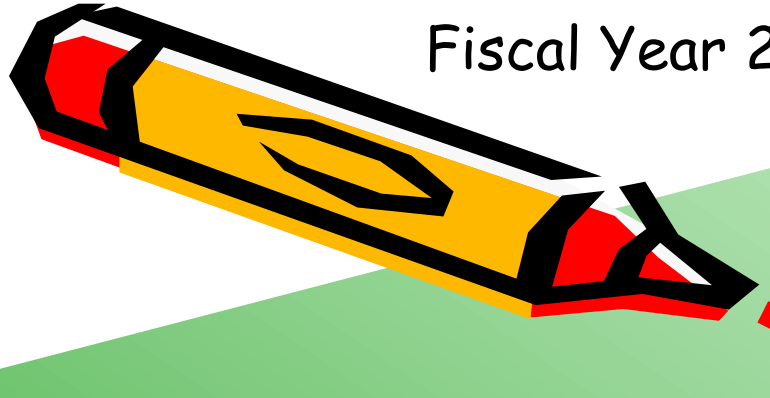


Fiscal Year 2024

Ver. 2025-01-22a

Course number: CSC.T433
School of Computing,
Graduate major in Computer Science

Advanced Computer Architecture

10. Multi-Processor: Distributed Memory and Shared Memory Architecture, Parallel Programming

www.arch.cs.titech.ac.jp/lecture/ACA/
Room No. W8E-308, Lecture (Face-to-face)
Mon 13:30-15:10, Thr 13:30-15:10

Kenji Kise, Department of Computer Science
kise _at_ c.titech.ac.jp

From multi-core era to many-core era

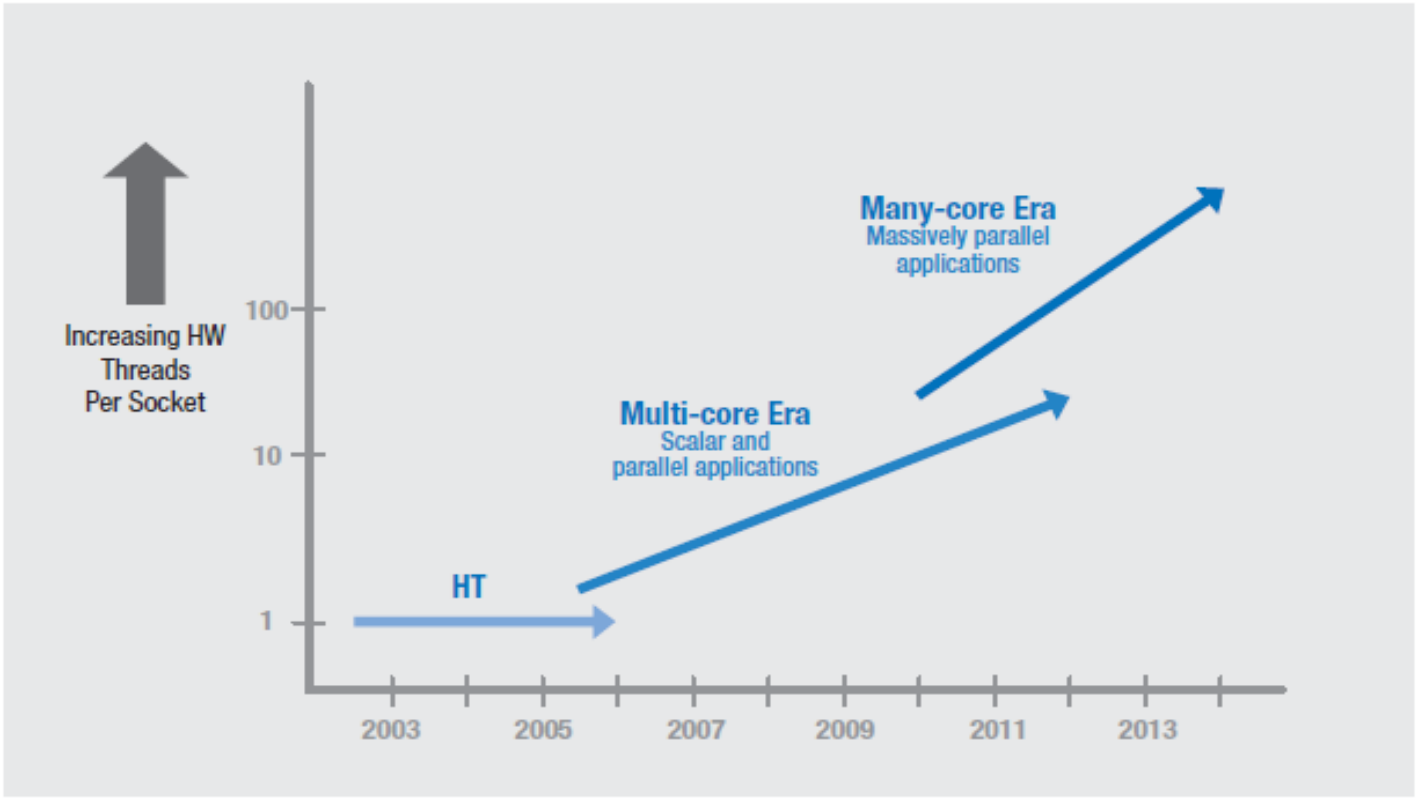
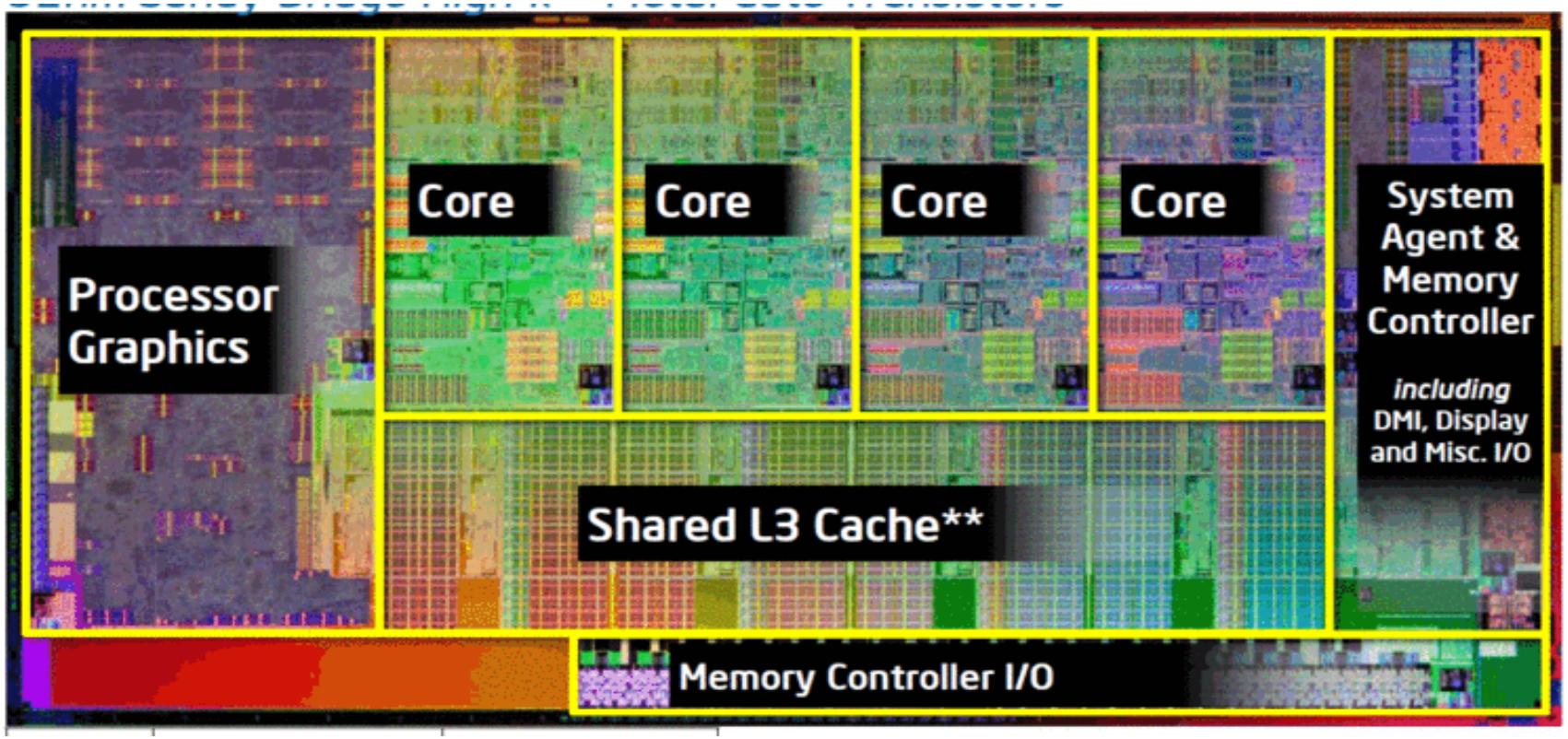


