_P}$

Time for parallel operations

Efficiency  $E = \frac{S}{p} = \frac{T_S}{pT_p}$

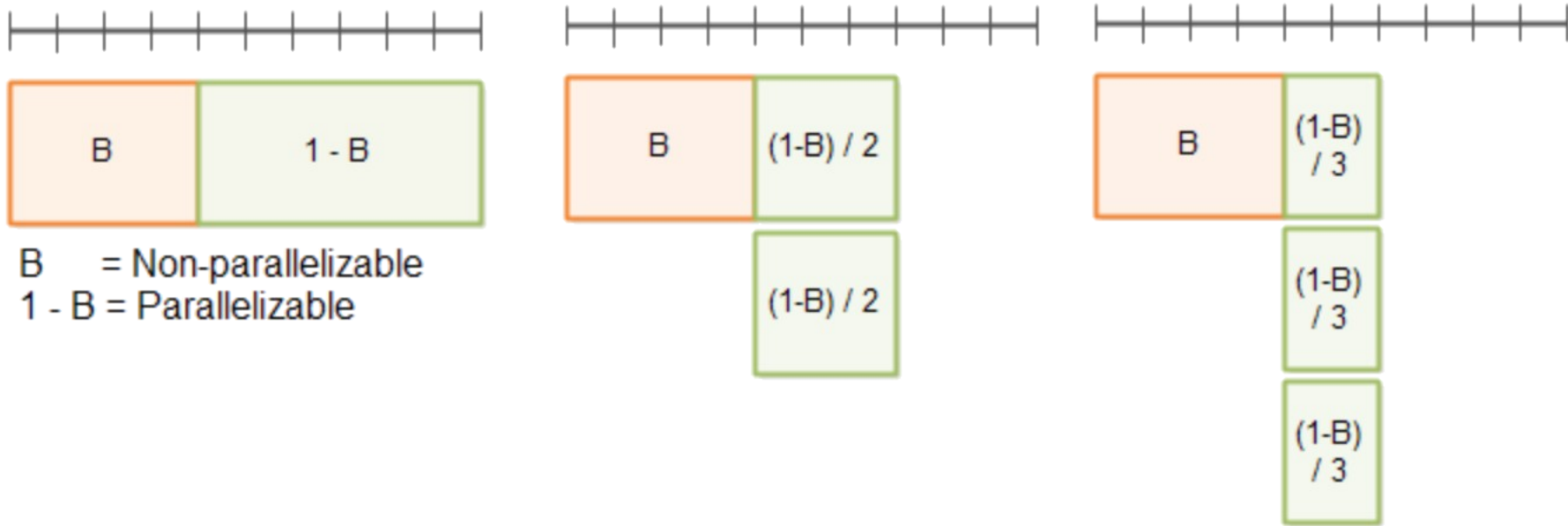
Number of processors



Why wouldn't it work?

# Challenge 1: Amdahl's Law

Not all the work can be decomposed



In parallel computing, Amdahl's law is mainly used to predict the theoretical maximum speedup for programs using multiple processors.



Why wouldn't it work?

# Challenge 3: Load imbalance

Parallelization is efficient only if every worker has the same amount of work

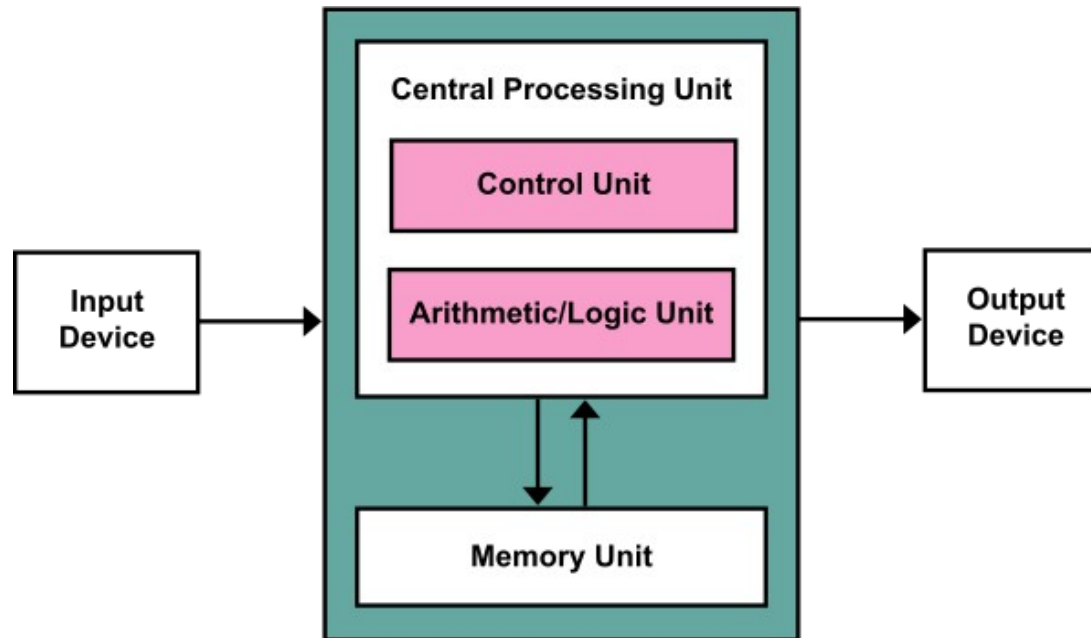


# 2.

## Hardware for parallel computing

# Von Neumann (serial) architecture

An abstract view of early computers





# Parallelism at the CPU (core) level

- Instruction-level parallelism (ILP)
  - Instruction pipelining
  - Out-of-order execution
  - Speculative execution
  - ...
- Single Instruction Multiple Data (SIMD)

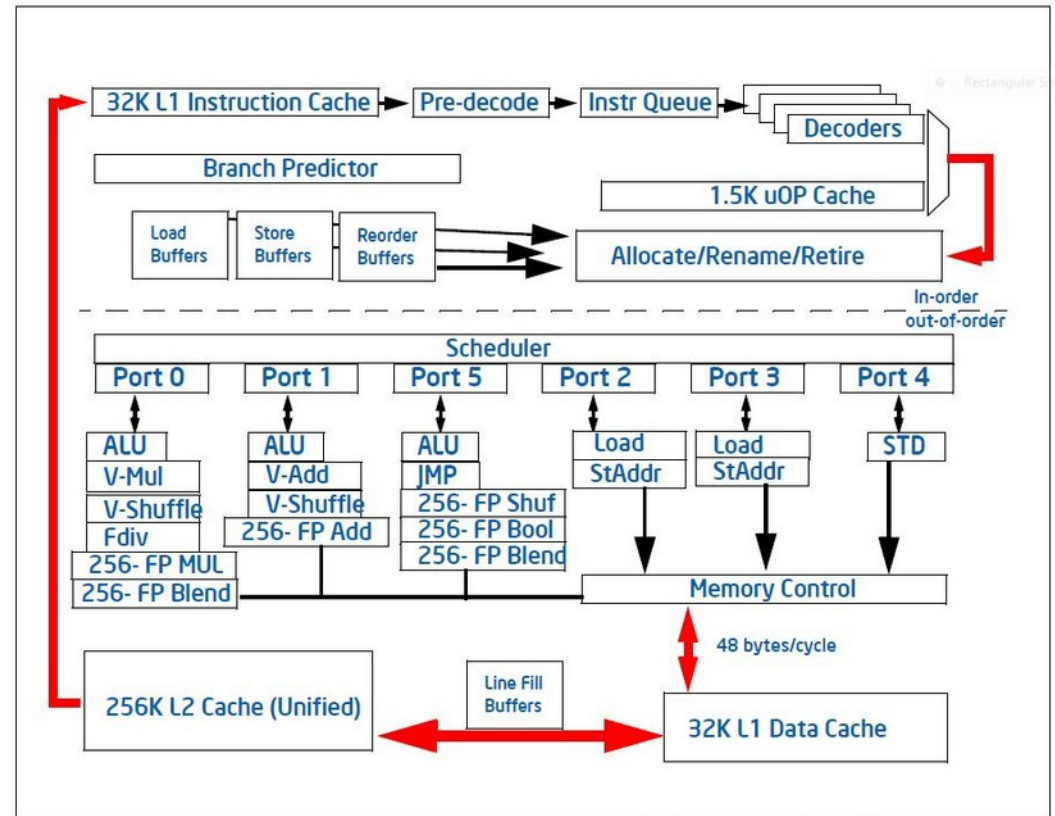
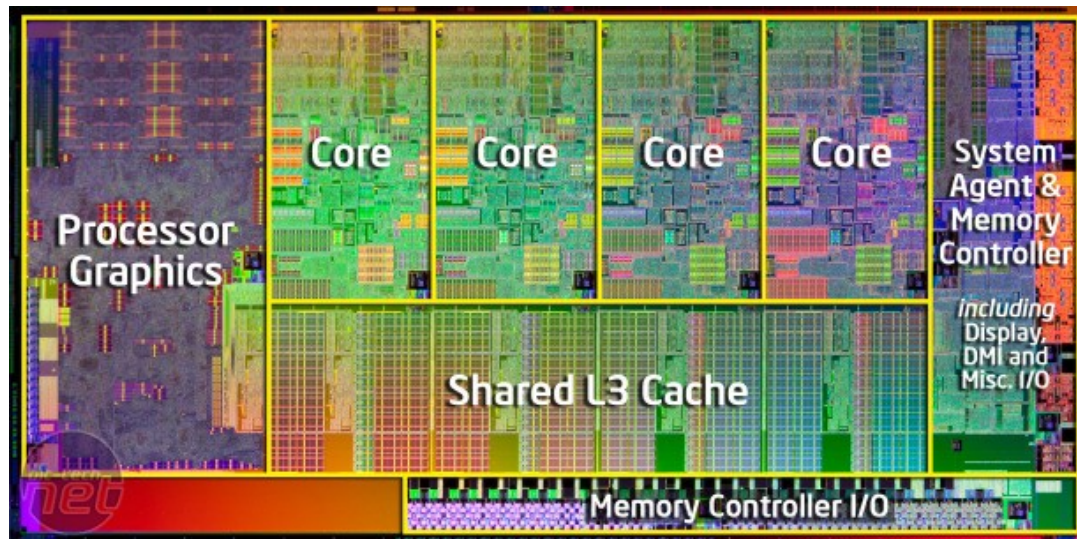


