# Tools Seminar

## Week 10 - Parallel Computing

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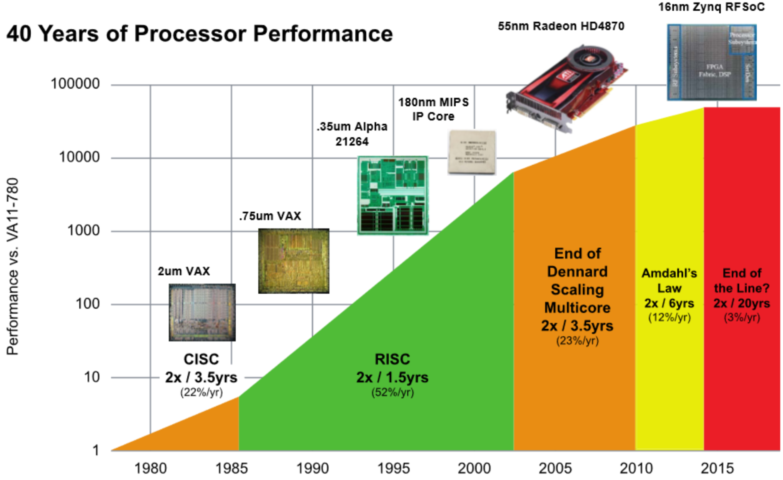
# Introduction

# Challenges: The End of Moore's Law and Scaling




*Source: John Hennessy and David Patterson, Computer Architecture: A Quantitative Approach, 6/e 2018*

* That's why Intel is called "toothpaste factory" now

# The End of Moore's Law and Scaling

*This shift toward* **increasing parallelism** *is not a triumphant stride forward based on breakthroughs in novel software and architectures for parallelism; instead, this plunge into parallelism is actually a* **retreat** *from even greater challenges that thwart efficient silicon implementation of traditional uniprocessor architectures.*

*— The Landscape of Parallel Computing Research: A View from Berkeley, 2006*

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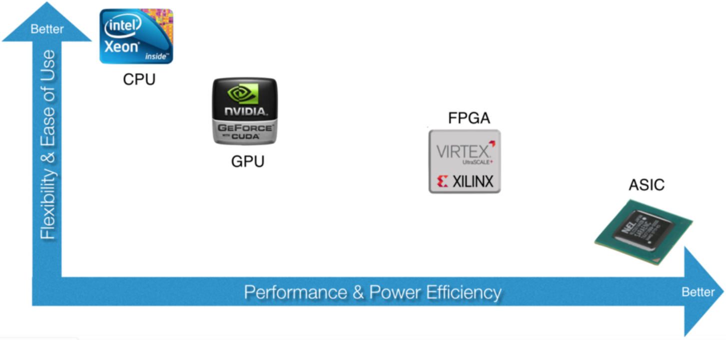
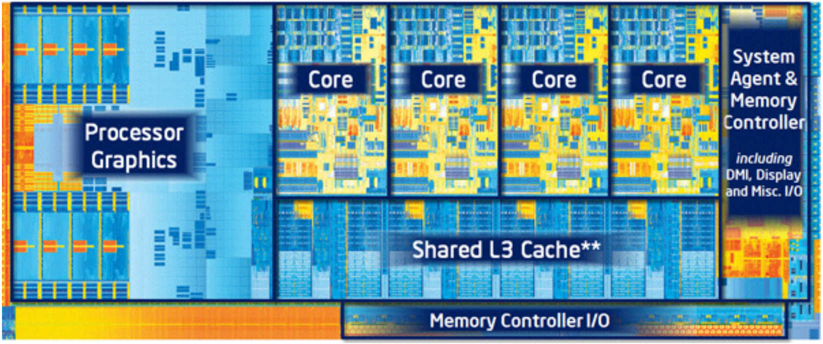
Thus, multicore processors put burdens from hardware to software, which needs programmers to code parallel programs.

# Different hardware




- CPU
- GPU (Graphical Processing Unit)
- FPGA (Field-Programmable Gate Array)
- ASIC (Application-Specific Integrated Circuit)

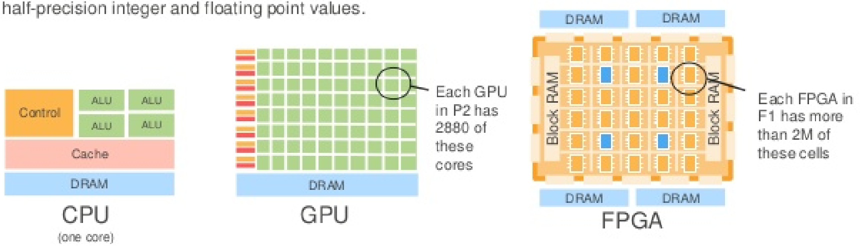
# CPU Architecture




Intel core i7 CPU (Ivy Bridge)

# Parallel Processing in GPUs and FPGAs

**A GPU** is effective at processing the <u>same set of operations</u> in parallel – single instruction, multiple data (SIMD). A GPU has a well-defined instruction-set, and fixed word sizes – for example single, double, or half-precision integer and floating point values.