Figure 1: Current and expected eras of Intel® processor architectures

Platform 2015: Intel® Processor and Platform Evolution for the Next Decade, 2005

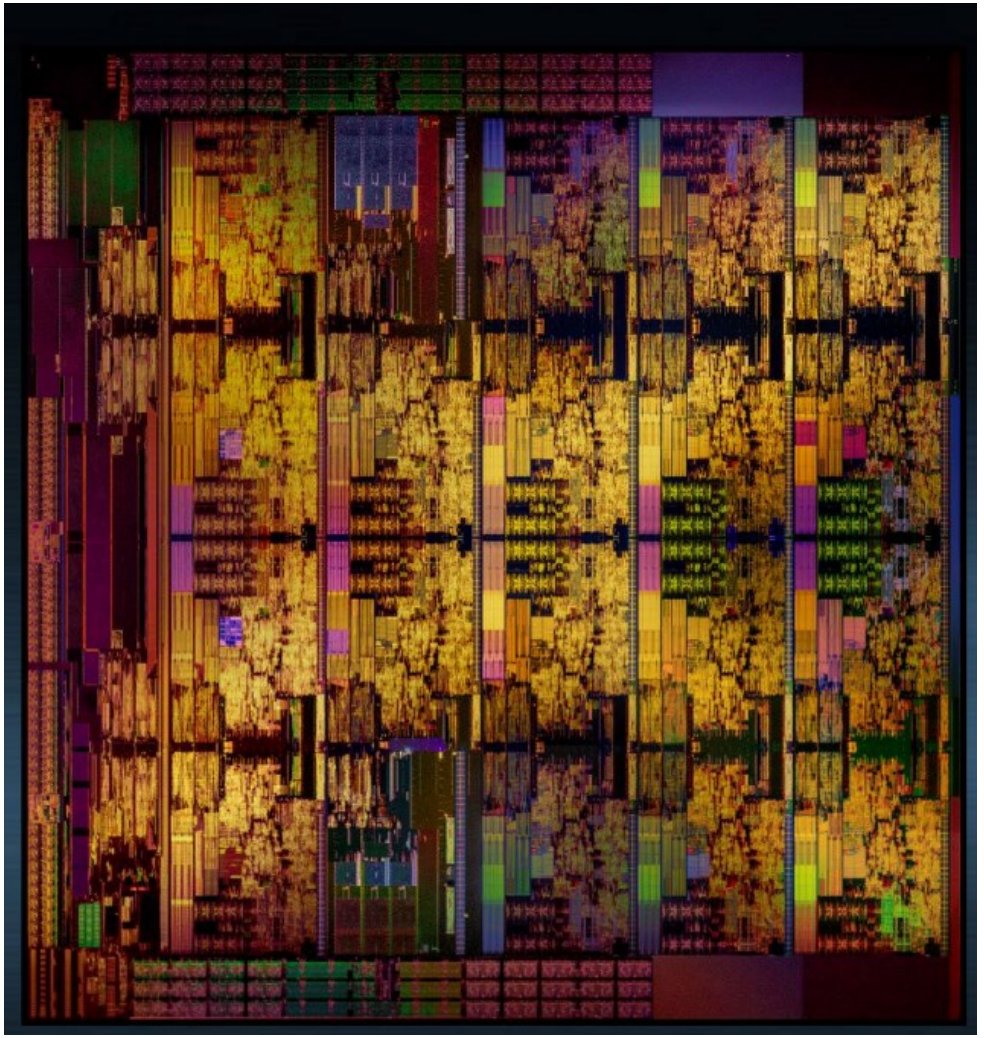
Intel Sandy Bridge, January 2011

- 4 to 8 core

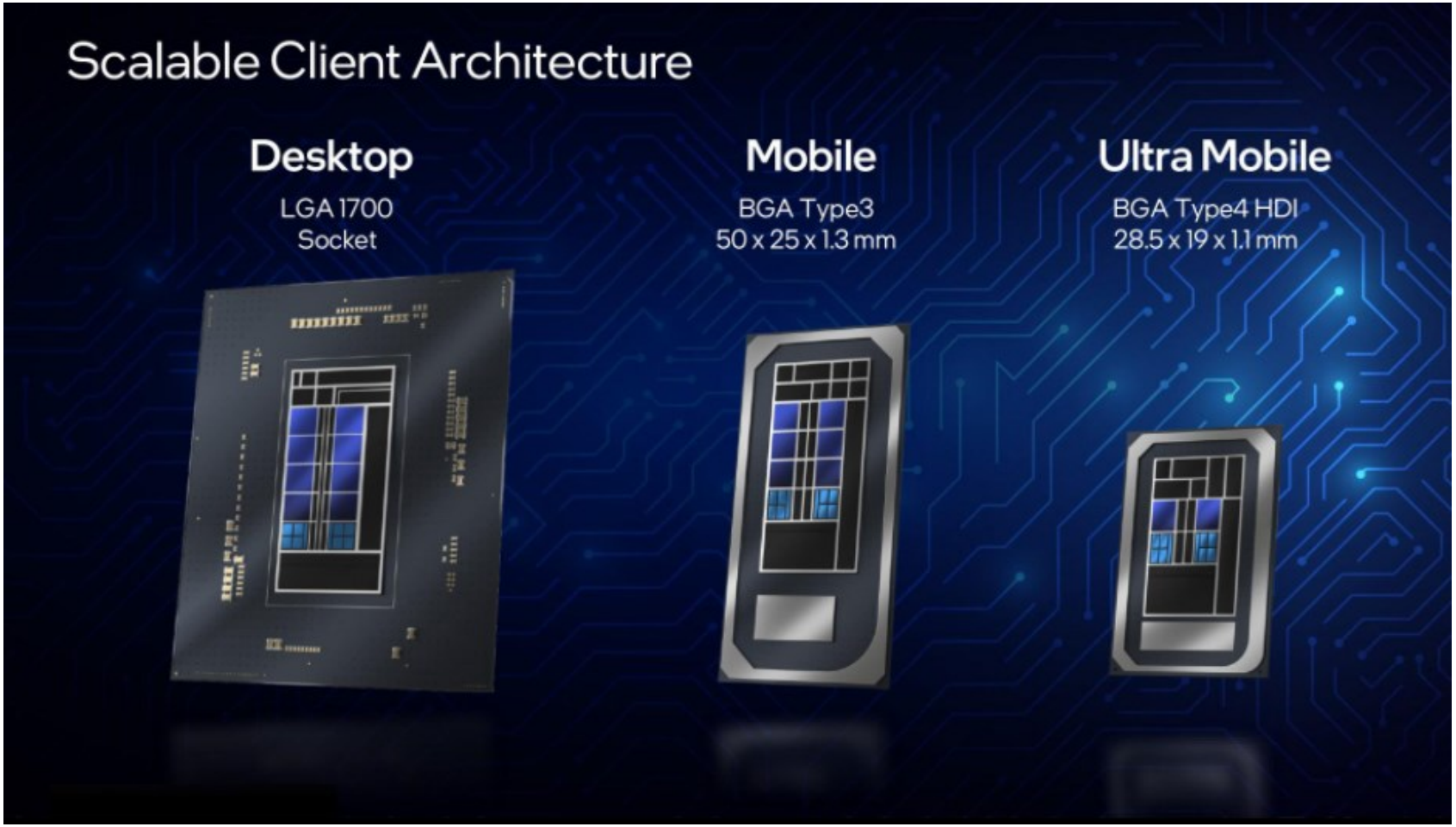


Intel Skylake-X, Core i9-7980XE, 2017

- 18 core



2021.11 Intel Alder Lake processor



2022.11 AMD EPYC 9654 processor with 96 cores

AMD EPYC™ 9004 Series Processor

All-in Feature Set support

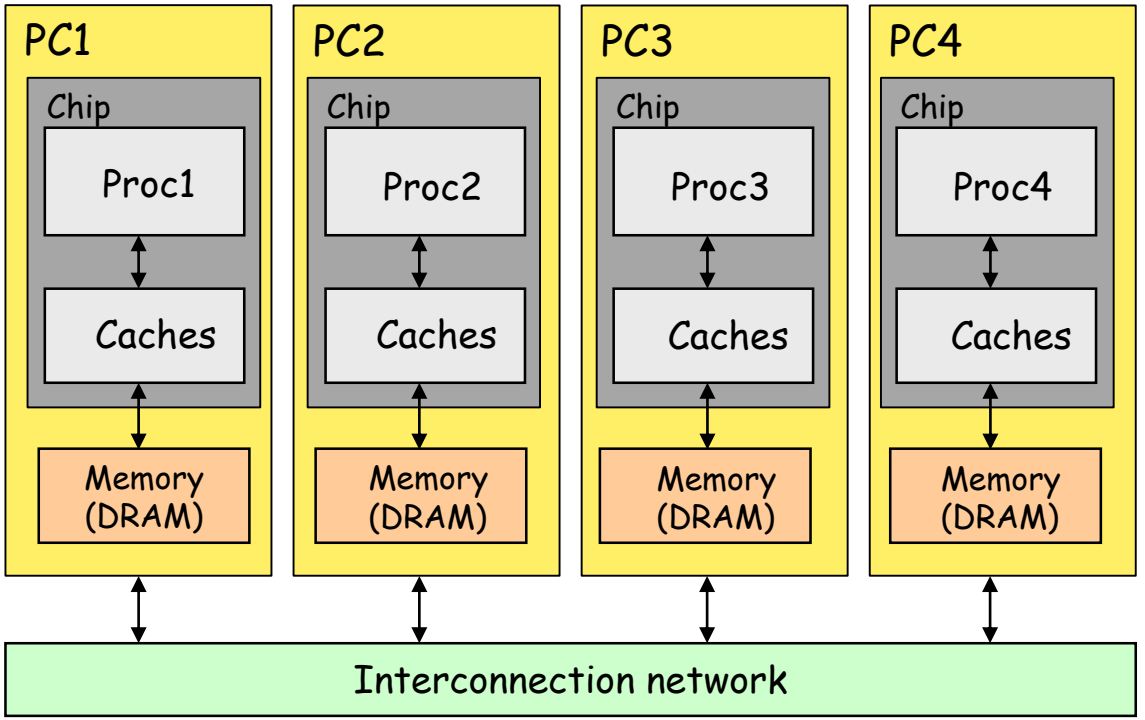
- 12 Channels of DDR5-4800
- Up to 6TB DDR5 memory capacity
- 128 lanes PCIe® 5
- 64 lanes CXL 1.1+
- AVX-512 ISA, SMT & core frequency boost
- AMD Infinity Fabric™
- AMD Infinity Guard

Cores	AMD EPYC	Base/Boost* (up to GHz)	Default TDP (w)	cTDP (w)
96 cores	9654/P	2.40/3.70	360w	320-400w
84 cores	9634	2.25/3.70	290w	240-300w
64 cores	9554/P	3.10/3.75	360w	320-400w
64 cores	9534	2.45/3.70	280w	240-300w
