Computer Architecture

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Summer 2020

Part I

Programming for Parallelism

Parallelism and its Implications

Moore's Law $\rightsquigarrow$ parallelism $\nearrow$

But:

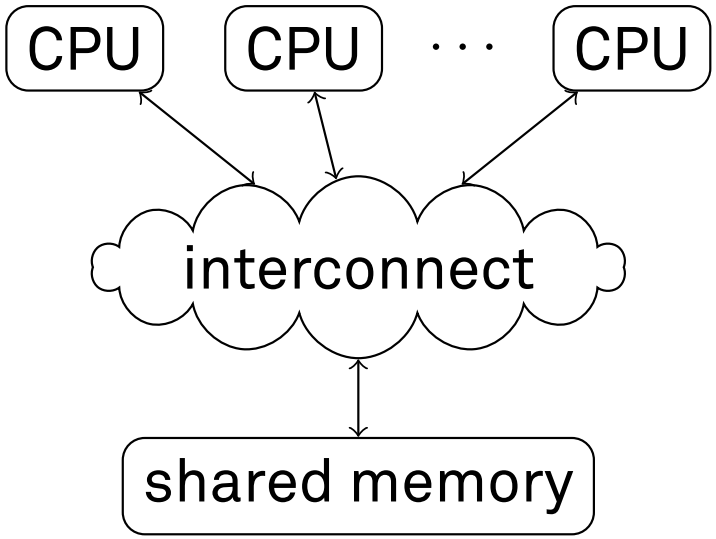
- Parallelism $\rightarrow$ communication/synchronization
- Amdahl's Law:
  - $\rightarrow$ Must keep sequential code parts **really** small.

Therefore:

- Need **efficient communication/synchronization mechanisms**
  - $\rightarrow$ What are the ways to realize that?
- Parallelize **aggressively**
  - $\rightarrow$ Tool support?

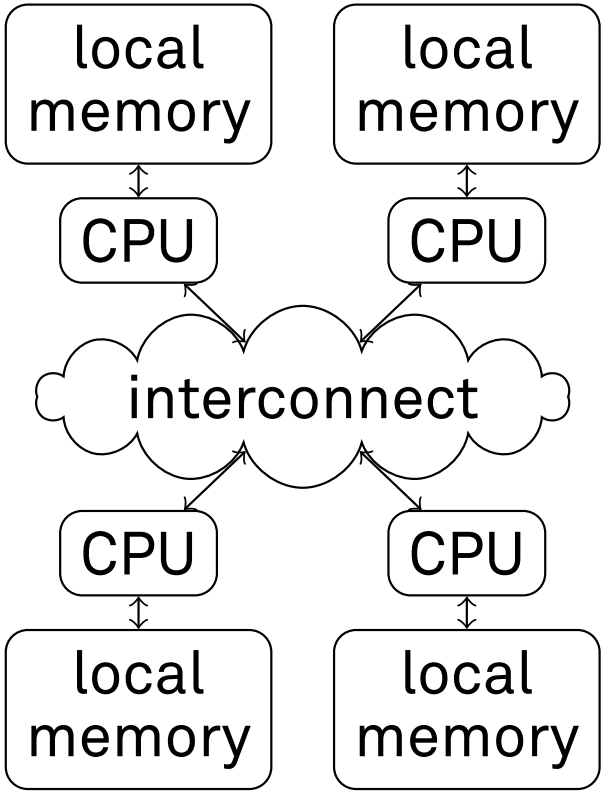
Communication/Synchronization

Shared Memory:



- Memory accessible by all CPUs/threads.
- Threads communicate through memory.

Message Passing:



- Threads communicate through messages.