Figure 2-1. Intel microarchitecture code name Sandy Bridge Pipeline Functionality



# Parallelism at the chip (socket) level

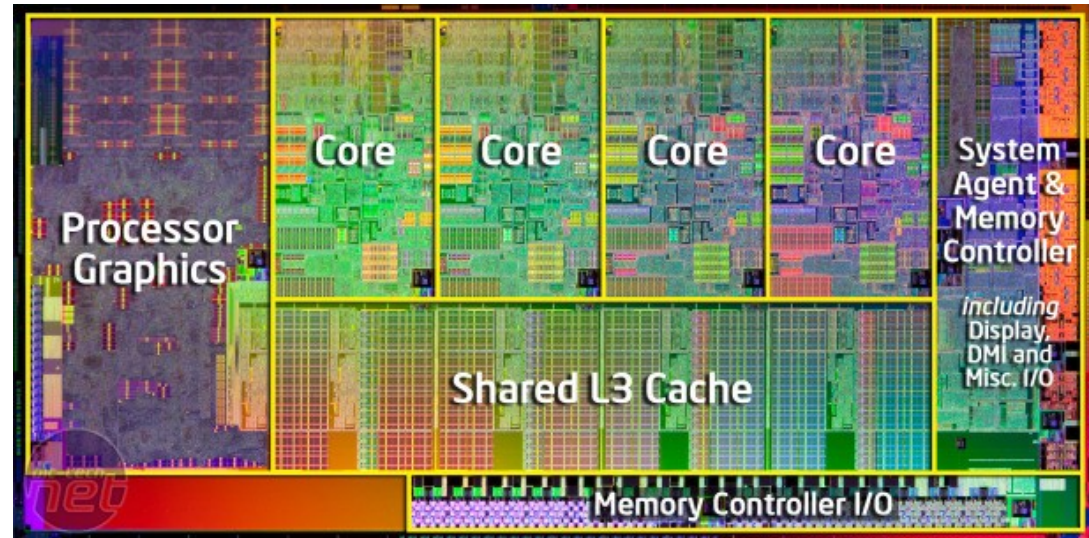
- Multicore parallelism



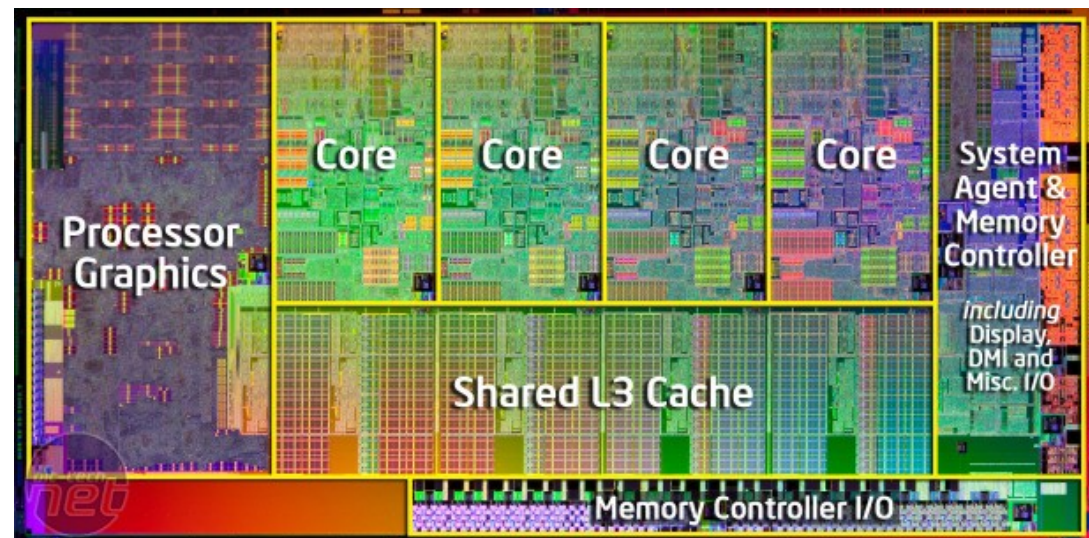
# Parallelism at the computer level



- Multi-socket parallelism
  - SMP
  - NUMA



- Accelerators





# Parallelism at the data center level



Multi-node parallelism



# Parallelism at the data center level

## Cluster computing



### Consortium des Équipements de Calcul Intensif

6 clusters, 10k cores, 1 login, 1 home directory

## About

CÉCI is the 'Consortium des Équipements de Calcul Intensif'; a consortium of high-performance computing centers of [UCL](#), [ULB](#), [ULg](#), [UMons](#), and [UNamur](#). [Read more.](#)



## The common storage is functional!

Have you tried it yet? [More info...](#)

## Latest News

SATURDAY, 23 SEPTEMBER 2017

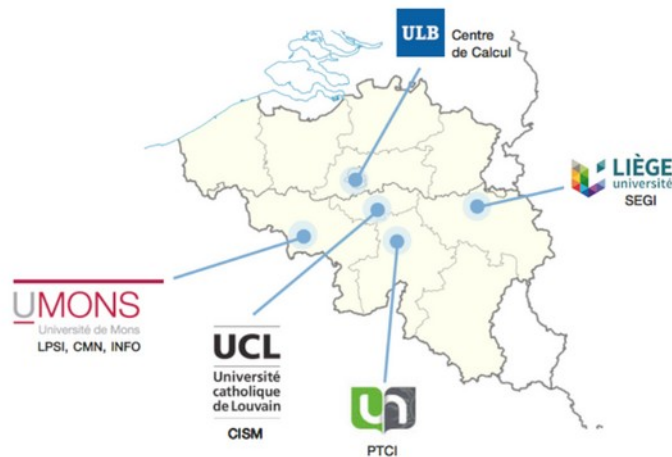
### A CECI user pictured in the ULiège news!

The ULiège website [published a story](#) (in French) about the work of Denis Baurain and his collaborators on the Tier-1 cluster Zenobe that lead to a publication in [Nature Ecology & Evolution](#).

TUESDAY, 01 AUGUST 2017

### Ariel Lozano is the new CÉCI logisticien

We are happy to announce the hire of a new CECI logisticien: Ariel Lozano. Welcome Ariel!



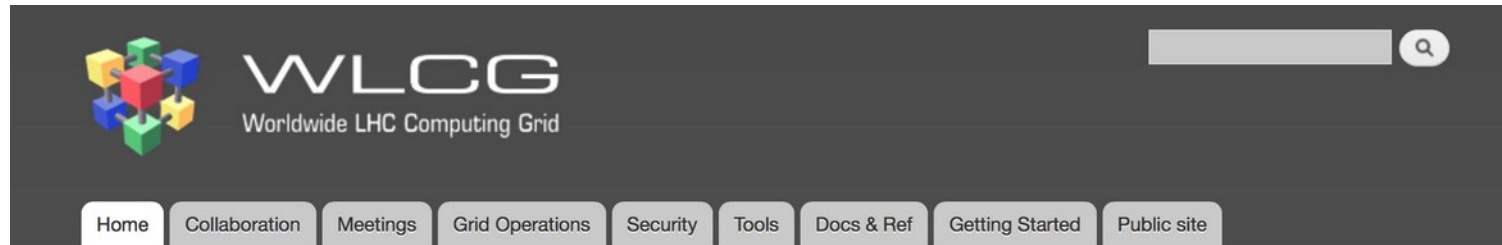
# Parallelism at the data center level

Cloud computing “someone else’s cluster”



# Parallelism at the world level

Grid computing – “cluster of clusters”

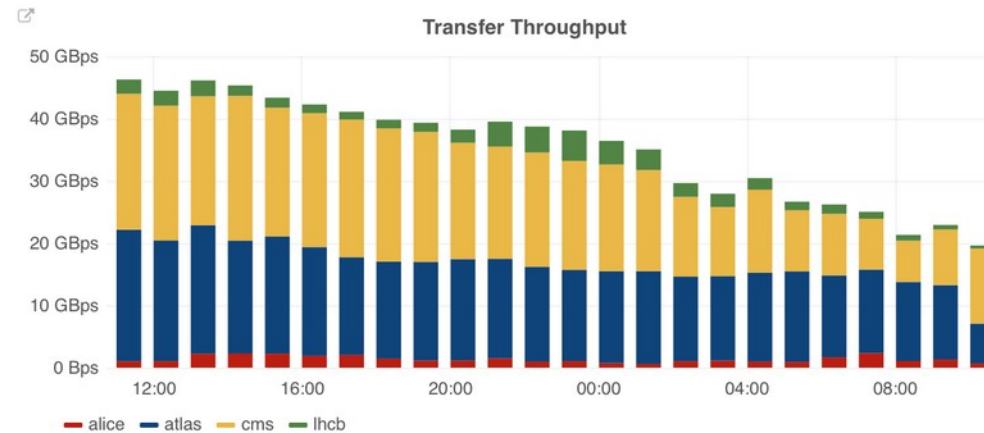


The header of the WLCG website features the logo on the left, which consists of a 3D arrangement of colored cubes (yellow, green, red, blue). To the right of the logo is the text "WLCG" in a large, bold, sans-serif font, with "Worldwide LHC Computing Grid" in a smaller font below it. Further right is a search bar with a magnifying glass icon. Below these elements is a horizontal navigation menu with buttons for "Home", "Collaboration", "Meetings", "Grid Operations", "Security", "Tools", "Docs & Ref", "Getting Started", and "Public site".

[Home](#)

## Welcome to the Worldwide LHC Computing Grid

Last 24 hours



The Worldwide LHC Computing Grid (**WLCG**) project is a global collaboration of more than 170 computing centres in 42 countries, linking up national and international grid infrastructures.

### About WLCG

[What is WLCG? See our public site...](#)

[Hangout with CERN: LHC and Grid - the world is our calculator](#)

### Jobs

No jobs currently published.