48 cores	→ 9474F	3.60/4.10	360w	320-400w
	9454/P	2.75/3.80	290w	240-300w
32 cores	→ 9374F	3.85/4.30	320w	320-400w
32 cores	9354/P	3.25/3.80	280w	240-300w
32 cores	9334	2.70/3.90	210w	200-240w
24 cores	→ 9274F	4.05/4.30	320w	320-400w
	9254	2.90/4.15	200w	200-240w
	9224	2.50/3.70	200w	200-240w
16 cores	→ 9174F	4.10/4.40	320w	320-400w
	9124	3.00/3.70	200w	200-240w

Distributed Memory Multi-Processor Architecture

- A PC cluster or parallel computers for higher performance
- Each memory module is associated with a processor
- Using explicit send and receive functions (message passing) to obtain the data required.
  - Who will send and receive data? How?

PC cluster



Cell Broadband Engine (2005)

- Cell Broadband Engine (2005)
  - 8 core (SPE) + 1 core (PPE)
    - each SPE has 256KB local memory
  - PS3, IBM Roadrunner(12k)

PlayStation3 の写真は
PlaySation.com (Japan) から

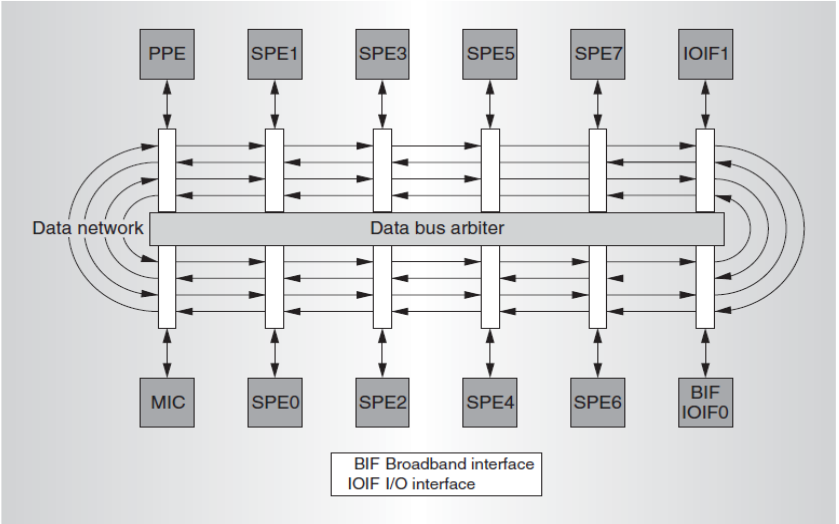


Figure 2. Element interconnect bus (EIB).

