

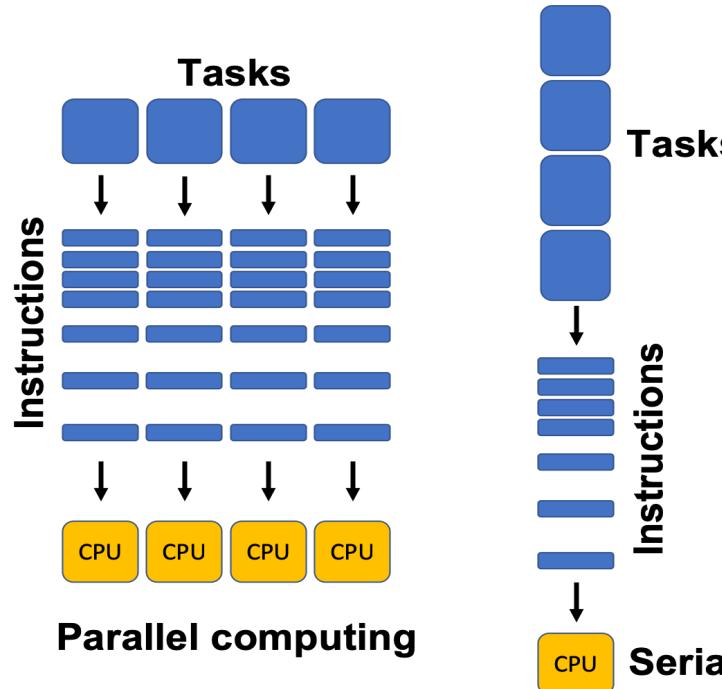
# Introducción a la computación paralela



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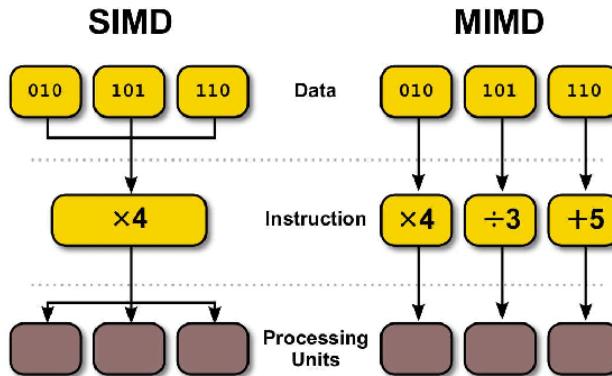
# Computación serie y computación paralela



- Arquitectura y diseño: *x86\_64, arm64, AVX*.
- Programación de versión serie:
  - Lenguaje de programación y compilador<sup>2,3</sup> (*GNU, Intel*).
- Localizar tareas/bucles paralelizables.
- Paralelizar dichas tareas/bucles:
  - Arquitectura (*SIMD, MIMD*)<sup>1</sup> y diseño: dependencia del dato, zonas críticas de memoria.
  - Lenguaje de programación, compilador<sup>2,3</sup> y librería de paralelización.
- Estudiar eficiencia de la paralelización (*SpeedUp*).
- Estudiar escalado de la paralelización (*HPC*)<sup>2</sup>.

- 1.- Taxonomía de *Flynn*
- 2.- Fuera ámbito *Workshop*
- 3.- No se aplicarán optimizaciones

# Programación de aplicaciones paralelas



**Fortran**  
Standard Parallelism

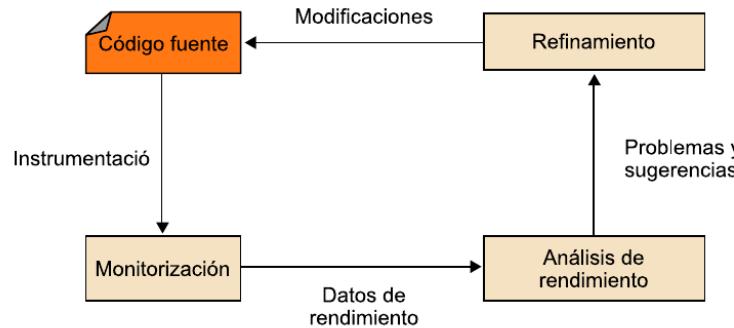
**OpenMP**



**OpenCoarrays**

- *Single Instruction Multiple Data:*
  - Procesadores vectoriales.
  - GPUs (SIMT).
- *Multiple Instruction Multiple Data.*
  - Computación distribuida, *Middleware*.
- Memoria compartida: *SMP, UMA, NUMA.*
  - Fortran SP, OpenMP, NVIDIA CUDA.
- Memoria distribuida: *MPI, HPC.*
  - OpenMPI, Fortran OpenCoarrays.
- Hibridación:
  - OpenMPI+OpenMP, OpenMPI+CUDA.