### News

- [TEG Reports](#)
- [Computing Model Update available](#)
- [Technology Market Cost Trends](#)





# Parallelism at the world level

Distributed computing – “no unused cycle”

**SETI@home**


Project ▾ Science ▾ Computing ▾ Community ▾ Site ▾ Sign Up Login

### What is SETI@home?

SETI@home is a scientific experiment, based at **UC Berkeley**, that uses Internet-connected computers in the Search for Extraterrestrial Intelligence (SETI). You can participate by running a free program that downloads and analyzes radio telescope data.

[Join SETI@home](#)

### User of the Day

 **The\_PC\_God**  
Hello community. My name is Daniel. I am 28 years old and i live in a small village called Kuhardt (Rhineland-Palatinate, Germany) which is located...

### News

#### BSRC Student Travel Fundraiser

Berkeley SETI Research Center is holding a fundraiser to raise \$7000 to send our student interns to conferences to present their work.

We've been working with some great students at Berkeley SETI, and we're optimistic that some of them will become the scientists and engineers who lead the field in future and maybe even find the signal we're searching for. In the meantime they have been doing amazing work and we'd like to send them to academic conferences to present their results, and for their own professional development. If you would like to help with this effort, we are running a crowdfunding campaign at <https://crowdfund.berkeley.edu/SETItravel> - every donation counts! We also have some fun perks including the chance to ask questions to members of the Berkeley SETI team, and to attend a party in our lab.

Although this does not directly benefit SETI@home (our annual fundraiser will start in a couple weeks), it's a worthy cause. I'll be contributing!

2 Oct 2017, 18:10:26 UTC · [Discuss](#)



# 3.

## Programming paradigms and programming models

# Is parallization automagic?

- **ILP**: yes
- **SIMD**: mostly, but the compiler can be fooled by your code (*→ pragmas*)
- **Intra-node**: can be if the library/software you use is designed for it (*→ \*\_NUM\_THREADS env vars, be aware of NUMA placement issues*)
- **GPUs**: can be if the library/software you use is designed for it (*→ CUDA\_VISIBLE\_DEVICES env vars, be aware of GPU/CPU memory transfers*)
- **Inter-node**: never automagic. You will at least need to explicitly start processes (*→ be aware of the network capabilities*)

If you are in charge of parallization, see next slides...

# Main parallel programming paradigms

- **Task-farming:**
  - Master program distributes work to worker programs (*leader/follower*); or
  - Worker programs pick up tasks from pool (*work stealing*).
- **SPMD** (Single program multiple data)
  - A single program that contains both the logic for distributing work and computing
  - Multiple instances are started and “linked” together
  - Instances are identified with a distinct index

# Other parallel programming paradigms

- **MPMD (Multiple program multiple data)**
- **Pipelining** : workers take care of a subtask in the processing chain and pass the intermediate result to the next worker
- **Divide and Conquer** :
  - workers are spawned at need and report their result to the parent
  - Speculative parallelism : workers are spawned and result possibly discarded

```
If (very_long_computation)
then
    do A
else
    do B
```

# Programming models

- Single computer:
  - **CPUs:** PThreads, *OpenMP*, TBB, OpenCL, ...
  - **Accelerators:** *CUDA*, OpenCL, *OpenAcc/OpenMP*, SYCL, Hipp, ROCm, ...
- Multi-computer:
  - **Clusters:**
    - Message passing: *MPI*, PVM
    - PGAS: CoArray Fortran, UPC, Global Arrays
  - **Clouds:** MapReduce, Spark RDD
  - **Distributed computing:** BOINC

# 4.

## User tools that GNU/Linux offers

- 4.1 Parallelized tools
- 4.2 Job control and parallel processes
- 4.3 Basic tools
- 4.4 GNU Parallel

# 4.1. Parallelized utilities

Some tools have a parallelized counterpart. Examples:

serial

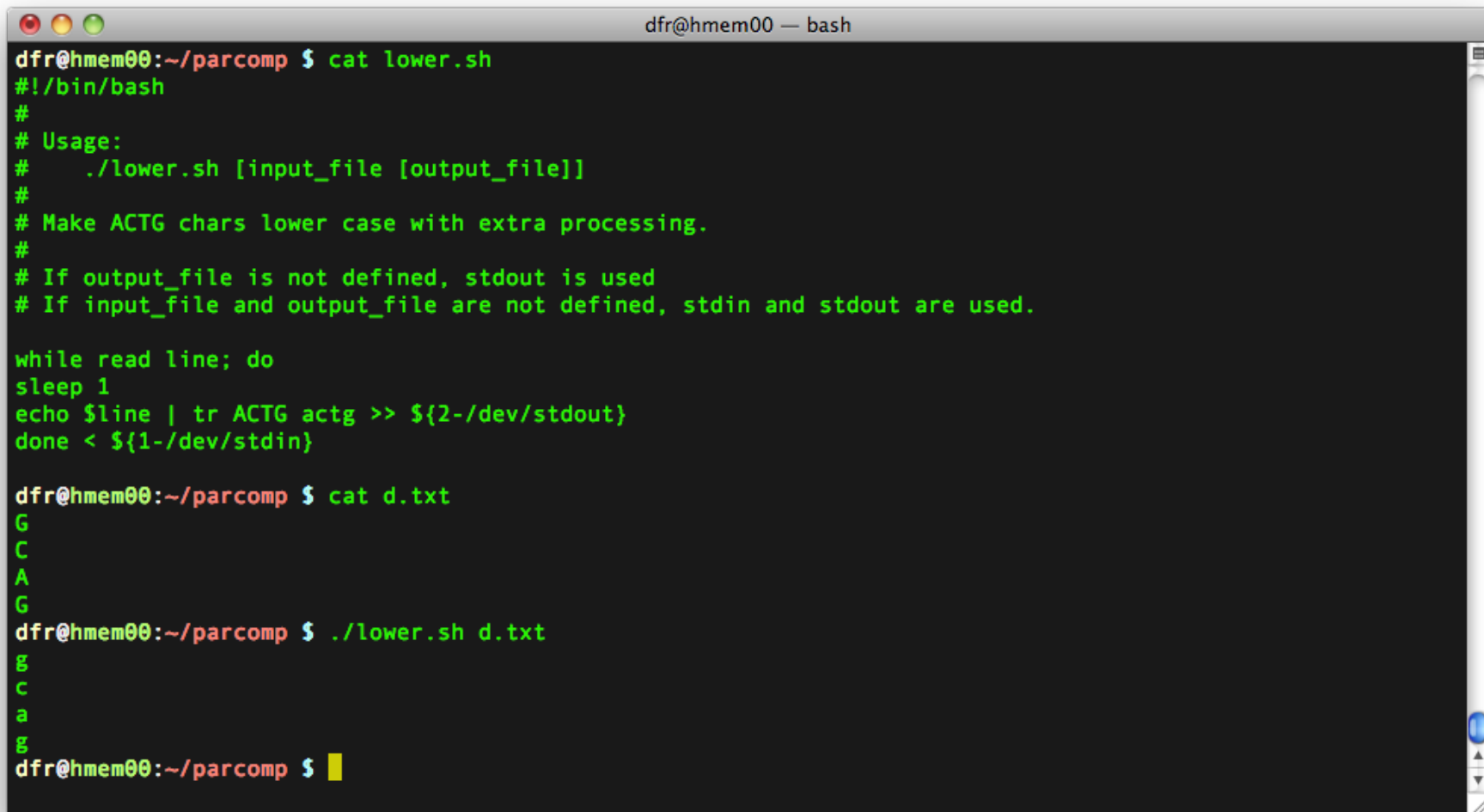
gzip  
grep  
ssh  
sort  
scp  
bc  
...

pigz  
ripgrep  
clustershell  
sort -parallel  
bbcp  
bcx  
...

parallel

## 4.2. Job control & Parallel processes in Bash

Consider the following example program



```
dfr@hmem00:~/parcomp $ cat lower.sh
#!/bin/bash
#
# Usage:
#   ./lower.sh [input_file [output_file]]
#
# Make ACTG chars lower case with extra processing.
#
# If output_file is not defined, stdout is used
# If input_file and output_file are not defined, stdin and stdout are used.

while read line; do
sleep 1
echo $line | tr ACTG actg >> ${2-/dev/stdout}
done < ${1-/dev/stdin}

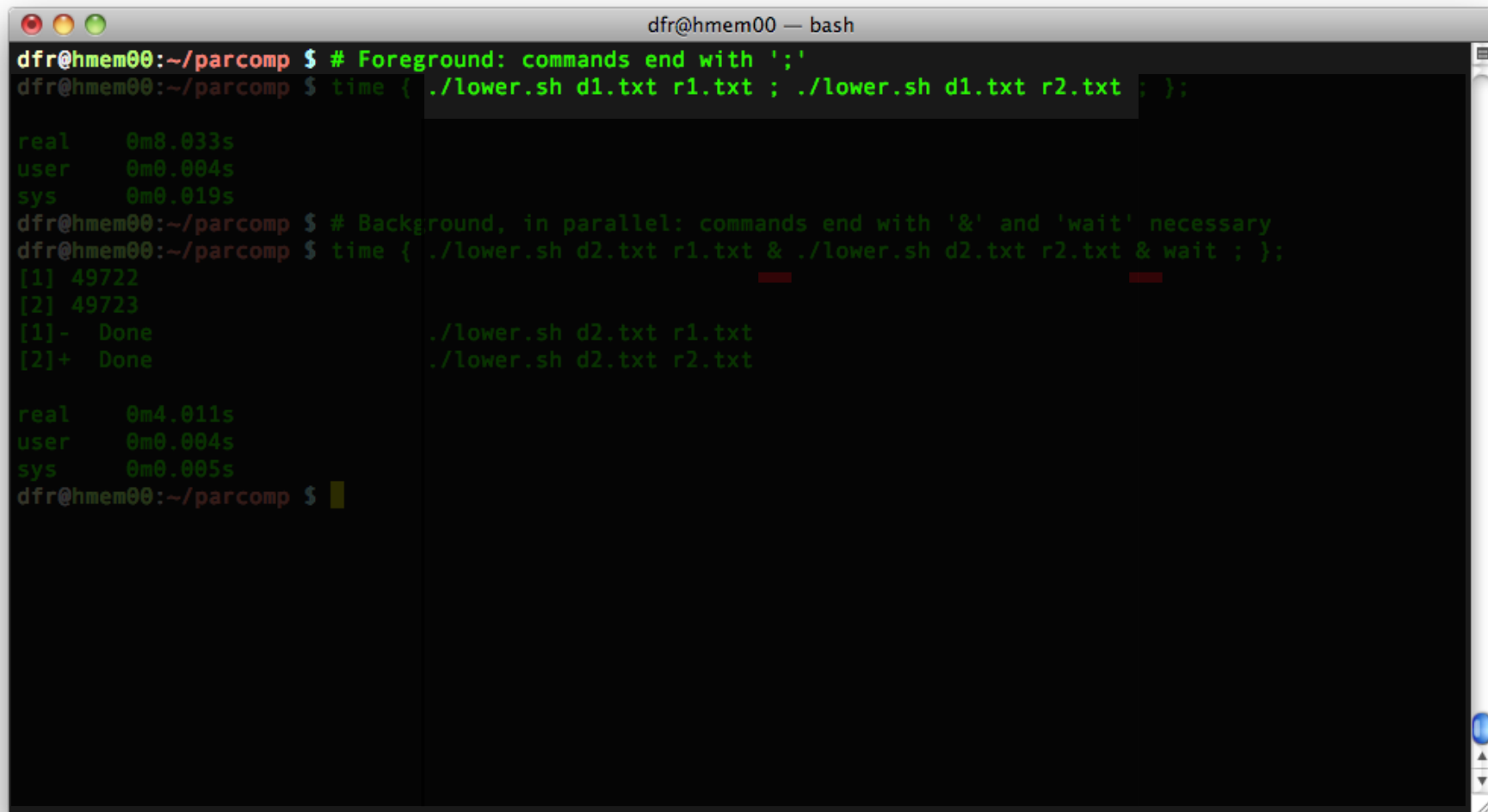
dfr@hmem00:~/parcomp $ cat d.txt
G
C
A
G
dfr@hmem00:~/parcomp $ ./lower.sh d.txt
g
c
a
g
dfr@hmem00:~/parcomp $
```