Shared Memory ↔ Message Passing

✎ **Pros/Cons of the two mechanisms?**

OpenMP

OpenMP: An API for Shared Memory Multiprocessing

- Non-profit industry consortium
- First version: October 1997 (for Fortran)
- Latest version: November 2018 (version 5.0; Fortran/C/C++)
- Supported by many modern compilers (*e.g.*, `gcc`, LLVM, `icc`)

Idea:

- **Shared memory**, parallelism through **threads**
- Start from **sequential code**, introduce parallelism through **pragmas** (`#pragma` in C/C++)

OpenMP Pragmas

Pragmas are directives for the **compiler.**

E.g., C/C++: (here: ignore warning for uninitialized variable)

```
#pragma diagnostic ignored "-Wuninitialized"
foo(b);
```

OpenMP pragmas begin with `#pragma omp`:

```
#pragma omp parallel for
for (unsigned int i=0; i<N; i++)
  a[i]=b[i] + k*c[i];
```

Pragmas are **ignored** if the compiler does not understand them.

“Hello World!” of OpenMP

```
#pragma omp parallel for
for (unsigned int i=0; i<N; i++)
  a[i]=b[i] + k*c[i];
```

- Compiler will automatically assign loop iterations to parallel threads.
  - → Number of threads created is (by default) at the compiler’s discretion.
- Pragma is ignored by a non-OpenMP-aware compiler.
  - → Above code will run just fine as sequential code.
- Strategy:
  - → Identify performance-critical loops.
  - → Parallelize using OpenMP pragmas.

OpenMP Fork/Join Model

The OpenMP `parallel` clause declares a **parallel region.**

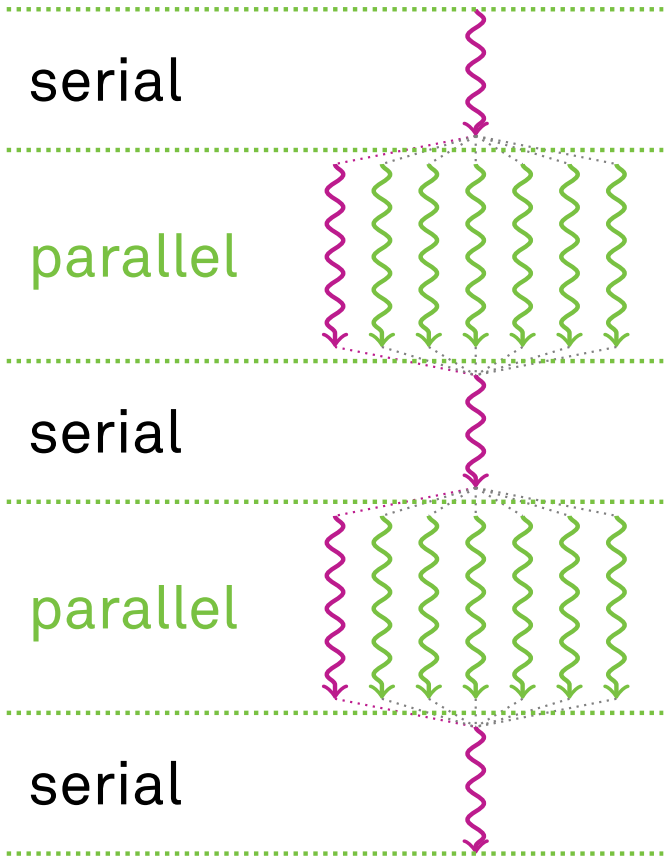
```
printf("Initializing...\n");

#pragma omp parallel for
for (int i=0; i<1000; i++)
  a[i]=random();

printf("Incrementing...\n");

#pragma omp parallel for
for (int i=0; i<1000; i++)
  a[i]=a[i]+1;

printf("Done.\n");
```



⇝ `pthread_create()` / `pthread_join()`

OpenMP `parallel` Directive

Actually...

- Most `#pragma omp` directives apply to the following **structured block of code.**
  - *E.g.*, a C statement or a block inside `{ / }`
  - Block must have **single entry** and **single exit.**
- `#pragma omp parallel` **only** tells the master thread to fork and create a team of threads
  - → **All** threads will execute all of the code in the block.
  - → Threads will share (almost[1]) **all** data.

✎ **What will be the output of the following code?**

```
#pragma omp parallel
printf("Hello World!\n");
```

[1] Each thread will have its own program counter and stack.