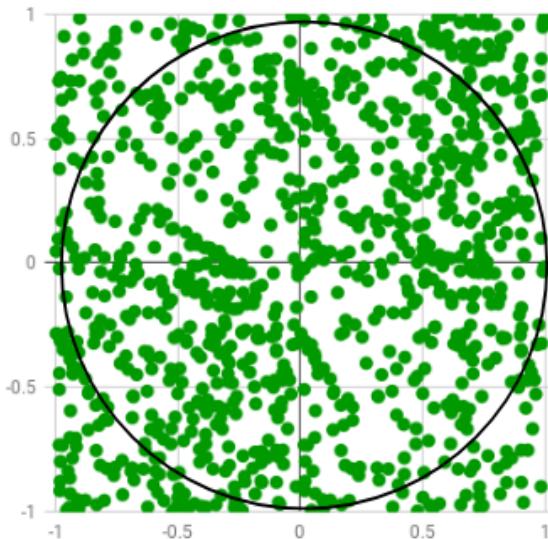
# Eficiencia (*SpeedUp*) y escalado



- T: tiempo de ejecución.
- P: núcleos o cores.
- N: tamaño del problema.
- *Overhead*: comunicación, barreras acceso a memoria, sincronización hilos/cores, etc

- Límite eficiencia paralelismo:  $T_{par} = \frac{T_{seq}}{P} \Rightarrow \frac{T_{seq}}{P} + T_{overhead}$
- *SpeedUp*:  $S = \frac{T_{seq}}{T_{par}}$
- Eficiencia energética CPU vs CPU:  $SpeedUp \geq EE_{cpu} \Leftrightarrow \frac{T_{seq}}{T_{par}} \geq \frac{P_{par}}{P_{seq}}$
- Escalado: mantener o mejorar la eficiencia al aumentar N y/o P.

# Estimar el valor de PI (Monte Carlo)



$$\frac{\text{Área círculo}}{\text{Área cuadrado}} = \frac{\text{Puntos círculo}}{\text{Puntos cuadrado}} \rightarrow \frac{\pi r^2}{4 r^2} = \frac{\text{Puntos círculo}}{\text{Puntos cuadrado}} \rightarrow \frac{\pi}{4} = \frac{\text{Puntos círculo}}{\text{Puntos cuadrado}} \rightarrow \pi \approx 4 \frac{\text{Puntos círculo}}{\text{Puntos cuadrado}}$$

- $P_{\text{círculo}}=0$ ,  $P_{\text{cuadrado}}=N_{\text{puntos}}$
- Para  $N_{\text{puntos}}$ 
  - Generar aleatoriamente, entre  $[-1,1]$ , punto  $(x,y)$ .
  - Calcular distancia al origen  $(0,0)$ :
    - o  $d_{\text{orig}}=(x-0)^2+(y-0)^2 \Rightarrow x^2+y^2$
  - Si  $d_{\text{orig}} \leq 1 \rightarrow P_{\text{círculo}}=P_{\text{círculo}}+1$
- Calcular  $\pi=4 \frac{\text{Puntos círculo}}{\text{Puntos cuadrado}}$

# pi\_serial.py (P=1 : N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

```
import random

circle_points = 0
square_points = 1073741824

for i in range(square_points):
    rand_x = float(random.uniform(-1, 1))
    rand_y = float(random.uniform(-1, 1))

    origin_dist = rand_x * rand_x + rand_y * rand_y

    if origin_dist <= 1.0:
        circle_points += 1

pi = float(4 * circle_points) / float(square_points)
print("Pi ~=", pi)
```

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time python pi_serial.py
Pi ~= 3.1415679417550564
real    7m48,696s
user    7m48,655s
sys     0m0,036s
```



# pi\_serial.c (P=1 : N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

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

int main()
{
    int i;
    int circle_points = 0;
    int square_points = 1073741824;
    float rand_x, rand_y, origin_dist, pi;

    srand(time(NULL));

    for (i = 0; i < square_points; i++)
    {
        rand_x = ((float)rand() / (RAND_MAX)) * 2 - 1;
        rand_y = ((float)rand() / (RAND_MAX)) * 2 - 1;

        origin_dist = rand_x * rand_x + rand_y * rand_y;

        if (origin_dist <= 1.0)
            circle_points++;
    }
    pi = (4 * (float)circle_points) / square_points;
    printf("Pi ~= %f\n", pi);
    return 0;
}
```

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -o pi_serial_c.exe pi_serial.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_serial_c.exe
Pi ~= 3.141565

real    0m24.719s
user    0m24.716s
sys     0m0.000s
```



$$\text{SpeedUp}(\text{Python/C}) = \frac{468.7}{24.7} \approx 19$$



# pi\_serial.f90 (P=1 : N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

```
program pi_serial
    implicit none

    integer :: i
    integer :: circle_points = 0
    integer :: square_points = 1073741824
    real :: rand_x, rand_y, origin_dist, pi