It is written in Bash and just transforms some upper case letters to lower case



## 4.2. Job control & Parallel processes in Bash

Run the program twice



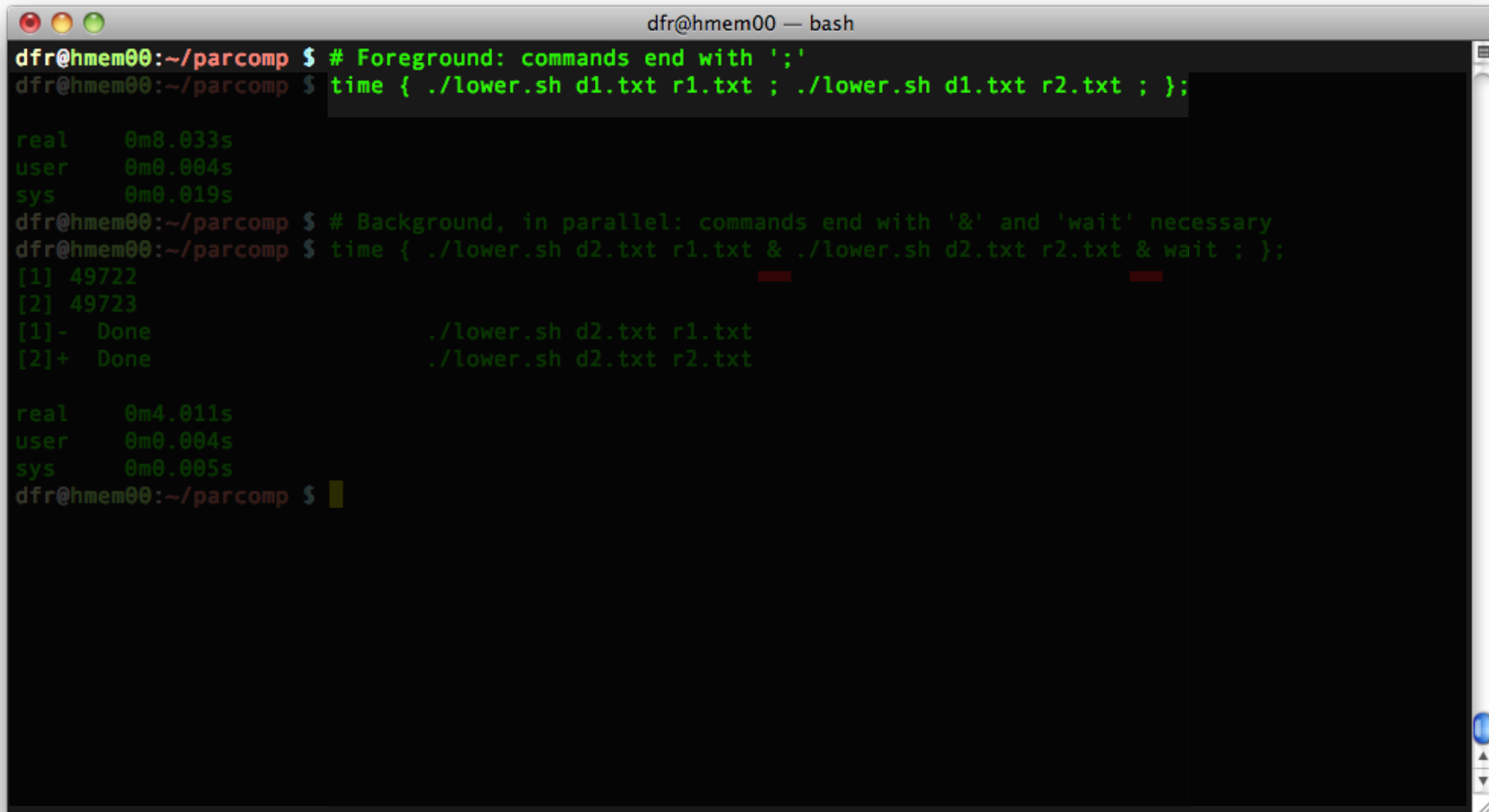
```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ # Foreground: commands end with ';'
dfr@hmem00:~/parcomp $ time { ./lower.sh d1.txt r1.txt ; ./lower.sh d1.txt r2.txt ; };

real    0m8.033s
user    0m0.004s
sys     0m0.019s
dfr@hmem00:~/parcomp $ # Background, in parallel: commands end with '&' and 'wait' necessary
dfr@hmem00:~/parcomp $ time { ./lower.sh d2.txt r1.txt & ./lower.sh d2.txt r2.txt & wait ; };
[1] 49722
[2] 49723
[1]-  Done                ./lower.sh d2.txt r1.txt
[2]+  Done                ./lower.sh d2.txt r2.txt

real    0m4.011s
user    0m0.004s
sys     0m0.005s
dfr@hmem00:~/parcomp $
```

## 4.2. Job control & Parallel processes in Bash

Run the program twice and measure the time it takes



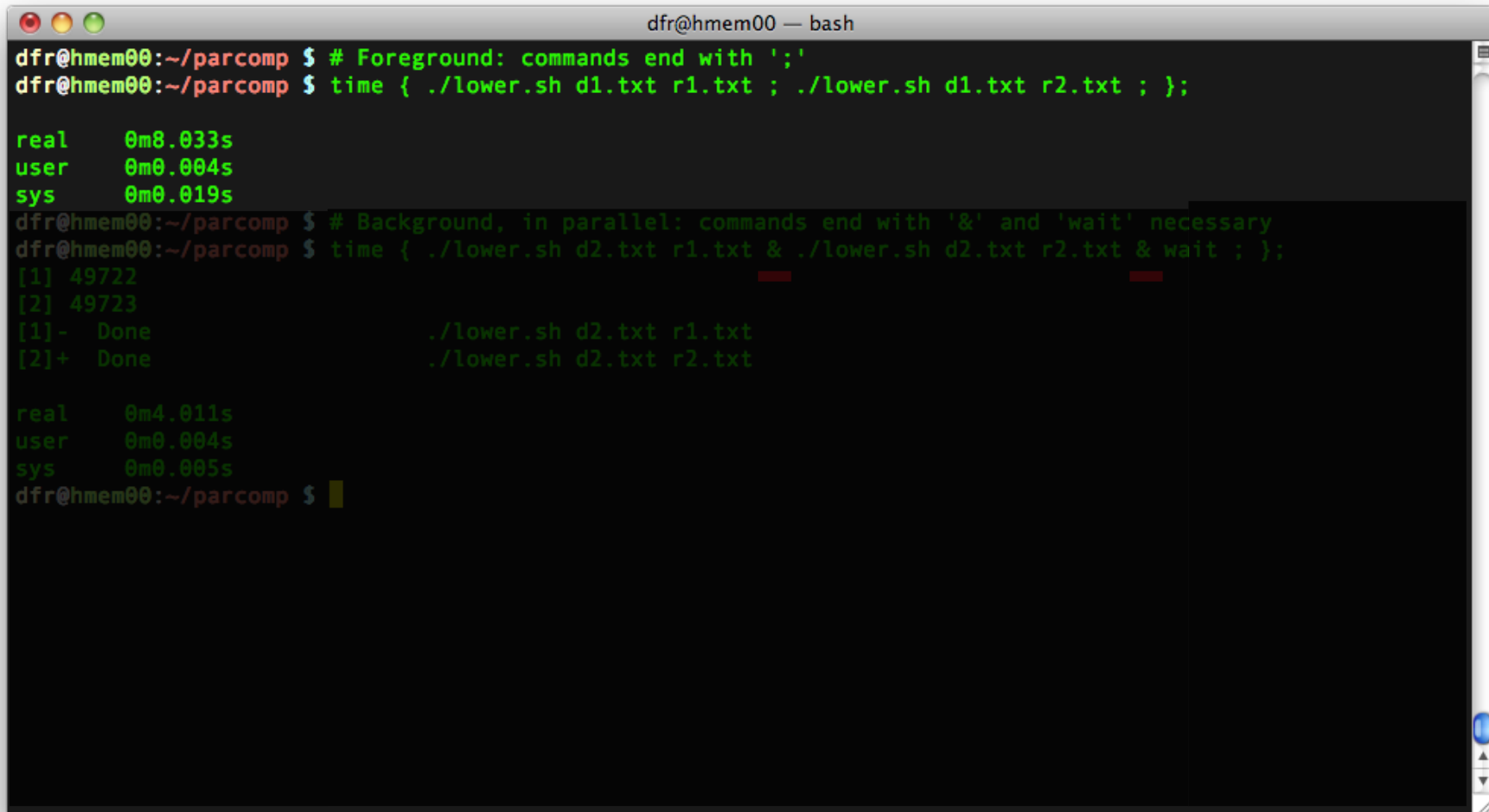
```
dfr@hmem00:~/parcomp $ # Foreground: commands end with ';'
dfr@hmem00:~/parcomp $ time { ./lower.sh d1.txt r1.txt ; ./lower.sh d1.txt r2.txt ; };

real    0m8.033s
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real    0m4.011s
user    0m0.004s
sys     0m0.005s
dfr@hmem00:~/parcomp $
```