Library Functions

Library functions help to interface with OpenMP.

```
#include <omp.h>
int
main(int argc, char **argv)
{
  omp_set_num_threads(4);
  #pragma omp parallel
  {
    unsigned int id  = omp_get_thread_num();
    unsigned int cnt = omp_get_num_threads();
    printf("I'm thread number %u (out of %u).\n",
           id, cnt);
  }
}
```

More About `#pragma omp parallel`

`#pragma omp parallel`:

- Implicit **barrier** at the end of the structured block.
  - → Execution continues only after all threads have joined.
- Threads may or may not actually terminate at block end.
  - → Thread creation is expensive.
  - → Compiler might decide to rather put threads to sleep and wake them up again later.

OpenMP `for` Directive

Parallelization of `for` loops is a common situation.

→ OpenMP `for` directive

```
#pragma omp for
for (unsigned int i = 0; i < 1000; i++)
    do_something (i);
```

If `#pragma omp for` is found **outside parallel region**:

→ Directive has no effect.

If `#pragma omp for` is found **inside parallel region**:

→ **Distribute** iterations over threads.

→ Only allowed for “simple” loops where number of iterations can be counted before the loop evaluation starts.

OpenMP `for` Directive

Example:

```
#pragma omp parallel
{
    #pragma omp for
    for (unsigned int i = 0; i < 1000; i++)
        do_something(i);
}
```

More convenient shortcut:

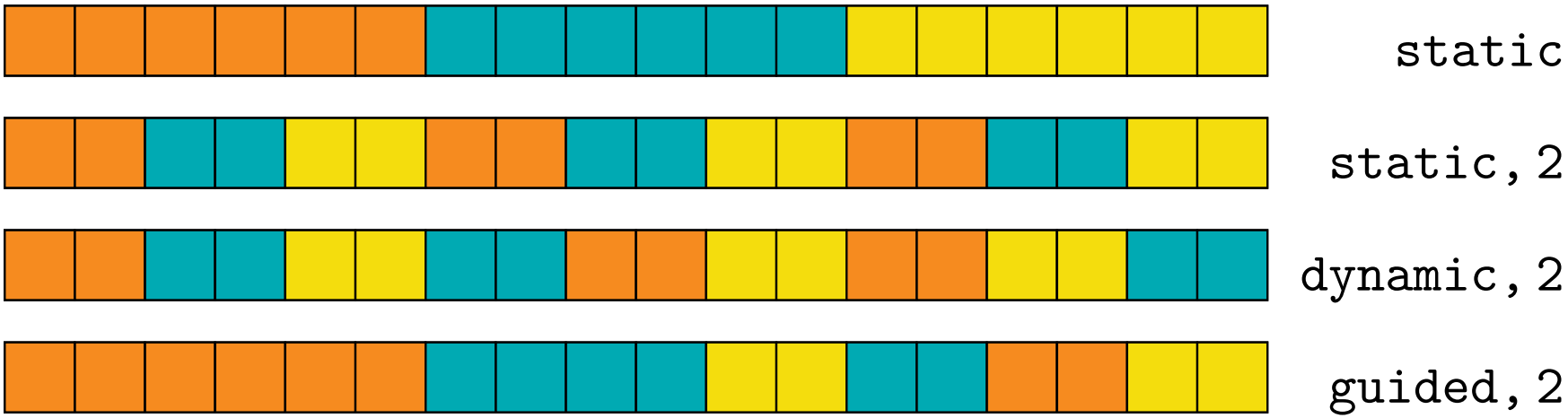
```
#pragma omp parallel for
for (unsigned int i = 0; i < 1000; i++)
    do_something(i);
```

Loop Scheduling

Scheduling of the following loop?

```
#pragma omp parallel for
for (unsigned int i = 0; i < 18; i++)
    do_something(i);
```

Possible strategies: (■: Thread 1; ■: Thread 2; ■: Thread 3)



Loop Scheduling (*cont.*)

Loop scheduling can be controlled using the `schedule` **clause**:

```
#pragma omp parallel for schedule(dynamic,2)
for (unsigned int i = 0; i < 18; i++)
    do_something (i);
```

- If no `schedule` clause is given, the compiler will use its **implementation-dependent default.**
- The `static` policy may be helpful when you need to know which thread processes which subset of the data.
- Use `dynamic` when you expect that execution time varies between iterations.