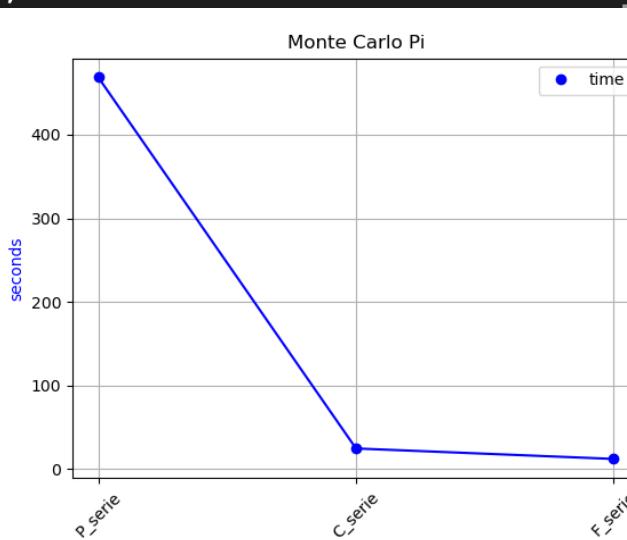
    do i = 1, square_points
        call random_number(rand_x)
        rand_x = rand_x*2 - 1
        call random_number(rand_y)
        rand_y = rand_y*2 - 1

        origin_dist = rand_x*rand_x + rand_y*rand_y

        if (origin_dist <= 1.0) &
            circle_points = circle_points + 1
    end do
    pi = 4*real(circle_points)/square_points
    print *, "Pi ~=", pi

end program pi_serial
```

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gfortran -o pi_serial_f.exe pi_serial.f90
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_serial_f.exe
Pi ~ 3.14152384
real    0m12,181s
user    0m12,181s
sys     0m0,000s
```



$$\text{SpeedUp}(\text{Python/C}) = \frac{468.7}{24.7} \approx 19$$

$$\text{SpeedUp}(\text{Python/Fortran}) = \frac{468.7}{12.2} \approx 38$$

$$\text{SpeedUp}(C/\text{Fortran}) = \frac{24.7}{12.2} \approx 2$$



# Tareas/bucles a parallelizar

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

int main()
{
    int i;
    int circle_points = 0;
    int square_points = 1073741824;
    float rand_x, rand_y, origin_dist, pi;

    srand(time(NULL));

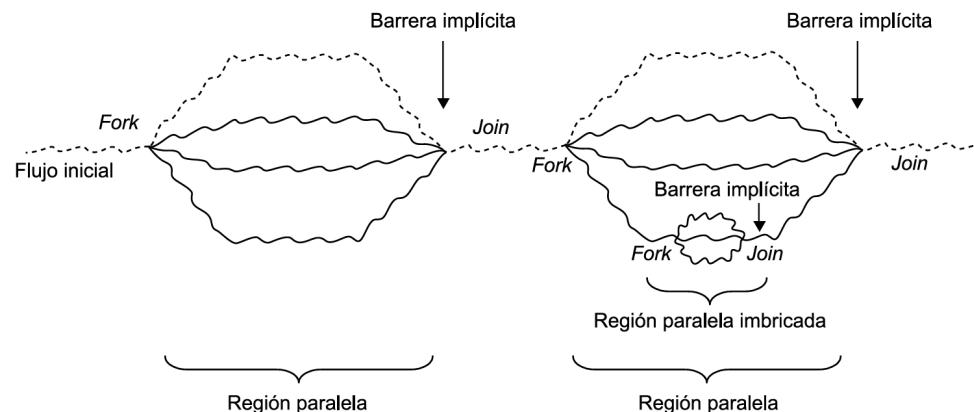
    for (i = 0; i < square_points; i++)
    {
        rand_x = ((float)rand() / (RAND_MAX)) * 2 - 1;
        rand_y = ((float)rand() / (RAND_MAX)) * 2 - 1;

        origin_dist = rand_x * rand_x + rand_y * rand_y;

        if (origin_dist <= 1.0)
            circle_points++;
    }

    pi = (4 * (float)circle_points) / square_points;
    printf("Pi ~= %f\n", pi);
    return 0;
}
```

- Arquitectura: *SIMD, SMP*.
- Dependencia del dato:
  - No dependencia del dato de origen
  - Cuidado *iRNG!*
- Zonas críticas de memoria: **circle\_points**.
- Lenguaje de programación: C.
- Librería de paralelización: OpenMP.



# pi\_openmp\_a.c (P=2 : N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

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

int main()
{
    int i;
    int circle_points = 0;
    int square_points = 1073741824;
    float rand_x, rand_y, origin_dist, pi;

    srand(time(NULL));

#pragma omp parallel for
    for (i = 0; i < square_points; i++)
    {
        rand_x = ((float)rand() / (RAND_MAX)) * 2 - 1;
        rand_y = ((float)rand() / (RAND_MAX)) * 2 - 1;

        origin_dist = rand_x * rand_x + rand_y * rand_y;

        if (origin_dist <= 1.0)
#pragma omp atomic
            circle_points++;
    }
    pi = (4 * (float)circle_points) / square_points;
    printf("Pi ~= %f\n", pi);
    return 0;
}
```