**An FPGA** is effective at processing the <u>same or different operations</u> in parallel – multiple instructions, multiple data (MIMD). An FPGA does not have a predefined instruction-set, or a fixed data width.

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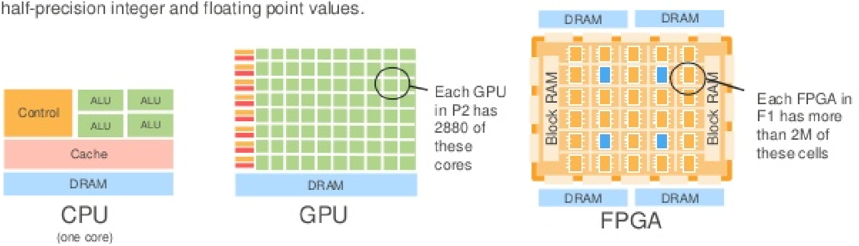


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We will focus on CPU parallelism in this seminar

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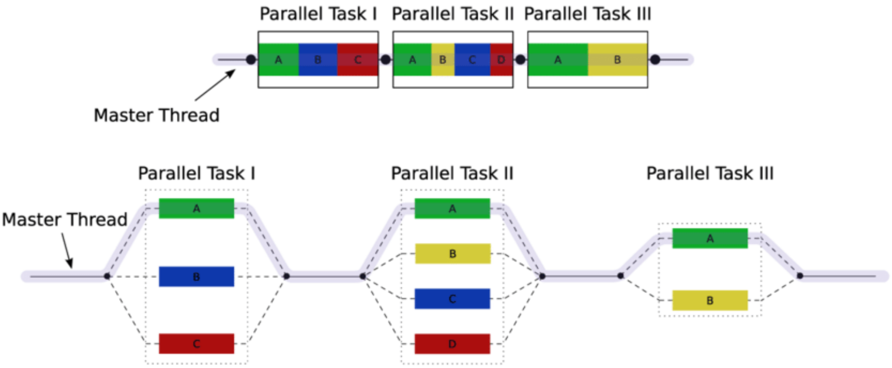
# Single Machine Parallelism

2.1

# Multi-threads

# Fork-Join Model




- Fork: Dispatch tasks to each processor / thread
- Join: Synchronization, wait till all threads are done

# pthread

POSIX (Portable Opearing System Interface for Unix)

- `<pthread.h>` is in Linux's system library and can be directly called

```
void *foo(void *arg)
{
    int* id = (int*) arg;
    printf("My id is %d\n", *id);
}

int main()
{
    pthread_t id[4];
    for (int i = 0; i < 4; ++i)
        // pass in function pointer and args
        pthread_create(&id[i], NULL, foo, &i);
    for (int i = 0; i < 4; ++i)
        pthread_join(&id[i], NULL);
    for (int i = 0; i < 4; ++i)
        pthread_exit(&id[i]);
}
```

Need to add `-lpthread` flag when compiling

# ¡thread¿

C++11 adds initial support for multi-threading in stl

```
#include <iostream>
#include <thread>
using namespace std;

void exec(int n){
    cout << "My id is" << n << endl;
}

int main(){
    thread myThread[4];
    for (int i = 0; i < 4; ++i)
        myThread = thread(exec,i);
    for (int i = 0; i < 4; ++i)
        myThread[i].join();
}
```

# Race Condition

Be careful of the shared data

| Thread A | Thread B |
|---|---|
| $\cdots$ | $\cdots$ |
| Count++ | Count−− |
| $\cdots$ | $\cdots$ |

| Thread A | | Thread B | |
|---|---|---|---|
| Load | Count | Load | Count |
| Add | #1 | Sub | #1 |
| Store | Count | Store | Count |

- Critical section: That part of the program where the shared memory is accessed
- Need to avoid conflicts and make data consistent

# Avoid Race Condition

Two basic methods:

- Corse-grained: Lock/mutex
- Fine-grained: Atomic operations

* There are lots of details about synchronization & consistency, please refer to books of OS