## 4.2. Job control & Parallel processes in Bash

Run the program twice and measure the time it takes



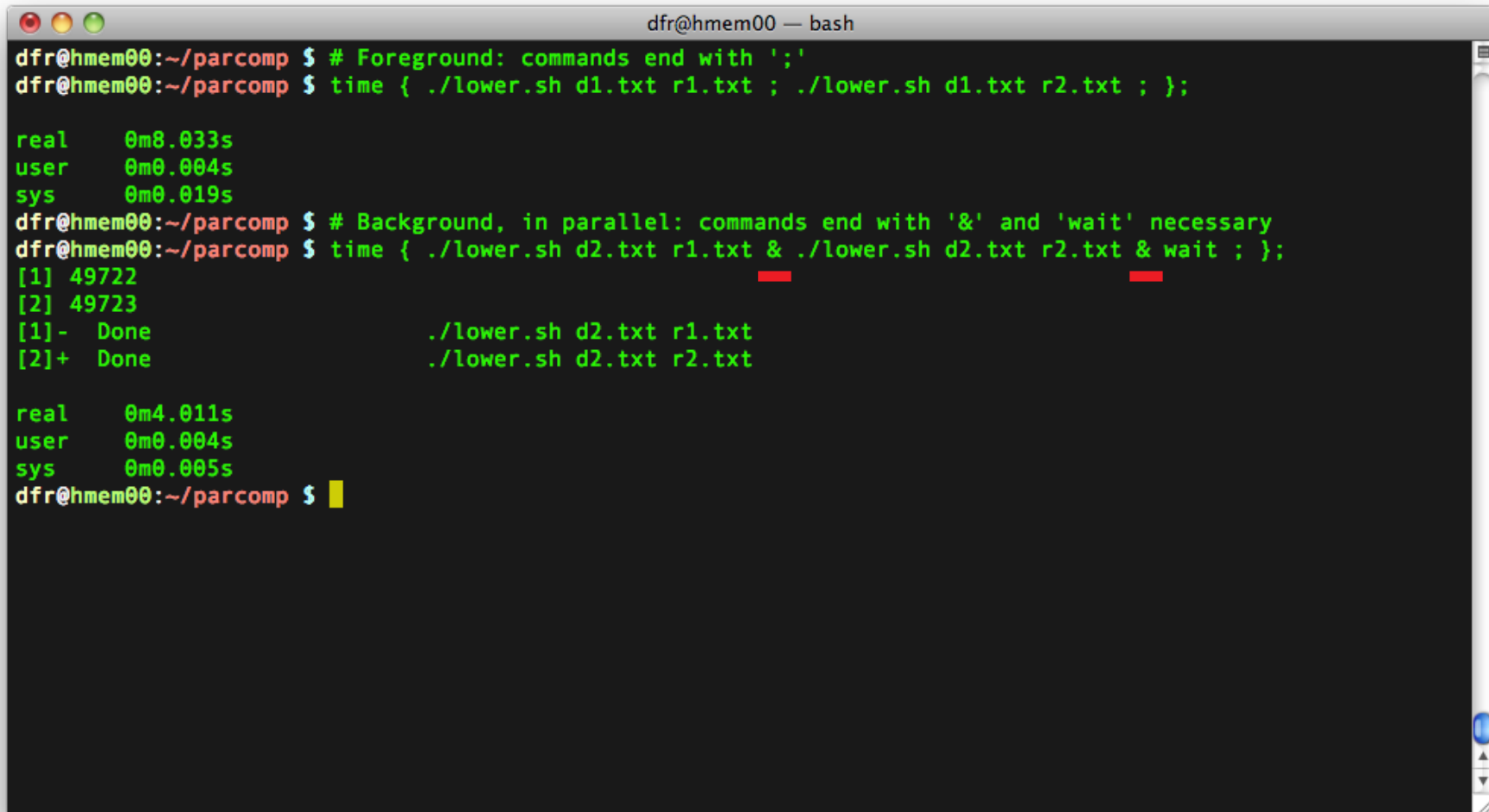
```
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dfr@hmem00:~/parcomp $ # Foreground: commands end with ';'
dfr@hmem00:~/parcomp $ time { ./lower.sh d1.txt r1.txt ; ./lower.sh d1.txt r2.txt ; };

real    0m8.033s
user    0m0.004s
sys     0m0.019s
dfr@hmem00:~/parcomp $ # Background, in parallel: commands end with '&' and 'wait' necessary
dfr@hmem00:~/parcomp $ time { ./lower.sh d2.txt r1.txt & ./lower.sh d2.txt r2.txt & wait ; };
[1] 49722
[2] 49723
[1]-  Done                  ./lower.sh d2.txt r1.txt
[2]+  Done                  ./lower.sh d2.txt r2.txt

real    0m4.011s
user    0m0.004s
sys     0m0.005s
dfr@hmem00:~/parcomp $
```

## 4.2. Job control & Parallel processes in Bash

Run the program twice “in the background” and measure the time



```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ # Foreground: commands end with ';'
dfr@hmem00:~/parcomp $ time { ./lower.sh d1.txt r1.txt ; ./lower.sh d1.txt r2.txt ; };

real    0m8.033s
user    0m0.004s
sys     0m0.019s
dfr@hmem00:~/parcomp $ # Background, in parallel: commands end with '&' and 'wait' necessary
dfr@hmem00:~/parcomp $ time { ./lower.sh d2.txt r1.txt & ./lower.sh d2.txt r2.txt & wait ; };
[1] 49722
[2] 49723
[1]-  Done                ./lower.sh d2.txt r1.txt
[2]+  Done                ./lower.sh d2.txt r2.txt

real    0m4.011s
user    0m0.004s
sys     0m0.005s
dfr@hmem00:~/parcomp $
```

## 4.2. Job control & Parallel processes in Bash

Parallel for loop in Bash:

```
for i in {1..10}; do
  command1
  command2
done
```

```
for i in {1..10}; do
(
  command1
  command2
) &
done; wait
```

(...) & : creates a sub-shell with all commands in the bloc and start it in the background  
wait : barrier to synchronize all sub-shells

## 4.3. Basic tools

### 4.3.1. One program and many files

The xargs command distributes data from stdin to program

```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ ls d?.txt
d1.txt d2.txt d3.txt d4.txt
dfr@hmem00:~/parcomp $ ls d?.txt | xargs -n 1 echo "File: "
File: d1.txt
File: d2.txt
File: d3.txt
File: d4.txt
dfr@hmem00:~/parcomp $ time { ls d?.txt | xargs -n 1 ./lower.sh > /dev/null ; }

real    0m16.041s
user    0m0.010s
sys     0m0.006s
dfr@hmem00:~/parcomp $ time { ls d?.txt | xargs -n 1 -P 4 ./lower.sh > /dev/null ; }

real    0m4.014s
user    0m0.008s
sys     0m0.016s
dfr@hmem00:~/parcomp $
```

Equivalent to  
./lower.sh d1.txt ;  
./lower.sh d2.txt ;  
./lower.sh d3.txt ;  
./lower.sh d3.txt ;

Equivalent to  
./lower.sh d1.txt &  
./lower.sh d2.txt &  
./lower.sh d3.txt &  
./lower.sh d3.txt &  
wait

## 4.3. Basic tools

### 4.3.2. Several programs and one file

Using UNIX pipes for pipelining operations

./upper.sh waits for ./lower.sh to finish  
Note the intermediate file

```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ # Using an intermediary file
dfr@hmem00:~/parcomp $ time { ./lower.sh d.txt tmp.txt ; ./upper.sh tmp.txt res.txt ; }

real    0m8.033s
user    0m0.005s
sys     0m0.017s
dfr@hmem00:~/parcomp $ # Using pipes (as our programs can handle stdin and stdout)
dfr@hmem00:~/parcomp $ time { ./lower.sh d.txt | ./upper.sh > res.txt ; }

real    0m5.014s
user    0m0.006s
sys     0m0.009s
dfr@hmem00:~/parcomp $ mkfifo tmpfifo
dfr@hmem00:~/parcomp $ ls -l tmpfifo
prw-rw-r-- 1 dfr dfr 0 Oct  7 10:27 tmpfifo
dfr@hmem00:~/parcomp $ time { ./lower.sh d.txt tmpfifo & ./upper.sh tmpfifo res.txt ; }
[1] 65343
[1]+  Done                  ./lower.sh d.txt tmpfifo

real    0m5.013s
user    0m0.002s
sys     0m0.007s
dfr@hmem00:~/parcomp $
```