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -o pi_serial_c.exe pi_serial.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_serial_c.exe
Pi ~= 3.141550

real    0m24.737s
user    0m24.736s
sys     0m0.000s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -fopenmp -o pi_openmp_c_a.exe pi_openmp_a.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=2 && time ./pi_openmp_c_a.exe
Pi ~= 3.141348

real    7m14.933s
user    7m35.609s
sys     6m53.205s
```

- No mantiene/mejora eficiencia
- $RNG(rand)$  no soporta paralelismo

# pi\_openmp\_b.c (P=2 : N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

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

int main()
{
    int i;
    int circle_points = 0;
    int square_points = 107341824;
    float rand_x, rand_y, origin_dist, pi;
    unsigned int seed;

#pragma omp parallel
    seed = ((unsigned)time(NULL) & 0xFFFFFFFF0) \
        | (omp_get_thread_num() + 1);
    srand(seed);

#pragma omp parallel for \
firstprivate(rand_x, rand_y, origin_dist, seed)
    for (i = 0; i < square_points; i++)
    {
        rand_x = ((float)rand_r(&seed) / (RAND_MAX)) * 2 - 1;
        rand_y = ((float)rand_r(&seed) / (RAND_MAX)) * 2 - 1;

        origin_dist = rand_x * rand_x + rand_y * rand_y;

        if (origin_dist <= 1.0)
#pragma omp atomic
            circle_points++;
    }
    pi = (4 * (float)circle_points) / square_points;
    printf("Pi ~= %f\n", pi);
    return 0;
}
```

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -o pi_serial_c.exe pi_serial.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_serial_c.exe
Pi ~= 3.141587

real    0m24.746s
user    0m24.741s
sys     0m0.005s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -fopenmp -o pi_openmp_c_b.exe pi_openmp_b.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=2 && time ./pi_openmp_c_b.exe
Pi ~= 3.141595

real    0m12.158s
user    0m24.159s
sys     0m0.153s
```

- Mejora eficiencia:  $SpeedUp = \frac{24.7}{12.2} \approx 2$
- *atomic*: sincronización de hilos/cores en acceso a zona crítica de memoria



# pi\_openmp\_c.c (P=2 : N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

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

int main()
{
    int i;
    int circle_points = 0;
    int square_points = 1073741824;
    float rand_x, rand_y, origin_dist, pi;
    unsigned int seed;

#pragma omp parallel
    seed = ((unsigned)time(NULL) & 0xFFFFFFFF0) \
        | (omp_get_thread_num() + 1);
    srand(seed);

#pragma omp parallel for \
firstprivate(rand_x, rand_y, origin_dist, seed) \
reduction(+:circle_points)
    for (i = 0; i < square_points; i++)
    {
        rand_x = ((float)rand_r(&seed) / (RAND_MAX)) * 2 - 1;
        rand_y = ((float)rand_r(&seed) / (RAND_MAX)) * 2 - 1;

        origin_dist = rand_x * rand_x + rand_y * rand_y;

        if (origin_dist <= 1.0)
            circle_points++;
    }
    pi = (4 * (float)circle_points) / square_points;
    printf("Pi ~= %f\n", pi);
    return 0;
}
```

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -o pi_serial_c.exe pi_serial.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_serial_c.exe
Pi ~= 3.141580

real    0m24.751s
user    0m24.750s
sys     0m0.000s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -fopenmp -o pi_openmp_c_c.exe pi_openmp_c.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=2 && time ./pi_openmp_c_c.exe
Pi ~= 3.141595

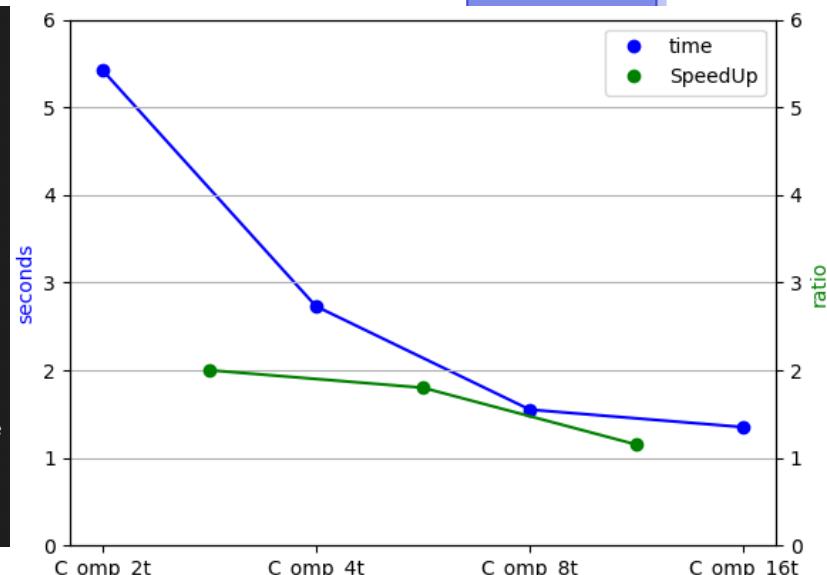
real    0m5.360s
user    0m10.712s
sys     0m0.004s
```

- Mejora eficiencia:  $SpeedUp = \frac{24.7}{12.2} \approx 4.6$
- *reduction*: no sincronización de hilos/cores en acceso a zona crítica de memoria

## Análisis: pi\_openmp\_c.c ( $P=2,4,8,16 : N=2^{30}$ )

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gcc -fopenmp -o pi_openmp_c_c.exe pi_openmp_c.c
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=2 && time ./pi_openmp_c_c.exe
Pi ≈ 3.141595
real    0m5,431s
user    0m10,846s
sys     0m0,012s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=4 && time ./pi_openmp_c_c.exe
Pi ≈ 3.141595
real    0m2,734s
user    0m10,919s
sys     0m0,005s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=8 && time ./pi_openmp_c_c.exe
Pi ≈ 3.141592
real    0m1,557s
user    0m12,341s
sys     0m0,089s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ export OMP_NUM_THREADS=16 && time ./pi_openmp_c_c.exe
Pi ≈ 3.141592
real    0m1,354s
user    0m19,106s
sys     0m0,516s
```