# Mutex Operations in pthread

`<pthread.h>`

- `pthread_mutex_init(&mutex1,NULL)`
- `pthread_mutex_destroy(&mutex1)`
- `pthread_mutex_lock(&mutex1)`
- `pthread_mutex_unlock(&mutex1)`

`<thread>`

- `std::mutex g_display_mutex`
- `std::lock_guard<std::mutex> guard(g_display_mutex)`

# Multi-threading in Python

- `threading.Thread`
- `multiprocessing.Process`
- `t1.start()`, `t1.join()`
- Global Interpreter Lock (GIL) limitation → CPython

> *An interpreter that uses GIL always allows exactly one thread to execute at a time, even if run on a multi-core processor.*

Ref: https://realpython.com/intro-to-python-threading/

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# OpenMP

# OpenMP

OpenMP (Open Multi-Processing): Shared-memory programming model

- Set of parallel commands, library, and routines
- Simplify multi-threading programming
- A spec suitable for different devices from desktop to supercomputer
- gcc has initial support for OpenMP

# OpenMP API

`#include <omp.h>` and only need to write compilation directives

```
#pragma omp <directive-name> [clause,...]
```

- `omp_get_thread_num`
- `omp_get/set_num_procs`
- `omp_get/set_num_threads`
- `#pragma omp parallel for`: The most commonly used!
- `#pragma omp ... private (<variable list>)`
- `#pragma omp ... reduction (op:list)`

# OpenMP Example (Matrix Multiplication)

```
# pragma omp for
for ( i = 0; i < n; i++ )
{
  for ( j = 0; j < n; j++ )
  {
    c[i][j] = 0.0;
    for ( k = 0; k < n; k++ )
    {
      c[i][j] = c[i][j] + a[i][k] * b[k][j];
    }
  }
}
```

# OpenMP Example (Summation)

```c
float sum(const float *a, size_t n)
{
    float total = 0.;

    #pragma omp parallel for reduction(+:total)
    for (size_t i = 0; i < n; i++) {
        total += a[i];
    }
    return total;
}
```

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## Cilk

# Intel Clik Plus

Intel Cilk Plus: A extremely light-weighted parallel framework

- `#include<cilk/cilk.h>`
- gcc 5.0+: `g++ -O3 -fcilkplus -lcilkrts <source>`
- Or compiled by Intel Compiler (icpc) — Better choice!
  - But from icpc 18.0, Intel uses Thread Building Block (TBB)

Only three keywords

- `cilk_spawn`: fork
- `cilk_sync`: join
- `cilk_for`: `parallel for`

# Clik Example (Fibbonacci)

```
int fib(int n)
{
    if (n < 2)
        return n;
    int x = fib(n-1);
    int y = fib(n-2);
    return x + y;
}

int fib(int n)
{
    if (n < 2)
        return n;
    int x = cilk_spawn fib(n-1);
    int y = fib(n-2);
    cilk_sync;
    return x + y;
}
```

# Cilk Runtime

The most powerful thing is Cilk runtime deploys **work-stealing** scheduling strategy, which greatly outperforms OpenMP's runtime

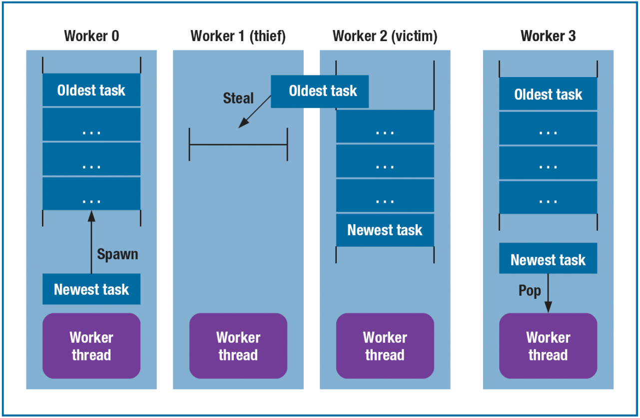


Fig source: Intel TBB

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# Finer-grained Parallelism

# Parallelism

- Thread-Level Parallelism (TLP)
- Instruction-Level Parallelism (ILP)
  - Pipelining
  - Hyperscalar
  - Very Long Instruction Word (VLIW)
  - Vector processing
  - Out-of-Order (OoO) execution
  - Spectacular execution
- Data-Level Parallelism
  - SIMD (Single Instruction Multiple Data) array processor $\rightarrow$ GPU