IEEE Micro, Cell Multiprocessor Communication Network: Built for Speed

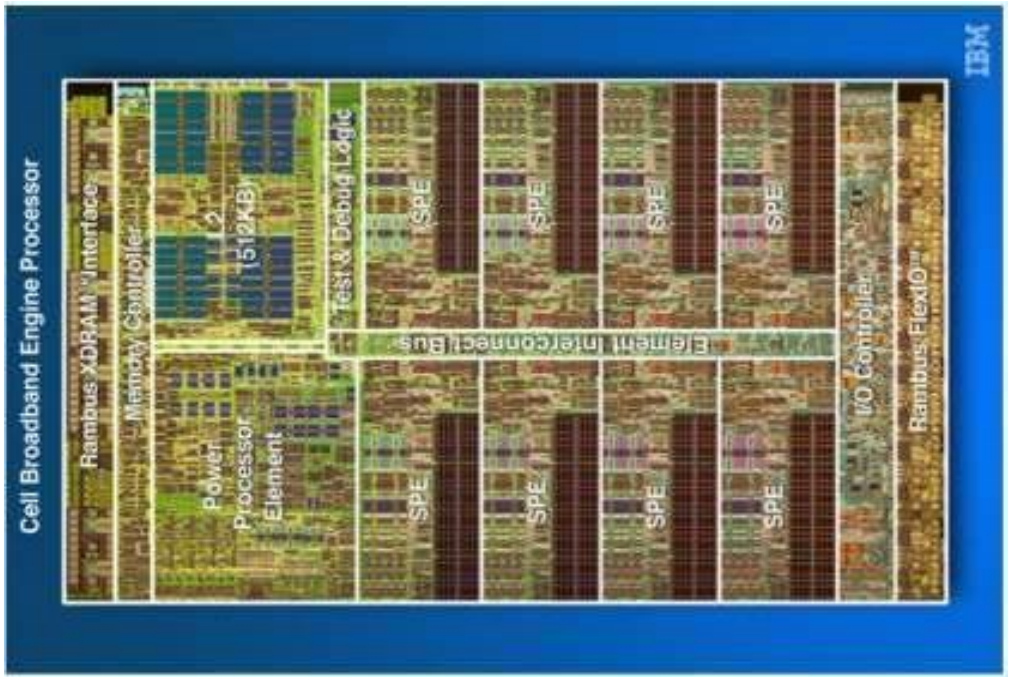
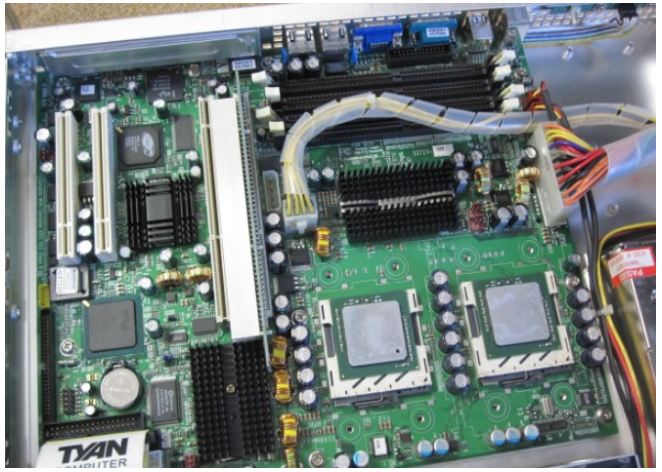
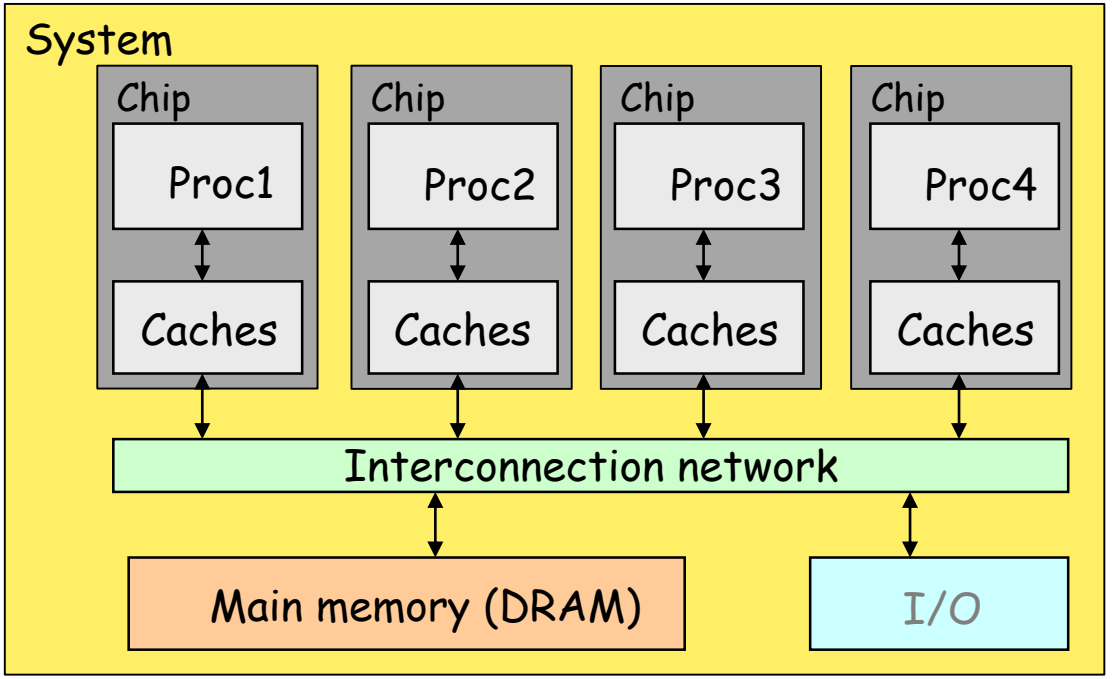


Diagram created by IBM to promote the CBEP, ©2005 from WIKIPEDIA

Shared Memory Multi-Processor Architecture

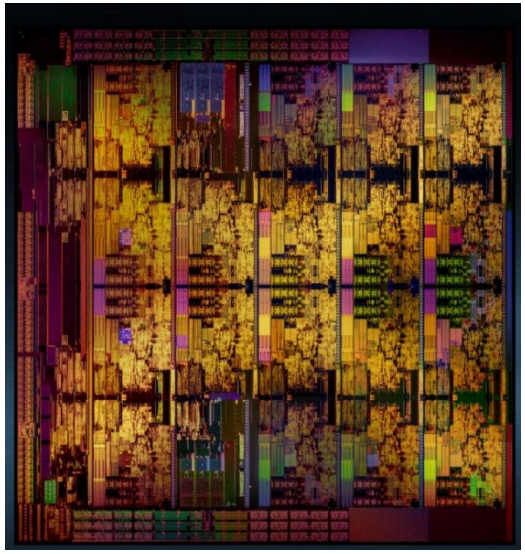
- All the processors can access the same address space of the main memory (shared memory) through an interconnection network.
- The shared memory or shared address space (SAS) is used as a means for communication between the processors.
  - What are the means to obtain the shared data?
  - What are the advantages and disadvantages of shared memory?