$$S(2t/4t) = \frac{5.43}{2.73} \approx 2 \geq 2 = \frac{4}{2} = EE(2t/4t)$$

$$S(4t/8t) = \frac{2.73}{1.55} \approx 1.8 \leq 2 = \frac{8}{4} = EE(4t/8t)$$

$$S(8t/16t) = \frac{1.55}{1.35} \approx 1.15 < 2 = \frac{16}{8} = EE(8t/16t)$$

- *SpeedUp* (decreciente) y eficiencia energética: escalado óptimo hasta 8 procs/cores

# pi\_fsp.f90 ( $P=arch/comp\ dep$ : $N=2^{30}$ )

i7 11700@2.5GHz, 16GB DDR4 3200MT/s

```
program pi_fsp
    implicit none

    integer :: i
    integer, parameter :: square_points = 1073741824
    real :: pi
    integer, allocatable:: circle_points(:)
    real, allocatable :: rand_x(:), rand_y(:)

    allocate(circle_points(square_points))
    allocate(rand_x(square_points), rand_y(square_points))

    call random_number(rand_x)
    call random_number(rand_y)
    rand_x = (rand_x**2 - 1)*(rand_x**2 - 1)
    rand_y = (rand_y**2 - 1)*(rand_y**2 - 1)

    do concurrent(i = 1:square_points)
        if ((rand_x(i) + rand_y(i)) <= 1.0) &
            circle_points(i) = 1
    end do

    pi = 4*real(sum(circle_points))/square_points
    print *, "Pi ~=", pi

end program pi_fsp
```

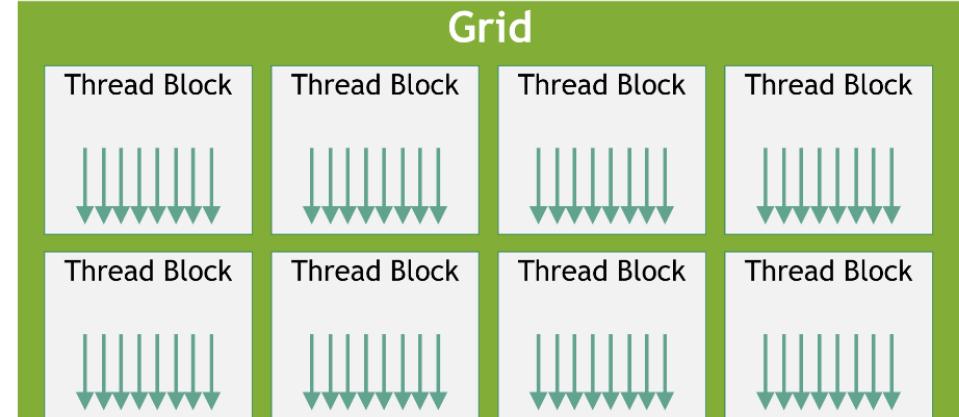
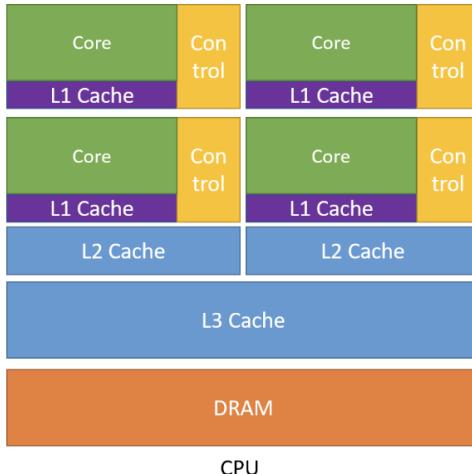
```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gfortran -Ofast -o pi_serial_f.exe pi_serial.f90
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_serial_f.exe
Pi ~ 3.14155102
real 0m11,485s
user 0m11,480s
sys 0m0,004s
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ gfortran -Ofast -o pi_serial_f.exe pi_serial.f90
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_fsp.exe
Pi ~ 3.14155936
real 0m7,965s
user 0m5,656s
sys 0m2,309s
```

$$SpeedUp(seq/par) = \frac{11.49}{7.97} \approx 1.45$$

- No dependencia del dato de entrada ni zonas críticas de memoria
- Funciones/subrutinas/bucles a paralelizar tienen que ser puras
- Uso de funciones/subrutinas elementales
- Optimización en compilación requerida
- Eficiencia y escalado dependiente de la arquitectura y compilador