## 4.3. Basic tools

### 4.3.2. Several programs and one file

Using UNIX fifos for pipelining operations

```
dfr@hmem00:~/parcomp $ # Using an intermediary file
dfr@hmem00:~/parcomp $ time { ./lower.sh d.txt tmp.txt ; ./upper.sh tmp.txt res.txt ; }

real    0m8.033s
user    0m0.005s
sys     0m0.017s
dfr@hmem00:~/parcomp $
dfr@hmem00:~/parcomp $

dfr@hmem00:~/parcomp $ mkfifo tmpfifo
dfr@hmem00:~/parcomp $ ls -l tmpfifo
prw-rw-r-- 1 dfr dfr 0 Oct 7 10:27 tmpfifo
dfr@hmem00:~/parcomp $ time { ./lower.sh d.txt tmpfifo & ./upper.sh tmpfifo res.txt ; }
[1] 65343
[1]+  Done                  ./lower.sh d.txt tmpfifo

real    0m5.013s
user    0m0.002s
sys     0m0.007s
dfr@hmem00:~/parcomp $
```

A FIFO file is a “fake” file to which a process can write at the end and another can read at the beginning

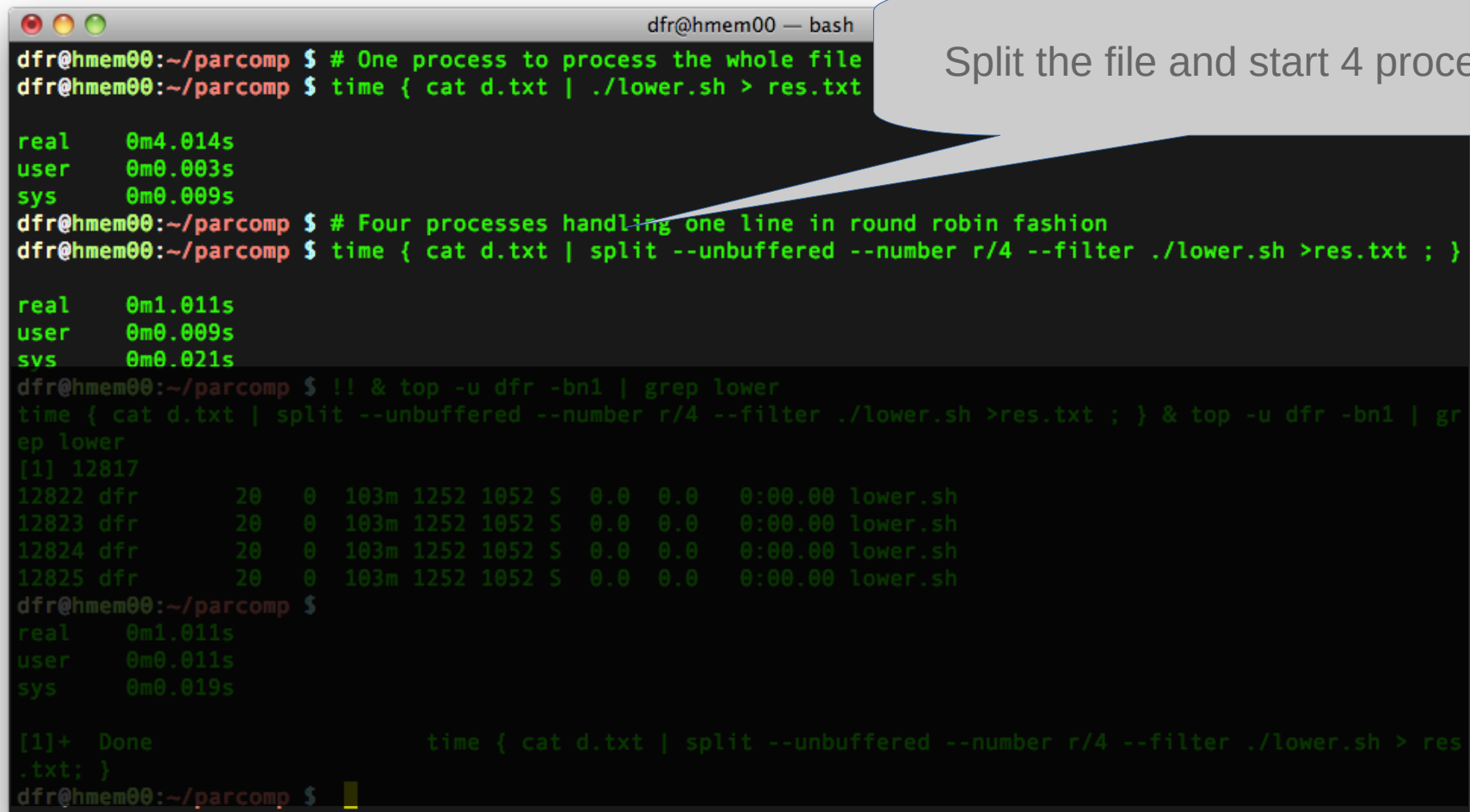
./upper.sh starts reading as soon as ./lower.sh starts writing



## 4.3. Basic tools

### 4.3.3. One program and one large file

The split command distributes data from stdin to program



```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ # One process to process the whole file
dfr@hmem00:~/parcomp $ time { cat d.txt | ./lower.sh > res.txt

real    0m4.014s
user    0m0.003s
sys     0m0.009s
dfr@hmem00:~/parcomp $ # Four processes handling one line in round robin fashion
dfr@hmem00:~/parcomp $ time { cat d.txt | split --unbuffered --number r/4 --filter ./lower.sh >res.txt ; }

real    0m1.011s
user    0m0.009s
sys     0m0.021s
dfr@hmem00:~/parcomp $ !! & top -u dfr -bn1 | grep lower
time { cat d.txt | split --unbuffered --number r/4 --filter ./lower.sh >res.txt ; } & top -u dfr -bn1 | gr
ep lower
[1] 12817
12822 dfr      20   0  103m 1252 1052 S   0.0  0.0   0:00.00 lower.sh
12823 dfr      20   0  103m 1252 1052 S   0.0  0.0   0:00.00 lower.sh
12824 dfr      20   0  103m 1252 1052 S   0.0  0.0   0:00.00 lower.sh
12825 dfr      20   0  103m 1252 1052 S   0.0  0.0   0:00.00 lower.sh
dfr@hmem00:~/parcomp $
real    0m1.011s
user    0m0.011s
sys     0m0.019s

[1]+  Done                  time { cat d.txt | split --unbuffered --number r/4 --filter ./lower.sh > res
.txt; }
dfr@hmem00:~/parcomp $
```

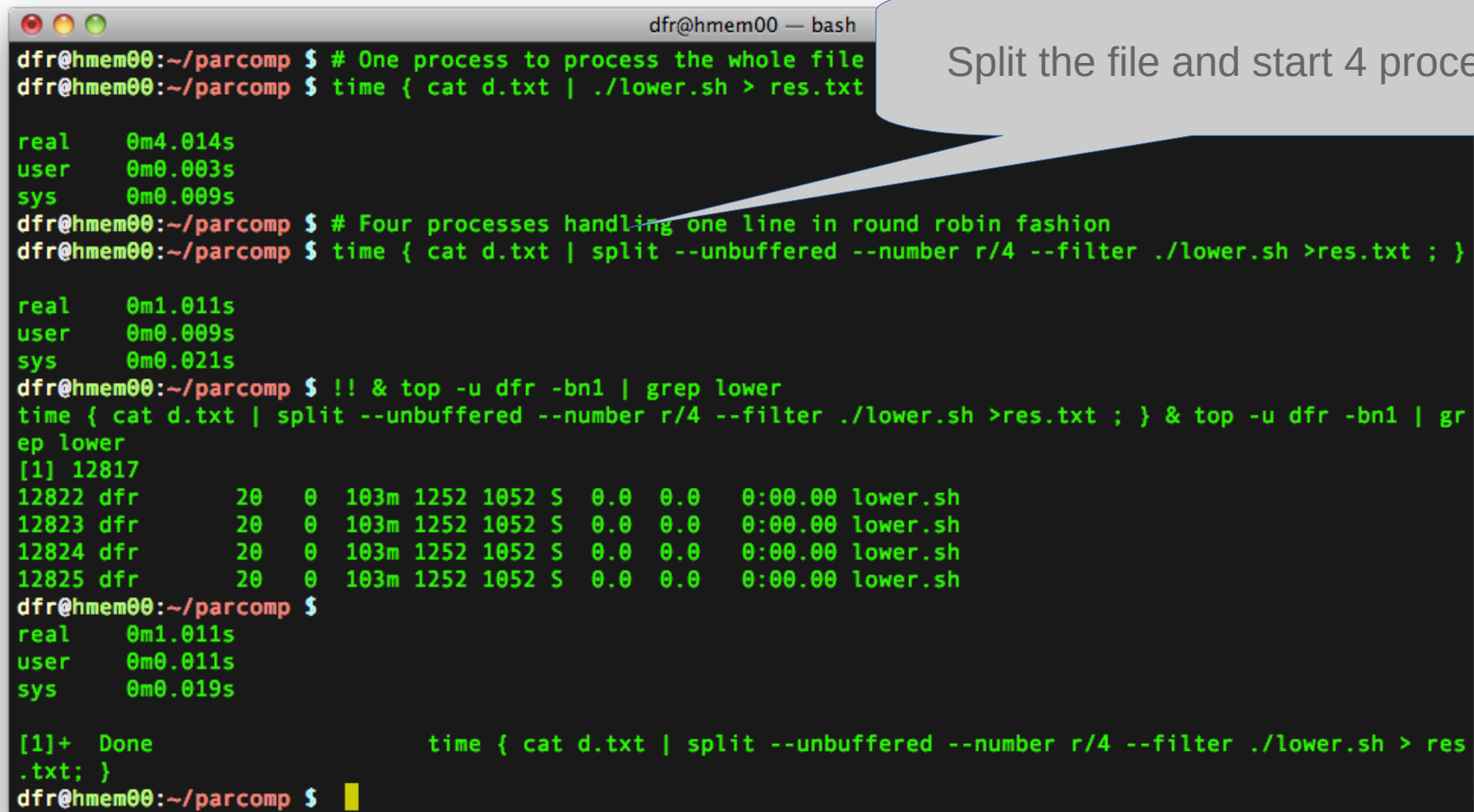
Split the file and start 4 processes

Need recent version of Coreutils/8.22-goolf-1.4.10

## 4.3. Basic tools

### 4.3.3. One program and one large file

The split command distributes data from stdin to program



```
dfr@hmem00 ~ /parcomp $ # One process to process the whole file
dfr@hmem00 ~ /parcomp $ time { cat d.txt | ./lower.sh > res.txt

real    0m4.014s
user    0m0.003s
sys     0m0.009s
dfr@hmem00 ~ /parcomp $ # Four processes handling one line in round robin fashion
dfr@hmem00 ~ /parcomp $ time { cat d.txt | split --unbuffered --number r/4 --filter ./lower.sh >res.txt ; }

real    0m1.011s
user    0m0.009s
sys     0m0.021s
dfr@hmem00 ~ /parcomp $ !! & top -u dfr -bn1 | grep lower
time { cat d.txt | split --unbuffered --number r/4 --filter ./lower.sh >res.txt ; } & top -u dfr -bn1 | gr
ep lower
[1] 12817
12822 dfr      20  0  103m 1252 1052 S  0.0  0.0   0:00.00 lower.sh
12823 dfr      20  0  103m 1252 1052 S  0.0  0.0   0:00.00 lower.sh
12824 dfr      20  0  103m 1252 1052 S  0.0  0.0   0:00.00 lower.sh
12825 dfr      20  0  103m 1252 1052 S  0.0  0.0   0:00.00 lower.sh
dfr@hmem00 ~ /parcomp $
real    0m1.011s
user    0m0.011s
sys     0m0.019s

[1]+  Done                  time { cat d.txt | split --unbuffered --number r/4 --filter ./lower.sh > res
.txt; }
dfr@hmem00 ~ /parcomp $
```