* Please refer to Computer Architecture books / CSAPP

# Intel CPU SIMD Instruction Set

- MME (Multi Media Extensions): Pentium, 1996
- SSE (Streaming SIMD Extensions): Pentium III, 1999
- AVX (Advanced Vector Extensions): Sandy Bridge 2008
- AVX2: Haswell, 2011

# Naming Conventions

`_mm<bit_width>_<name>_<data_type>`

- `<bit_width>`: the return size, 128 - empty, 256 - 256
- `<name>`: describes the operation performed by the intrinsic
- `<data_type>`: the function's primary arguments

| Instructions | Description |
|---|---|
| ps | packed single-precision |
| pd | packed double-precision |
| epi8/epi16/epi32/epi64 | signed integers |
| epu8/epu16/epu32/epu64 | unsigned integers |
| si128/si256 | unspecified vector |
| m128/m128i/m128d | input vector types |

e.g. `_mm256_srlv_epi64`: 64-bit signed int $\rightarrow$ 256-bit vector

# AVX Example

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

int main() {

    /* Initialize the two argument vectors */
    __m256 evens = _mm256_set_ps(2.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0);
    __m256 odds = _mm256_set_ps(1.0, 3.0, 5.0, 7.0, 9.0, 11.0, 13.0, 15.0);

    /* Compute the difference between the two vectors */
    __m256 result = _mm256_sub_ps(evens, odds);

    /* Display the elements of the result vector */
    float* f = (float*) &result; // type conversion
    printf("%f %f %f %f %f %f %f %f\n",
      f[0], f[1], f[2], f[3], f[4], f[5], f[6], f[7]);

    return 0;
}
```

Add `-mavx` flag when compiling

* Be careful that redundant movements reduce performance!

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# Distributed Parallelism

# Message Passing Interface (MPI)

Need to install MPI compiler

- `#include<mpi.h>`
- `mpicc`, `mpic++`
- `mpirun -np 2 foo : -np 4 bar`

# MPI Hello World

```
#include <mpi.h>

int main(int argc, char* argv[])
{
    int npes, myrank;
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &npes);
    MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
    printf("From process %d out of %d, Hello World!\n", myrank,
        ↪ npes);
    MPI_Finalize();
}
```

# Message Passing

Message communication is the central part of MPI

```
MPI_Send(
    void* data,
    int count,
    MPI_Datatype datatype,
    int destination ,
    int tag,
    MPI_Comm communicator)

MPI_Recv(
    void* data,
    int count,
    MPI_Datatype datatype,
    int source,
    int tag,
    MPI_Comm communicator,
    MPI_Status* status)
```

# MPI Example Program (Ping Pong)

```
int ping_pong_count = 0;
int partner_rank = (world_rank + 1) % 2;
while (ping_pong_count < PING_PONG_LIMIT) {
    if (world_rank == ping_pong_count % 2) {
        // Increment the ping pong count before you send it
        ping_pong_count++;
        MPI_Send(&ping_pong_count, 1, MPI_INT, partner_rank, 0,
                MPI_COMM_WORLD);
        printf("%d sent and incremented ping_pong_count "
               "%d to %d\n", world_rank, ping_pong_count,
               partner_rank);
    } else {
        MPI_Recv(&ping_pong_count, 1, MPI_INT, partner_rank, 0,
                MPI_COMM_WORLD, MPI_STATUS_IGNORE);
        printf("%d received ping_pong_count %d from %d\n",
               world_rank, ping_pong_count, partner_rank);
    }
}
```

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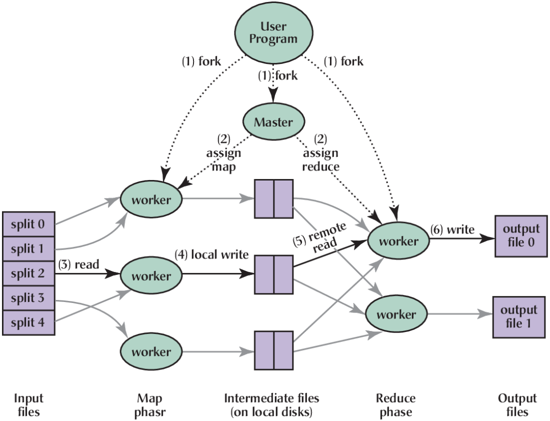
# Parallel Computing Frameworks

# Frameworks




- MapReduce: Big data programming model → Hadoop
- Spark: Better data management
- Ray: Machine Learning

# 5 Summary

# Summary

- Introduction to parallelism
- Shared-memory: pthreads, OpenMP, Cilk, AVX
- Distributed-memory: MPI
- Parallel computing frameworks: MapReduce