**Fortran**  
Standard Parallelism

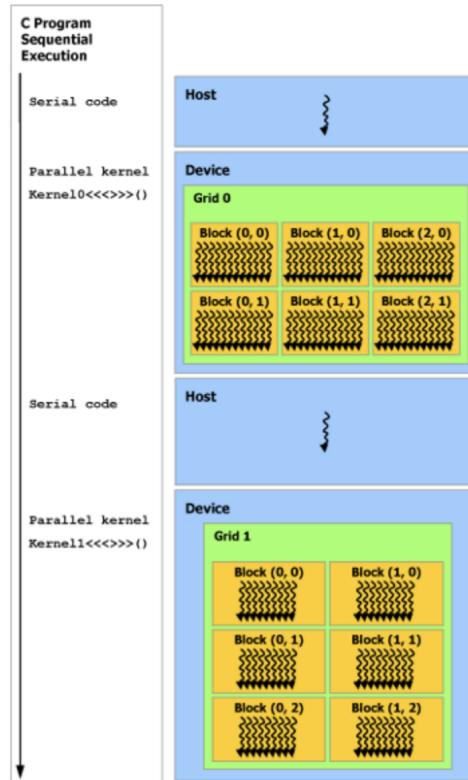
# NVIDIA CUDA



- Respecto a una *CPU*, una *GPU* posee más transistores para el procesamiento de datos
- Cada hilo se ejecuta en una unidad de procesamiento de la *GPU*
- Los hilos se agrupan en bloques, los cuales se ejecutan de forma paralela
- Los bloques se agrupan en un *Grid*



# NVIDIA CUDA



- *SIMT: Single Instruction Multiple Thread*
- *CPU → host, GPU → device*
- *CPU-RAM ↔ GPU-RAM: transferencia datos*
- *GPU-RAM: shared, global, constant, texture*
- Modelo de programación:
  - *CPU [Código serie]: preprocessamiento (E/S, inicializar memoria), CPU-RAM → GPU-RAM y lanzar kernel GPU*
  - *GPU [Código paralelo kernel (asíncrono)]: obtener identificador de hilo, todos los hilos realizarán las mismas operaciones sobre los datos transferidos a la GPU-RAM*
  - *CPU [Código serie]: GPU-RAM → CPU-RAM y posprocesamiento (E/S, liberar memoria)*



## pi\_cuda\_main/mod\_a.cuf (N=2^30)

```

program pi_cuda
use cudafor
use pi_mod
implicit none

integer :: i, n_blocks
integer, parameter :: n_threads = 128
integer, parameter :: square_points = 1073741824
real :: pi
integer, allocatable:: circle_points(:)
real, allocatable :: rand_x(:), rand_y(:)

allocate (circle_points(square_points))
allocate (dev_circle_points(square_points))
allocate (rand_x(square_points), rand_y(square_points))
allocate (dev_rand_x(square_points))

call random_number(rand_x)
call random_number(rand_y)
rand_x = (rand_x*2 - 1)*(rand_x*2 - 1)
rand_y = (rand_y*2 - 1)*(rand_y*2 - 1)
rand_x = rand_x + rand_y

dev_rand_x = rand_x

n_blocks = square_points/n_threads
if (mod(n_blocks, n_threads) > 0) n_blocks = n_blocks + 1
call pi_kernel<<<n_blocks, n_threads>>>(square_points)

circle_points = dev_circle_points

pi = 4*real(sum(circle_points))/square_points
print *, "Pi ~=", pi

end program pi_cuda

```

```

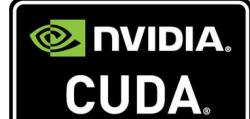
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ nvfortran -o pi_cuda_a.exe pi_cuda_mod_a.cuf pi_cuda_main_a.cuf
pi_cuda_mod_a.cuf:
pi_cuda_main_a.cuf:
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_cuda_a.exe
Pi ~ 3.141579

real 0m16.930s
user 0m12.607s
sys 0m4.319s

module pi_mod
implicit none
real, allocatable, device :: dev_rand_x(:)
integer, allocatable, device:: dev_circle_points(:)
contains
attributes(global) subroutine pi_kernel(square_points)
integer, value, intent(in) :: square_points
integer :: i
i = (blockidx%  - 1)*blockdim%  + threadidx%
if (i <= square_points) then
    if (dev_rand_x(i) <= 1.0) then
        dev_circle_points(i) = 1
    else
        dev_circle_points(i) = 0
    end if
end if
end subroutine pi_kernel
end module pi_mod

```

- Transferencias memoria  $CPU \leftrightarrow GPU$
- ¡Cada vector ocupa 4 GB!
- RNG en CPU



## pi\_cuda\_main/mod\_b.cuf (N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s, GeForce RTX 3060 (12GB)

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ nvfortran -cudalib=curand -o pi_cuda_b.exe pi_cuda_mod_b.cuf pi_cuda_main_b.cuf
pi_cuda_mod_b.cuf:
pi_cuda_main_b.cuf:
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_cuda_b.exe
Pi ~ 3.141623

real 0m2.925s
user 0m2.020s
sys 0m0.902s
```

- Reducción transferencias memoria CPU  $\leftrightarrow$  GPU
- RNG dentro del *kernel* de la GPU (*curand*)
- Uso de la hora del sistema para la semilla del RNG