Split the file and start 4 processes

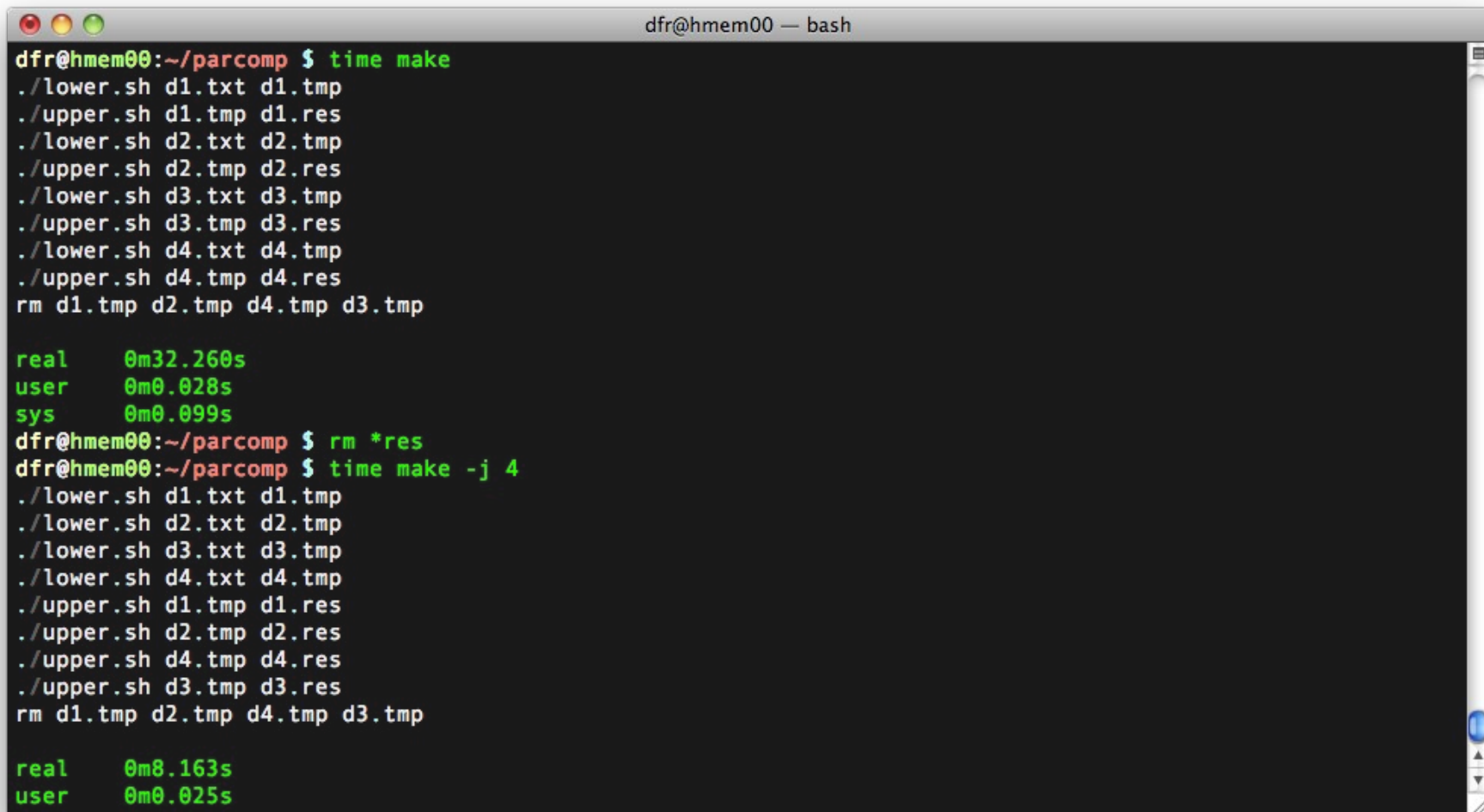
Need recent version of Coreutils/8.22-golf-1.4.10



## 4.3. Basic tools

### 4.3.4. Several programs and many files

The 'make' command can operate in parallel



```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ time make
./lower.sh d1.txt d1.tmp
./upper.sh d1.tmp d1.res
./lower.sh d2.txt d2.tmp
./upper.sh d2.tmp d2.res
./lower.sh d3.txt d3.tmp
./upper.sh d3.tmp d3.res
./lower.sh d4.txt d4.tmp
./upper.sh d4.tmp d4.res
rm d1.tmp d2.tmp d4.tmp d3.tmp

real    0m32.260s
user    0m0.028s
sys     0m0.099s
dfr@hmem00:~/parcomp $ rm *res
dfr@hmem00:~/parcomp $ time make -j 4
./lower.sh d1.txt d1.tmp
./lower.sh d2.txt d2.tmp
./lower.sh d3.txt d3.tmp
./lower.sh d4.txt d4.tmp
./upper.sh d1.tmp d1.res
./upper.sh d2.tmp d2.res
./upper.sh d4.tmp d4.res
./upper.sh d3.tmp d3.res
rm d1.tmp d2.tmp d4.tmp d3.tmp

real    0m8.163s
user    0m0.025s
```

# Summary

- You have either
  - one very large file to process
    - with one program: `split`
    - with several programs: `fifo` (or `pipes`)
  - many files to process
    - with one program `xargs`
    - with many programs `make`

# 4.4. GNU Parallel

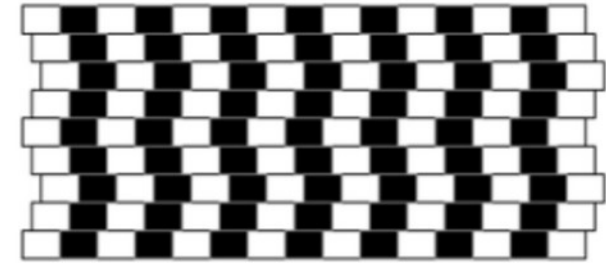
## GNU Parallel

GNU **parallel** is a shell tool for executing jobs in parallel using one or more computers. A job can be a single command or a small script that has to be run for each of the lines in the input. The typical input is a list of files, a list of hosts, a list of users, a list of URLs, or a list of tables. A job can also be a command that reads from a pipe. GNU **parallel** can then split the input and pipe it into commands in parallel.

If you use `xargs` and `tee` today you will find GNU **parallel** very easy to use as GNU **parallel** is written to have the same options as `xargs`. If you write loops in shell, you will find GNU **parallel** may be able to replace most of the loops and make them run faster by running several jobs in parallel.

GNU **parallel** makes sure output from the commands is the same output as you would get had you run the commands sequentially. This makes it possible to use output from GNU **parallel** as input for other programs.

For each line of input GNU **parallel** will execute *command* with the line as arguments. If no *command* is given, the line of input is executed. Several lines will be run in parallel. GNU **parallel** can often be used as a substitute for `xargs` or `cat | bash`.