Data Sharing

Shared Memory programming model:

- By default, all resources are **shared** between threads.
- **Except:**
  - Program counter, register contents, etc. are private.
  - Each thread has its private stack.
    Locally created variables are thus private, too.
- Sharing can be controlled using **clauses** in the `parallel`/`for` constructs.
- **Private** variables:
  - → Each thread gets its own copy.
  - → These copies are **not initialized** by OpenMP.
- `for` construct → **loop variable** becomes **private**

Data Sharing Clauses

`shared` (*list of variables*)

→ All threads read/write to **same memory location.**

→ No (automatic) protection by OpenMP.

`private` (*list of variables*)

→ Each thread gets an **uninitialized copy** of the variable.

→ Only visible to the respective thread.

`default` (`shared` | `private`[2] | `none`)

→ `shared`: All variables shared by default.

→ `private`: All variables private by default.

→ `none`: Sharing mode for each variable must be explicitly declared.

More sharing modes:

- `lastprivate`, `firstprivate`, `reduction`, `copyin`; `threadprivate`, ...

[2] Only allowed in Fortran.

Synchronized Access to Shared Variables

Critical sections can be specified using the `critical` construct:

```
unsigned int aggregate = 0;

#pragma omp parallel for
for (unsigned int i = 0; i < 100; i++)
{
    unsigned int foo;
    foo = compute_something(a[i]);

    #pragma omp critical
    { aggregate += foo; }
}
```

For some simple assignments, `atomic` can be used instead:

```
#pragma omp atomic
aggregate += foo;
```

✎ **Advantage?**

`reduction` Clause

`reduction` helps to handle a common task:

```
#pragma omp parallel for reduction(+:sum)
for (unsigned int i = 0; i < 100; i++)
    sum += a[i];
```

→ **Local variable** (copied from shared during fork)

→ At join, local variables are combined and assigned to shared variable.

→ The `reduction` clause contains

(a) an **operator** using which local variables are combined and

(b) a **variable name** (as for the other data sharing clauses).

Barrier Synchronization

By default, parallel threads will synchronize at **end of structured block.**

To synchronize in-between, use `#pragma omp barrier`:

→ Threads will wait until **all** threads have reached the barrier.

```
#pragma omp parallel
{
    do_this();

    #pragma omp barrier
    /* Execute only after all threads have
       finished do_this() */
    do_that();
}
```

nowait

(For performance reasons,) automatic barrier synchronization can be skipped.

```
#pragma omp parallel
{
    #pragma omp for nowait
    for (unsigned int i = 0; i < N; i++)
        do_this(i);

    /* Some threads will still be running do_this(),
       while others will already be doing do_that() */
    do_that();
}
```

Ordering

The **order** in which threads execute and finish loop iterations is unspecified.

The `ordered` clause can be used to control the order of some operations within a loop.

```
#pragma omp for ordered schedule(dynamic)
for (unsigned int i = 0; i < 100; i++)
{
    compress (files[i]);

    #pragma omp ordered
    send (files[i]);
}
```

→ The `compress()` part will be executed in **unspecified** order.

→ Order **will be enforced** for the `send()` call.

Work-Sharing Constructs

for is also called a **work-sharing** construct.

Another work-sharing construct is `sections`:

```
#pragma omp parallel sections
{
    work_one();

    #pragma omp section
    { work_two();
      work_three(); }

    #pragma omp section
    work_four();
}
```

→ All `work_x` calls will be executed **exactly once.**

→ The tasks `work_one()`, `work_two()` + `work_three()`, and `work_four()` may be run in parallel.

Running Code by Just One Thread

The directives

- `#pragma omp single` and
- `#pragma omp master`

can be used to enforce execution of code blocks by just one thread.