```
program pi_cuda
use cudafor
use pi_mod
implicit none

integer :: i, n_blocks, time
integer, parameter :: n_threads = 128
integer, parameter :: square_points = 1073741824
real :: pi
integer, allocatable:: circle_points(:)
integer date_time(8)
character*10 b(3)
call date_and_time(b(1), b(2), b(3), date_time)
read(b(2),*) time

allocate (circle_points(square_points))
allocate (dev_circle_points(square_points))

n_blocks = square_points/n_threads
if (mod(n_blocks, n_threads) > 0) n_blocks = n_blocks + 1

call pi_kernel<<<n_blocks, n_threads>>>(square_points, time)
circle_points = dev_circle_points

pi = 4*real(sum(circle_points))/square_points
print *, "Pi ~=", pi

end program pi_cuda
```

```
module pi_mod
use curand_device
implicit none
integer, allocatable, device:: dev_circle_points(:)
contains
attributes(global) subroutine pi_kernel(square_points, time)
integer, value, intent(in) :: square_points
integer, value, intent(in) :: time
type(curandStateXORWOW) :: h
integer(8) :: seed, seq, offset
integer :: i
real(8) :: rand_x, rand_y, origin_dist

i = (blockIdx% - 1)*blockDim% + threadIdx%
seed = i * 1024 + time
seq = 0
offset = 0
call curand_init(seed, seq, offset, h)

if (i <= square_points) then
    rand_x = curand_uniform_double(h) * 2 - 1
    rand_y = curand_uniform_double(h) * 2 - 1

    origin_dist = rand_x*rand_x + rand_y*rand_y

    if (origin_dist <= 1.0) then
        dev_circle_points(i) = 1
    else
        dev_circle_points(i) = 0
    end if
end if
end subroutine pi_kernel
end module pi_mod
```

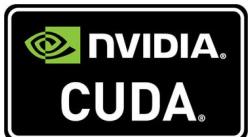


## pi\_cuda\_main/mod\_c.cuf (N=2^30) i7 11700@2.5GHz, 16GB DDR4 3200MT/s, GeForce RTX 3060 (12GB)

```
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ nvfortran -cudaLib=curand -o pi_cuda_c.exe pi_cuda_mod_c.cuf pi_cuda_main_c.cuf
pi_cuda_mod_c.cuf:
pi_cuda_main_c.cuf:
(minimal) adpozuelo@tyrion:~/ownCloud/Development/mc_pi$ time ./pi_cuda_c.exe
Pi ~ 3.141734

real 0m0.230s
user 0m0.150s
sys 0m0.075s
```

- Mínima transferencia memoria  $CPU \leftrightarrow GPU$
- Uso de operaciones atómicas en *kernel*
- *RNG* en GPU (*curand*)



```
program pi_cuda
use cudafor
use pi_mod
implicit none

integer :: i, n_blocks, time, circle_points
integer, parameter :: n_threads = 128
integer, parameter :: square_points = 1073741824
real :: pi
integer date_time(8)
character*10 b(3)
call date_and_time(b(1), b(2), b(3), date_time)
read(b(2),*) time

dev_circle_points = 0

n_blocks = square_points/n_threads
if (mod(n_blocks, n_threads) > 0) n_blocks = n_blocks + 1

call pi_kernel<<<n_blocks, n_threads>>>(square_points, time)
circle_points = dev_circle_points

pi = 4*real(circle_points)/square_points
print *, "Pi ~=", pi

end program pi_cuda
```

```
module pi_mod
use curand_device
implicit none
integer, device:: dev_circle_points
contains
attributes(global) subroutine pi_kernel(square_points, time)
    integer, value, intent(in) :: square_points
    integer, value, intent(in) :: time
    type(curandStateXORWOW) :: h
    integer(8) :: seed, seq, offset
    integer :: i, istat
    real(8) :: rand_x, rand_y, origin_dist

    i = (blockIdx%x - 1)*blockDim%x + threadIdx%x
    seed = i * 1024 + time
    seq = 0
    offset = 0
    call curand_init(seed, seq, offset, h)

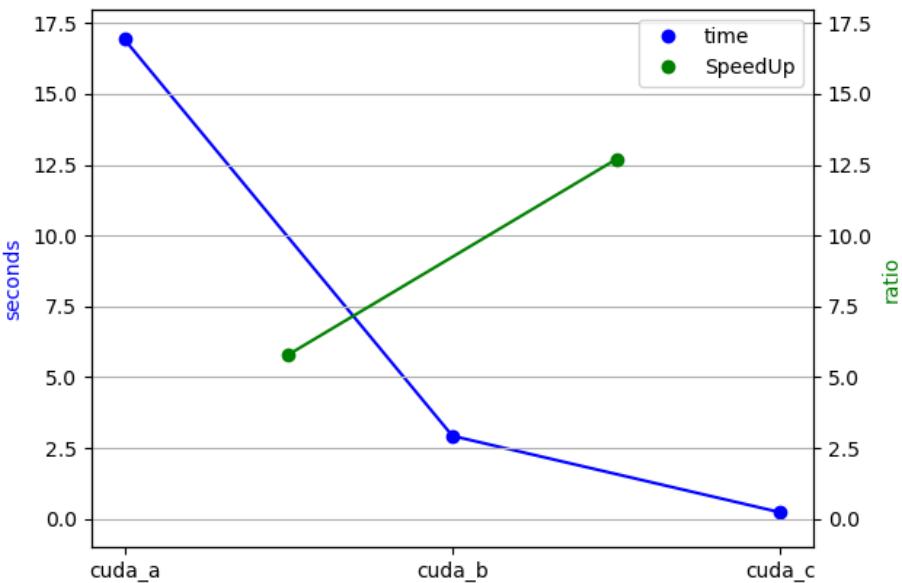
    if (i <= square_points) then
        rand_x = curand_uniform_double(h) *2 - 1
        rand_y = curand_uniform_double(h) *2 - 1