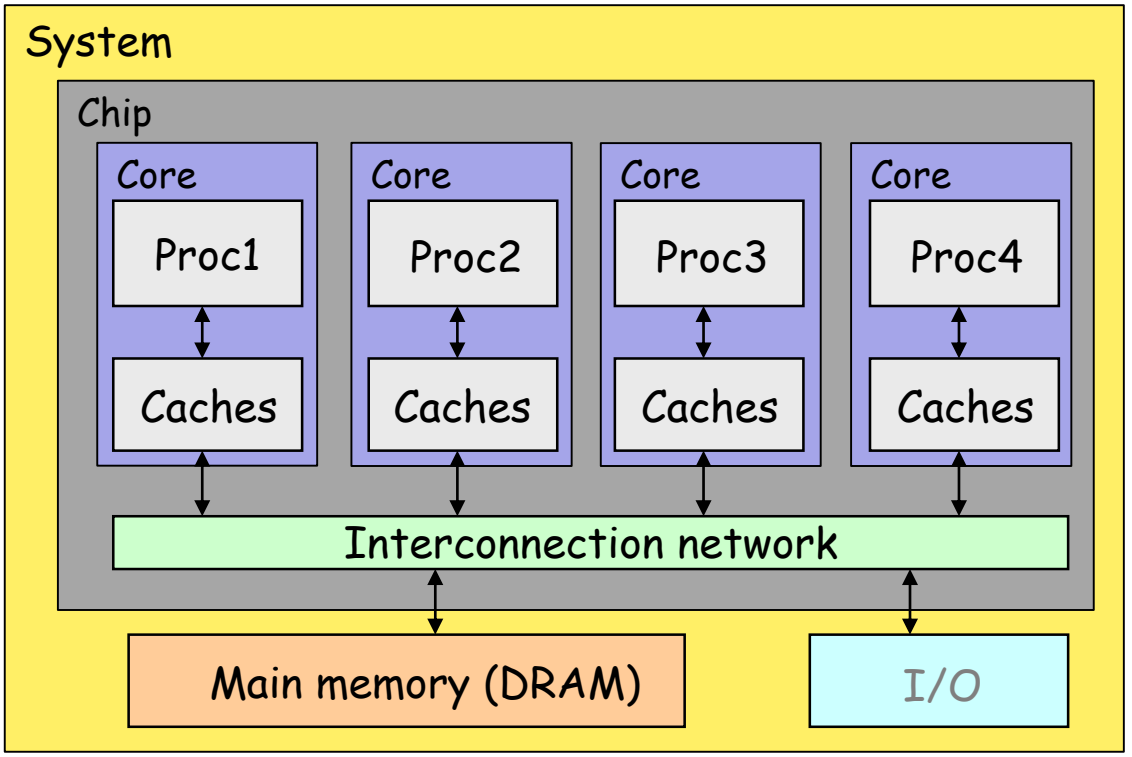


Shared memory many-core architecture

- The single-chip integrates many cores (conventional processors) and an interconnection network.
- The shared memory or shared address space (SAS) is used as a means for communication between the processors.



Intel Skylake-X, Core i9-7980XE, 2017



The free lunch is over

- Programmers have to worry much about performance and concurrency
- Parallel programming & multi-processor (multi-core) architectures

Free Lunch

Programmers haven't really had to worry much about performance or concurrency because of Moore's Law

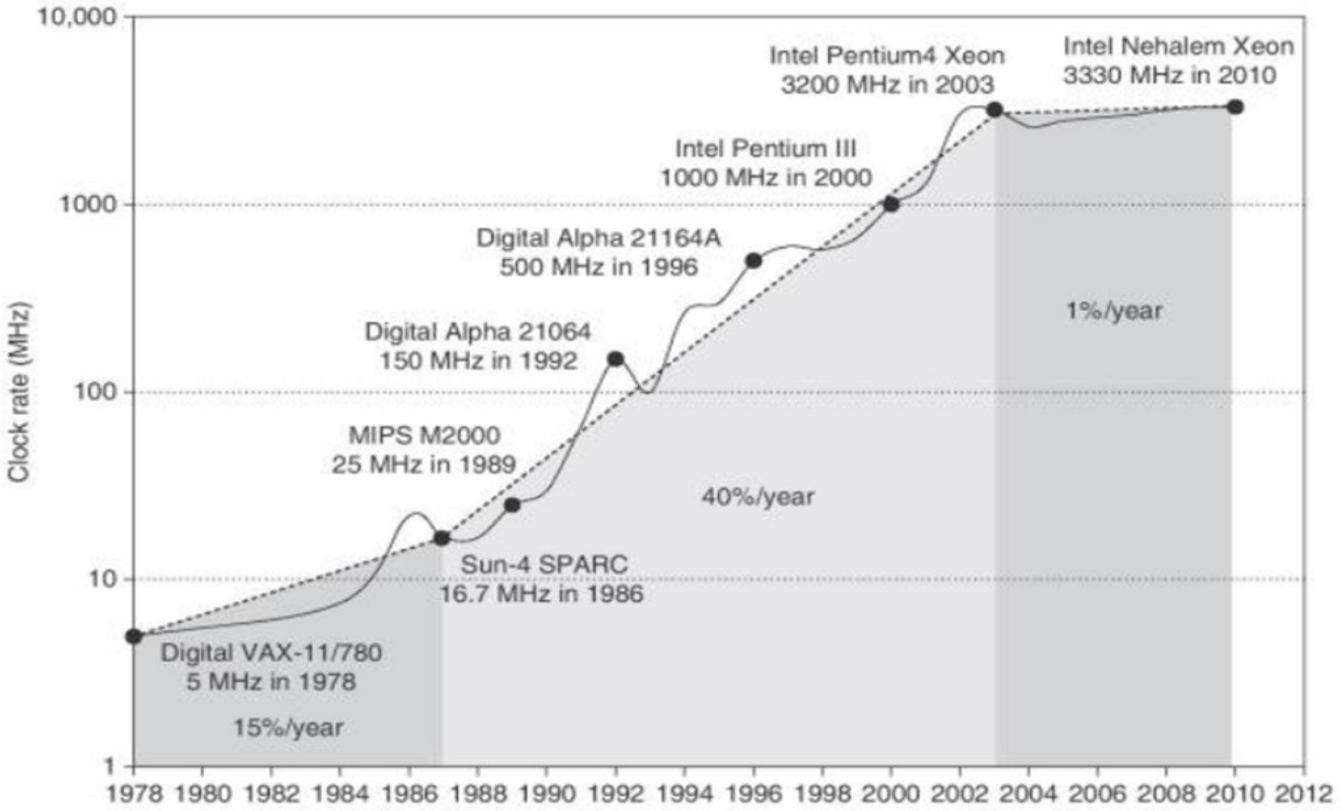
Why we did not see 4GHz processors in Market?

The traditional approach to application performance was to simply wait for the next generation of processor; most software developers did not need to invest in performance tuning, and enjoyed a "free lunch" from hardware improvements.