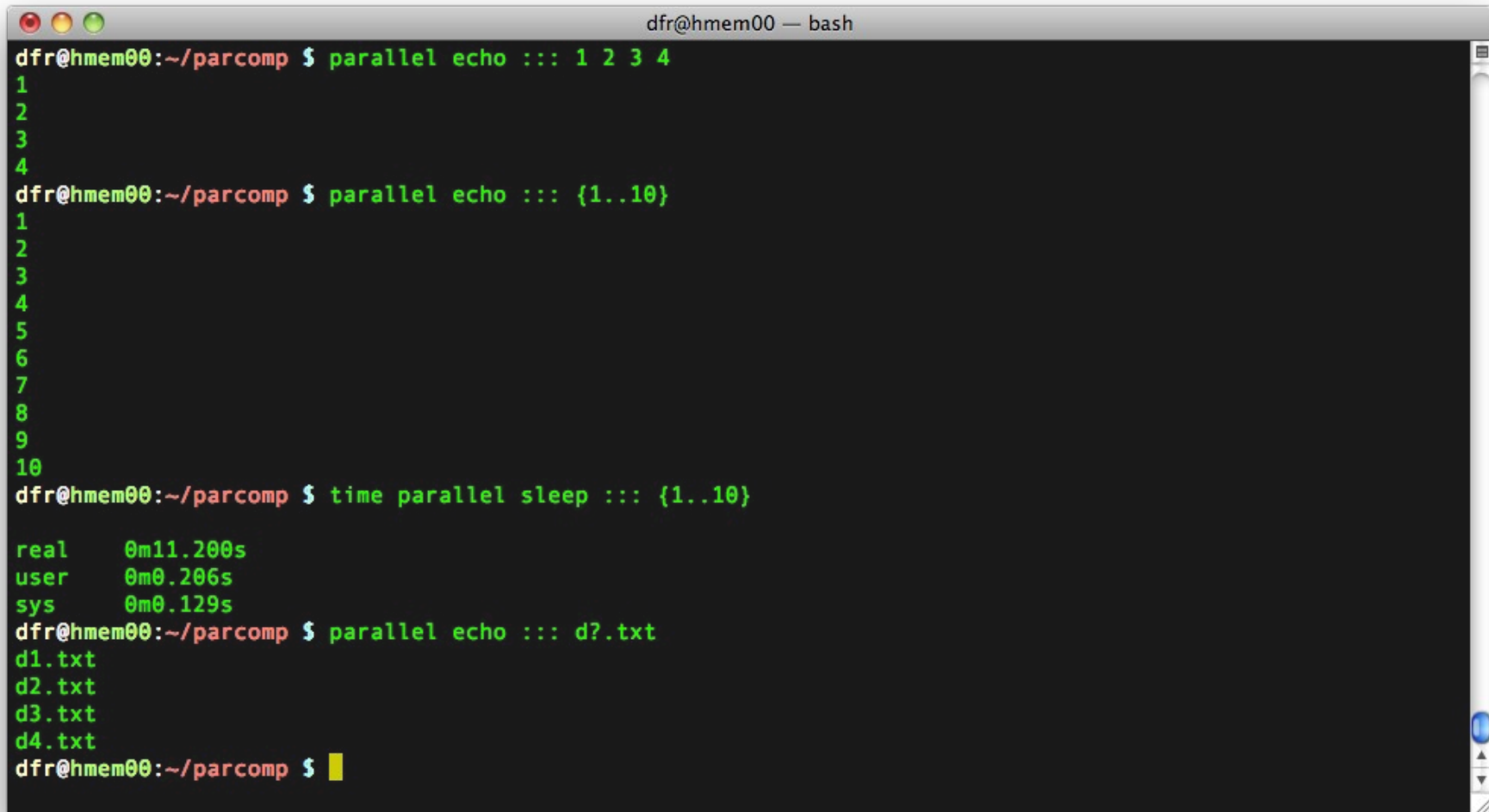
# GNUparallel

For people who live life in the parallel lane.

More complicated to use but very powerful  
Might not be available everywhere

## 4.4. GNU Parallel

- Syntax: `parallel command ::: argument list`



```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ parallel echo ::: 1 2 3 4
1
2
3
4
dfr@hmem00:~/parcomp $ parallel echo ::: {1..10}
1
2
3
4
5
6
7
8
9
10
dfr@hmem00:~/parcomp $ time parallel sleep ::: {1..10}

real    0m11.200s
user    0m0.206s
sys     0m0.129s
dfr@hmem00:~/parcomp $ parallel echo ::: d?.txt
d1.txt
d2.txt
d3.txt
d4.txt
dfr@hmem00:~/parcomp $
```

## 4.4. GNU Parallel

- Syntax: {} as argument placeholder.

```
d1.txt
d2.txt
d3.txt
d4.txt
dfr@hmem00:~/parcomp $ parallel echo {} {..}.res ::: d?.txt
d1.txt d1.res
d2.txt d2.res
d3.txt d3.res
d4.txt d4.res
dfr@hmem00:~/parcomp $ parallel echo {} ::: ../parcomp/d?.txt
../parcomp/d1.txt
../parcomp/d2.txt
../parcomp/d3.txt
../parcomp/d4.txt
dfr@hmem00:~/parcomp $ parallel echo {/} ::: ../parcomp/d?.txt
d1.txt
d2.txt
d3.txt
d4.txt
dfr@hmem00:~/parcomp $
dfr@hmem00:~/parcomp $
dfr@hmem00:~/parcomp $
```



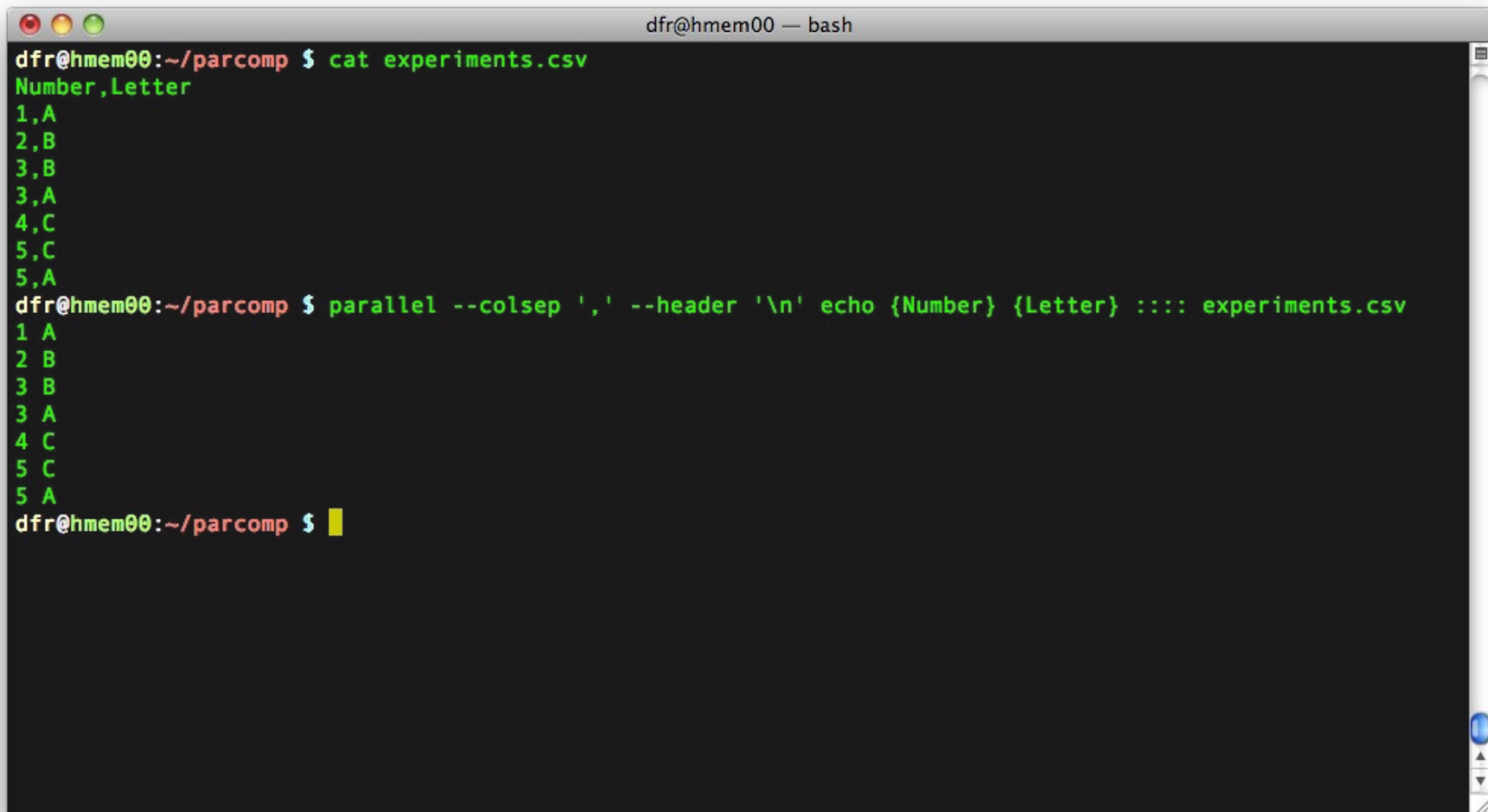
## 4.4. GNU Parallel

- Multiple parameters and --xapply

```
dfr@hmem00 — bash
dfr@hmem00:~/parcomp $ parallel echo ::: 1 2 3 4 ::: A B
1 A
1 B
2 A
2 B
3 A
3 B
4 A
4 B
dfr@hmem00:~/parcomp $ parallel --xapply echo ::: 1 2 3 4 ::: A B C D
1 A
2 B
3 C
4 D
dfr@hmem00:~/parcomp $ parallel echo {1} and {2} ::: 1 2 3 4 ::: A B C D
1 and A
1 and B
1 and C
1 and D
2 and A
2 and B
2 and C
2 and D
3 and A
3 and B
3 and C
3 and D
4 and A
```

## 4.4. GNU Parallel

- When arguments are in a file : use ::: (4x ':')

A terminal window titled 'dfr@hmem00 — bash' showing the execution of GNU Parallel. The first command is 'cat experiments.csv', which outputs a CSV file with 5 rows of data. The second command is 'parallel --colsep ',' --header '\n' echo {Number} {Letter} ::: experiments.csv', which outputs the same 5 rows of data, demonstrating parallel execution. The terminal text is as follows:

```
dfr@hmem00:~/parcomp $ cat experiments.csv
Number,Letter
1,A
2,B
3,B
3,A
4,C
5,C
5,A
dfr@hmem00:~/parcomp $ parallel --colsep ',' --header '\n' echo {Number} {Letter} ::: experiments.csv
1 A
2 B
3 B
3 A
4 C
5 C
5 A
dfr@hmem00:~/parcomp $
```

# Other interesting options

- `--pipe` Split a file
- `-S` Use remote servers through SSH
- `-j n` Run n jobs in parallel
- `-k` Keep same order
- `--delay n` Ensure there are n seconds between each start
- `--timeout n` Kill task after n seconds if still running

Author asks to be cited: O. Tange (2011): *GNU Parallel - The Command-Line Power Tool*, The USENIX Magazine, February 2011:42-47.

# Homework

Reproduce the examples from the previous slides  
with `./lower` and `./upper.sh`  
using GNU Parallel

# Solutions

- One program and many files

```
$ time parallel -k ./lower.sh {} > res.txt ::: d?.txt
```

- One program and one large file

```
$ time cat d.txt | parallel -k -N1 --pipe ./lower.sh {} > res.txt
```

- Several programs and several files

```
$ time { parallel ./lower.sh {} {}.tmp ::: d?.txt ; \  
> parallel ./upper.sh {} {}.res ::: d?.tmp ; }
```

# Summary

1. General concepts, definitions, challenges
2. Hardware for parallel computing
3. Programming models
4. User tools