        origin_dist = rand_x*rand_x + rand_y*rand_y

        if (origin_dist <= 1.0) &
            istat = atomicadd(dev_circle_points, 1)
    end if
end subroutine pi_kernel
end module pi_mod
```

## Análisis: pi\_cuda\_main/mod.cuf (N=2^30)

i7 11700@2.5GHz, 16GB DDR4 3200MT/s, GeForce RTX 3060 (12GB)



- **SpeedUp (creciente):**

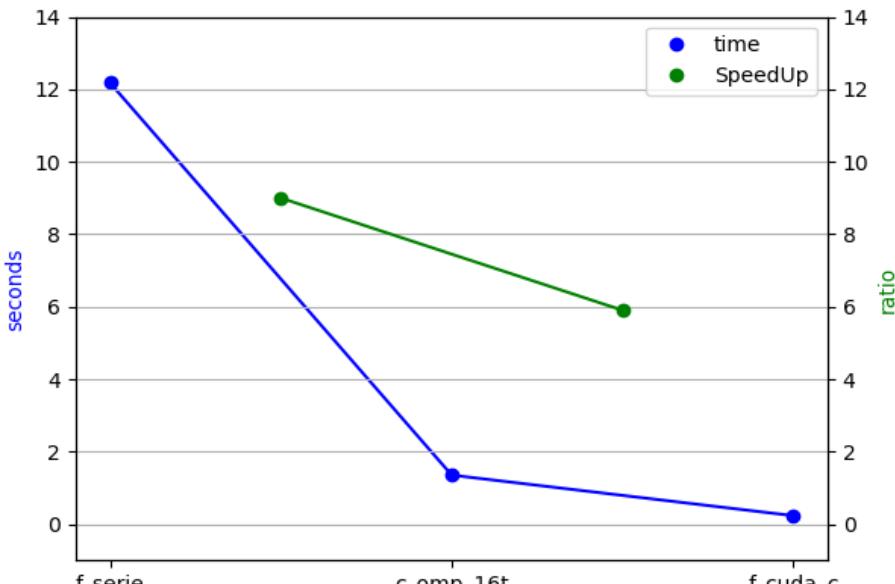
$$S(a/b) = \frac{16.93}{2.93} \approx 5.98 \quad S(b/c) = \frac{2.93}{0.23} \approx 12.7 \quad S(a/c) = \frac{16.93}{0.23} \approx 73.6$$

- Cálculo de eficiencia energética mediante consumo/tiempo y no mediante SpeedUP:  
 $EE_{CPU}$  vs  $EE_{CPU} \neq EE_{CPU}$  vs  $EE_{GPU}$
- Consideraciones importantes:

- Minimizar transferencias memoria  $CPU \leftrightarrow GPU$
- Uso de operaciones atómicas en *kernel*
- RNG válidos para paralelización



# Análisis códigos más rápidos y conclusiones



$$S(p_{serie}/f_{cuda-c}) = \frac{468.7}{0.23} \approx 2038$$



- *SpeedUp* (decreciente):  
 $S(f_{serie}/c_{omp\ 16t}) = \frac{12.18}{1.35} \approx 9$        $S(c_{omp\ 16t}/f_{cuda-c}) = \frac{1.35}{0.23} \approx 5.9$
- La computación paralela permite mitigar y abordar:
  - Límites físicos procesadores (nm, °C)
  - Límites consumo energético
  - Problemas *NP* (*Nondeterministic Polynomial*)
- Sin la computación paralela no sería posible resolver problemas complejos, en tiempos razonables

## Futuro

¡Muchas gracias por vuestra atención!

- *GPUs*: coste bajo/medio y rendimiento muy alto
- *SMP*: aumenta relación cores/procesador: coste medio y rendimiento alto
- *Infiniband/Similares*: coste y rendimiento altos
- Soluciones híbridas: (*SMP/MPI*)+*GPU [aceleradores]*
- Lenguajes de programación convertidos en un negocio empresarial
  - Reinventar la rueda una y otra vez
  - Efecto “caja negra” o “darle al botón”
  - Afecta a la formación/educación
- Descarga del *Workshop*:
  - [https://github.com/adpozuelo/Workshop\\_ICP](https://github.com/adpozuelo/Workshop_ICP)