The Free Lunch Is Over: A Fundamental Turn Toward Concurrency in Software by Herb Sutter, 2005

Growth in clock rate F of microprocessors

Intel 4004 clocked at 740KHz in 1971



From CAQA 5th edition

13th Generation Intel® Core™ i9 Processors

Products formerly Raptor Lake

Desktop

i9-13900K

Launched

Q4'22

Intel 7

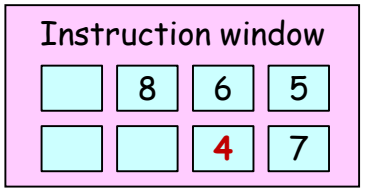
$589.00 - $599.00

CPU Specifications

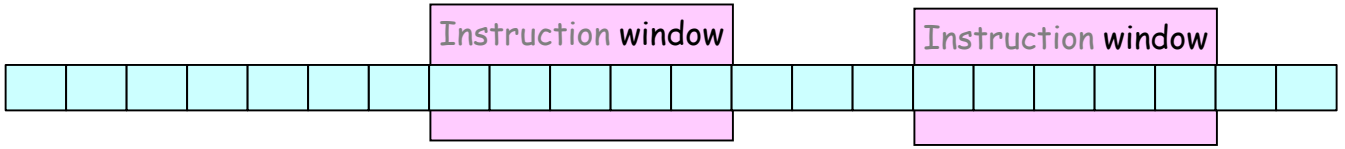
Total Cores	24
# of Performance-cores	8
# of Efficient-cores	16
Total Threads	32
Max Turbo Frequency	5.80 GHz
Intel® Thermal Velocity Boost Frequency	5.80 GHz
Intel® Turbo Boost Max Technology 3.0 Frequency ‡	5.70 GHz
Performance-core Max Turbo Frequency	5.40 GHz
Efficient-core Max Turbo Frequency	4.30 GHz
Performance-core Base Frequency	3.00 GHz
Efficient-core Base Frequency	2.20 GHz

Multiprogramming

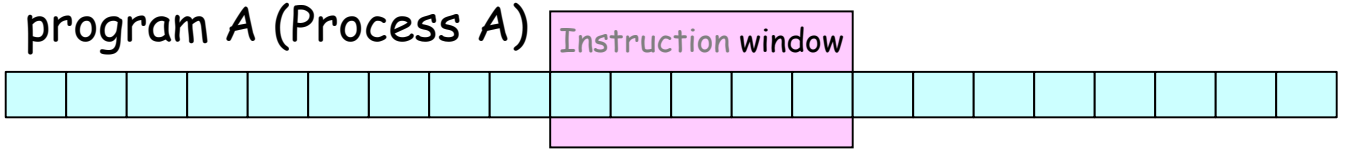
- Several independent programs (processes) run at the same time.

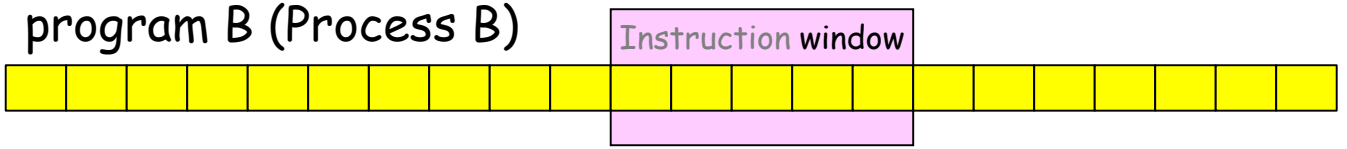


(c)



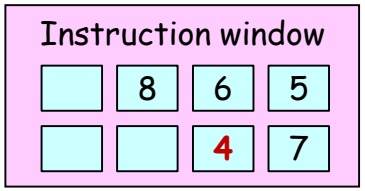
(d)



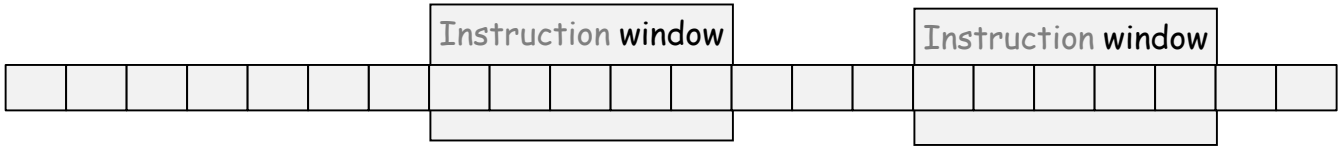


Parallel programming

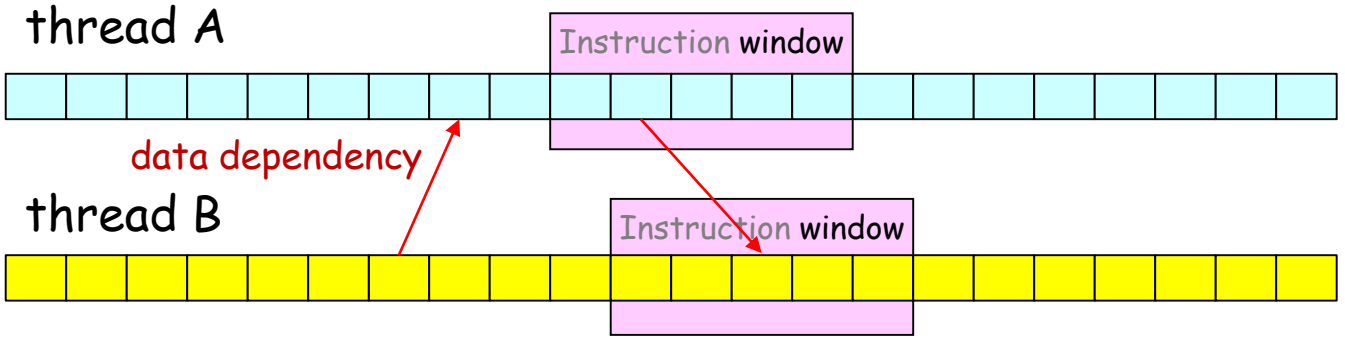
- Several dependent threads run at the same time on a multi-processor (many-core) system.



(c)

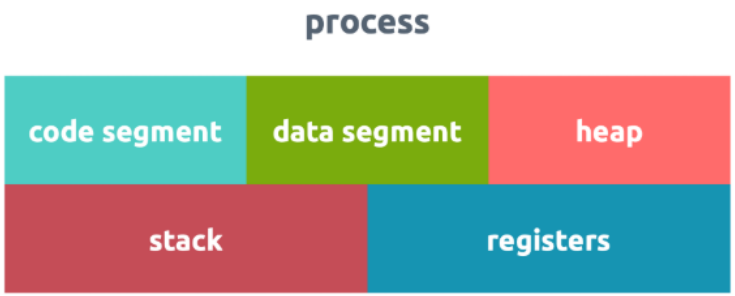


(e)

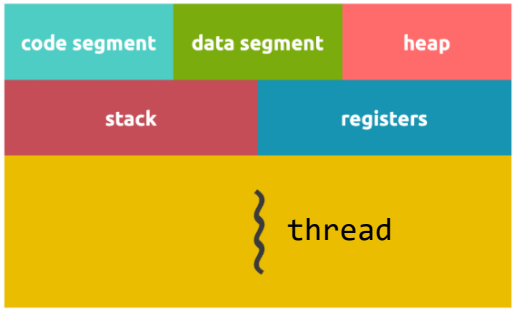


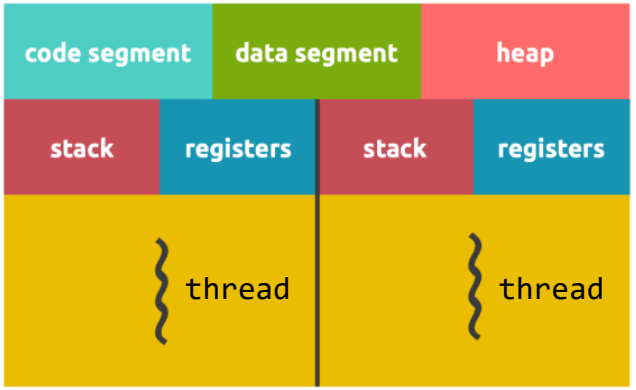
Program, process, and thread

- A process is an instance of a program that is being executed whereas a thread is part of a process.
- A process can have more than one thread. All the threads within one process are interrelated to each other. Threads have some common information, such as code segment, data segment, heap, etc., that is shared to their threads. But contains its own stack and registers (PC and x0 – x32 registers).