→ `single` → **some** thread will run it

→ `master` → the **master** thread will run it

```
#pragma omp parallel
{
    work_one();

    #pragma omp single
    { work_two();
      work_three(); }

    work_four();
}
```

MPI—Message Passing Interface

- De facto standard for **communication protocol** in large-scale computing systems.
- Driven mostly by **researchers** (from academia and industry).
- Designed to be **portable**.
- Effort started in 1991, current version is 3.1 (June 2015)[3].
- Several free implementations available.

Programming Model:

- MPI defines an **API** for **message passing**.
- Implementations available for numerous communication substrates
  - → "Real networks"
  - → Shared memory

[3] This is a book of 868 pages!

MPI—Message Passing Interface

The core of MPI are the `send` and `receive` functions.

`send` (“buffer”, “dest”, *tag*)

→ Send data (specified by “buffer”) to the machine given by “dest”.

→ *tag*: message “type”

`receive` (“buffer”, “source”, *tag*)

→ Listen for messages of type *tag*, coming from “source”

→ Put received data into “buffer”

Two-sided communication:

- There must be matching processes that `send` and `receive` data.

`send` API

More specifically:

`MPI_Send` (*address* , *count* , *datatype* , *destination* , *tag* , *comm*)

- Send *count* elements of type *datatype*, starting from memory address *address*.
- *destination* is an integer, also called **rank**
  - → Processes in an MPI group are identified by integers $0 \ldots n$.
- *tag* is also an integer, used for message matching.
- *comm*: communication context
  - → Identifies a group of MPI processes.

`receive` API

`MPI_Recv(` *address*, *maxcount*, *datatype*, *source*, *tag*, *comm*, *status* `)`

- The receive buffer at *address* must be large enough to hold *maxcount* objects of type *datatype*.
- *source* is the rank of the node that we want to receive from
  - → or use wildcard `MPI_ANY_SOURCE`
- *status* is a return parameter with information about actual size, source, and tag.

Note:

→ For both, `send` and `receive`, **blocking** and **non-blocking** versions exist.

Data Types

All data in MPI is **typed.**

→ Types are **machine- and language-independent.**

→ This increases **portability.**

MPI base types:

MPI type	C type
`MPI_CHAR`	`char`
`MPI_SHORT`	`signed short int`
`MPI_INT`	`signed int`
`MPI_LONG`	`signed long int`
⋮	⋮

Derived Types

Derived datatype: sequence of basic data types.

→ Represented as a **type map**:

$$type\ map = \left\{ \langle type_0, disp_0 \rangle, \ldots, \langle type_{n-1}, disp_{n-1} \rangle \right\} \quad .$$

Displacement $disp_i$:

→ Data elements need **not** be contiguous in memory.

✎ **Why is this useful, even important?**

The **type signature** is a list of type, without the displacements:

$$type\ signature = \left\{ type_0, \ldots, type_{n-1} \right\} \quad .$$

MPI “Hello World!”

```
#include <mpi.h>
int main(int argc, char **argv) {
    char msg[40];
    int  myrank;
    MPI_Status status;
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
    if (myrank == 0) {
        strcpy(msg, "Hello, there");
        MPI_Send(msg, strlen(msg)+1, MPI_CHAR, 1, 99, MPI_COMM_WORLD);
    }
    else if (myrank == 1) {
        MPI_Recv(msg, 40, MPI_CHAR, 0, 99, MPI_COMM_WORLD, &status);
        printf("received: %s\n", msg);
    }
    MPI_Finalize();
}
```

Communication Patterns

API functions exist for typical patterns; *e.g.*:

- `MPI_Bcast ()`
  → Replicate data (broadcast) to a group of processes
- `MPI_Reduce ()`
  → Collect data and reduce ($\rightsquigarrow$ OpenMP's `reduce`)
- `MPI_Scatter ()`
  → Distribute an array of data; one piece to every process
- `MPI_Gather ()`
  → Opposite of `MPI_Scatter ()`
- `MPI_Allgather ()`, `MPI_Allreduce ()`
  → `MPI_Gather ()`/`MPI_Reduce ()`, plus `MPI_Bcast ()`
- `MPI_Barrier ()`
  → Wait for all processes to reach the barrier.