Multiprogramming





Parallel programming

https://zenn.dev/farstep/articles/process-thread-difference

Sample of a wrong parallel program using pthread

```
% gcc main1.c -O0 -lpthread -lm -o a.out1
% ./a.out1
main: 20000000
```

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000

int a = 0;

int func1(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int func2(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int main(){
  func1();
  func2();

  printf("main: %d¥n", a);
  return 0;
}
```

main1.c
sequential program

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000    // ten million

int a = 0;

int func1(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int func2(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int main(){
  pthread_t t1, t2;
  pthread_create(&t1, NULL,
    (void *)func1, NULL);
  pthread_create(&t2, NULL,
    (void *)func2, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);

  printf("main: %d¥n", a);
  return 0;
}
```

main2.c
parallel program with func1 and func2

Single Program Multiple Data (SPMD)

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000    // ten million

int a = 0;

int func1(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int main(){
  pthread_t t1, t2;
  pthread_create(&t1, NULL,
    (void *)func1, NULL);
  pthread_create(&t2, NULL,
    (void *)func1, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);

  printf("main: %d¥n", a);
  return 0;
}
```

main3.c
parallel program with func1

Sample of some parallel programs using pthread

```
% gcc main1.c -O0 -lpthread -lm -o a.out1
% ./a.out1
main: 20000000
```

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000

int a = 0;

int func1(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int func2(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int main(){
  func1();
  func2();

  printf("main: %d¥n", a);
  return 0;
}
```

main1.c
sequential program

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000    // ten million

int a = 0;

int func1(){
  int i;
  for(i=0; i<N; i++){ a=a+1; }
};

int main(){
  pthread_t t1, t2;
  pthread_create(&t1, NULL,
    (void *)func1, NULL);
  pthread_create(&t2, NULL,
    (void *)func1, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);

  printf("main: %d¥n", a);
  return 0;
}
```

main3.c
parallel program with func1

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000    // ten million

int a = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;

int func1(){
  int i;
  for(i=0; i<N; i++){
    pthread_mutex_lock(&m);
    a=a+1;
    pthread_mutex_unlock(&m);
  }
};

int main(){
  pthread_t t1, t2;
  pthread_create(&t1, NULL,
    (void *)func1, NULL);
  pthread_create(&t2, NULL,
    (void *)func1, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);

  printf("main: %d¥n", a);
  return 0;
}
```

main4.c
parallel program with func1, lock, and unlock

Sample of some parallel programs using pthread

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000    // ten million

int a = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;

int func1(){
  int i;
  for(i=0; i<N; i++){
    pthread_mutex_lock(&m);
    a=a+1;
    pthread_mutex_unlock(&m);
  }
};

int main(){
  pthread_t t1, t2;
  pthread_create(&t1, NULL,
    (void *)func1, NULL);
  pthread_create(&t2, NULL,
    (void *)func1, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);

  printf("main: %d¥n", a);
  return 0;
}
```

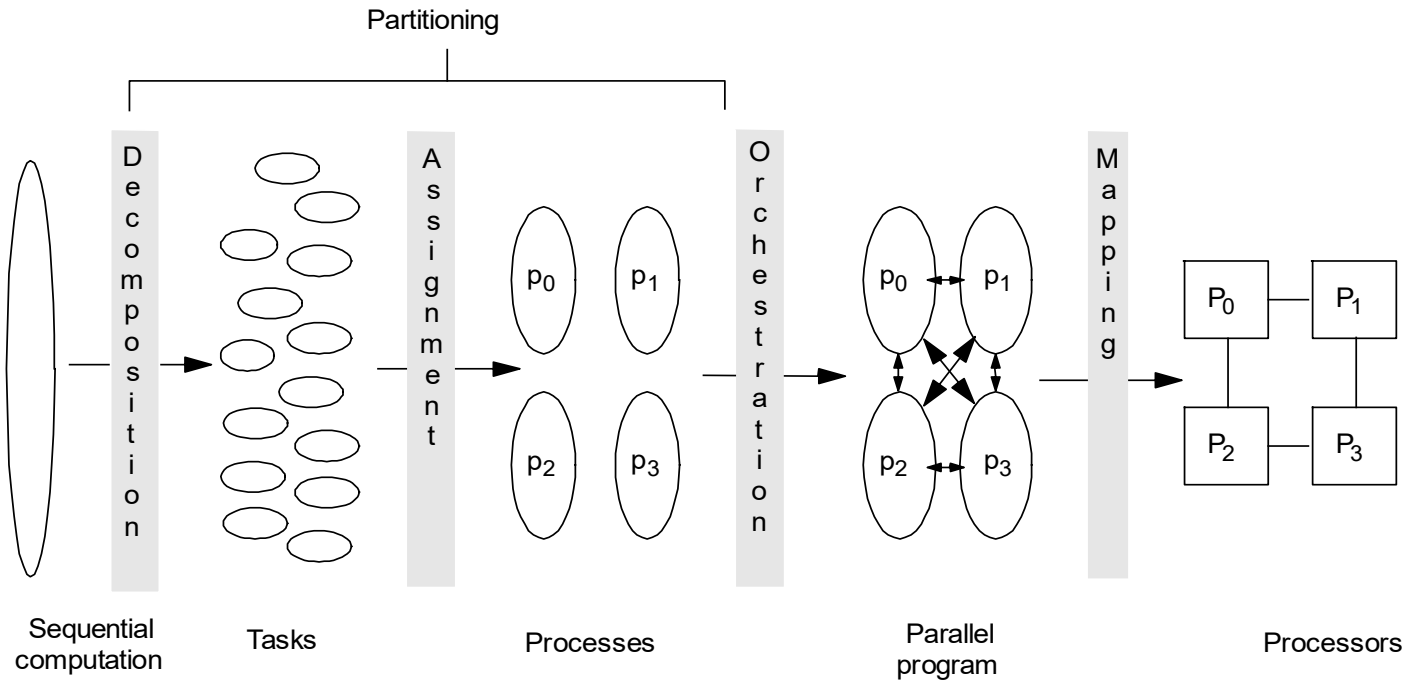
main4.c
parallel program with func1, lock, and unlock

```c
#include <stdio.h>
#include <pthread.h>
#define N 10000000    // ten million

int a = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;

int func1(){
  int i;
  int my_a = 0;
  for(i=0; i<N; i++){
    my_a=my_a+1;
  }
  pthread_mutex_lock(&m);
  a = a + my_a;
  pthread_mutex_unlock(&m);
};

int main(){
  pthread_t t1, t2;
  pthread_create(&t1, NULL,
    (void *)func1, NULL);
  pthread_create(&t2, NULL,
    (void *)func1, NULL);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);

  printf("main: %d¥n", a);
  return 0;
}
```

main5.c : parallel program with func1, local sum, lock, and unlock

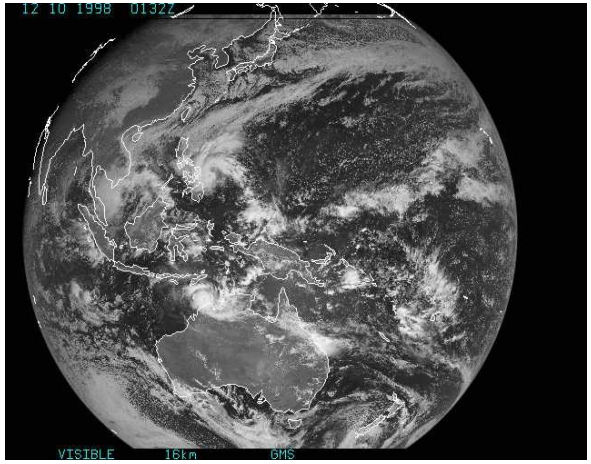
Four steps in creating a parallel program

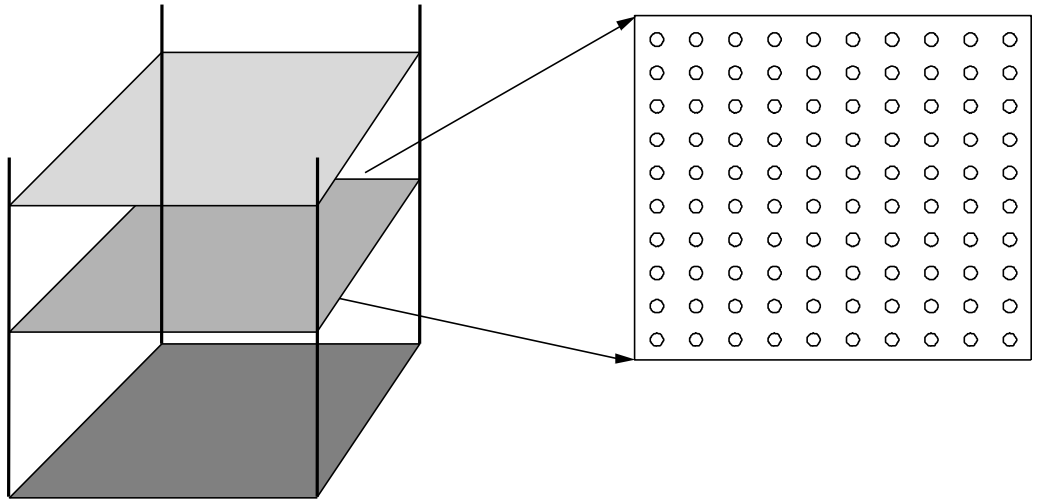
0. Preparing an optimized sequential program (baseline)
1. Decomposition of computation in tasks
2. Assignment of tasks to processes
3. Orchestration of data access, comm, synch.
4. Mapping processes to processors (cores)



Adapted from *Parallel Computer Architecture*, David E. Culler

Simulating ocean currents





(a) Cross sections

(b) Spatial discretization of a cross section

- Model as two-dimensional grids
  - Discretize in space and time
  - finer spatial and temporal resolution enables greater accuracy
- Many different computations per time step
  - Concurrency across and within grid computations
- We use one-dimensional grids for simplicity

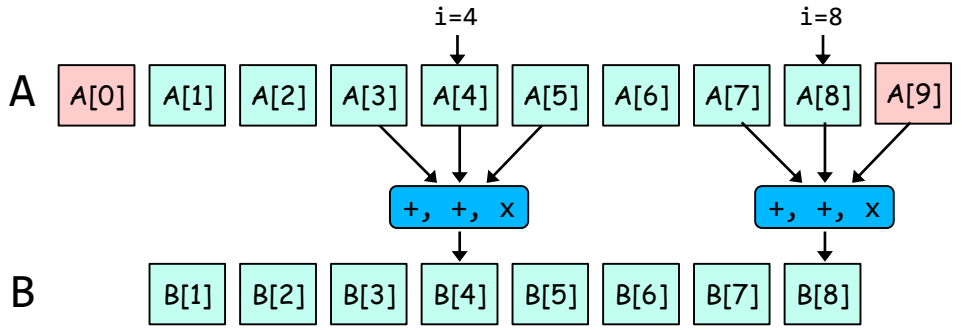
Sequential version as the baseline

- A sequential program main6.c and the execution result
- Computations in blue color are fully parallel

```
#define N 8      /* the number of grids */
#define TOL 15.0 /* tolerance parameter */
float A[N+2], B[N+2];

void solve () {
    int i, done = 0;
    while (!done) {
        float diff = 0.0;
        for (i=1; i<=N; i++) {
            B[i] = 0.333 * (A[i-1] + A[i] + A[i+1]);
            diff = diff + fabsf(B[i] - A[i]);
        }
        if (diff <TOL) done = 1;
        for (i=1; i<=N; i++) A[i] = B[i];

        for (i=0; i<=N+1; i++) printf("%6.2f ", B[i]);
        printf("| diff=%6.2f¥n", diff); /* for debug */
    }
}

int main() {
    int i;
    for (i=1; i<N-1; i++) A[i] = 100+i*i; // initialize
    for (i=0; i<=N+1; i++) printf("%6.2f ", A[i]);
    printf("¥n");
    solve();
}
```

main6.c sequential program

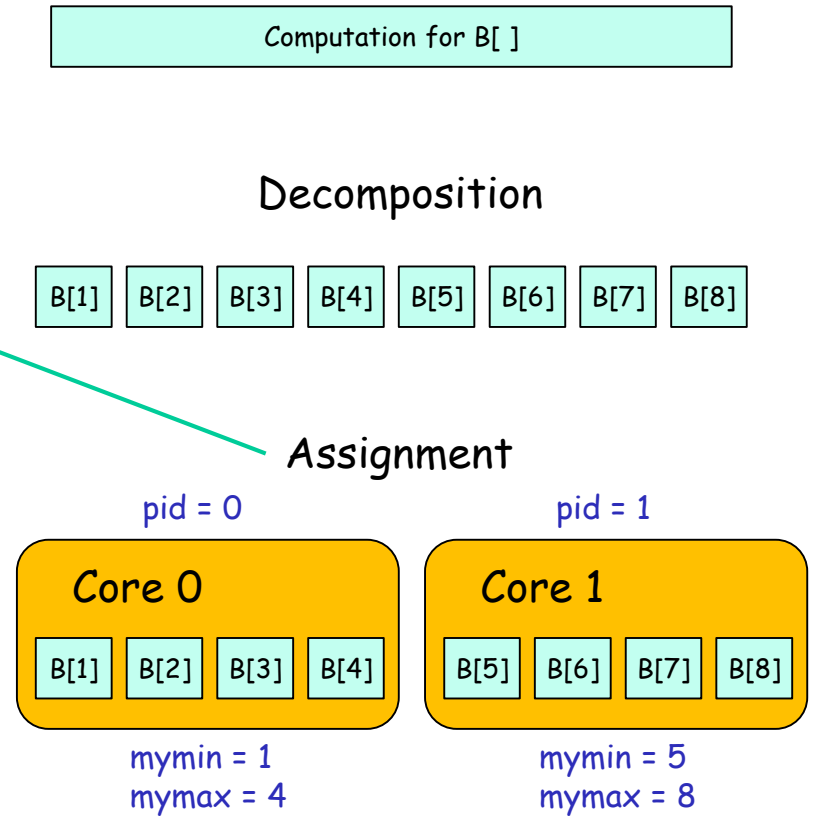
```
  0.00 101.00 104.00 109.00 116.00 125.00 136.00   0.00   0.00   0.00
  0.00  68.26 104.56 109.56 116.55 125.54  86.91  45.29   0.00   0.00 | diff=129.32
  0.00  57.55  94.03 110.11 117.10 109.56  85.83  44.02  15.08   0.00 | diff= 55.76
  0.00  50.48  87.15 106.97 112.14 104.06  79.72  48.26  19.68   0.00 | diff= 42.50
  0.00  45.83  81.45 101.99 107.62  98.54  77.27  49.17  22.63   0.00 | diff= 31.68
  0.00  42.38  76.35  96.92 102.61  94.38  74.92  49.64  23.91   0.00 | diff= 26.88
  0.00  39.54  71.81  91.87  97.87  90.55  72.91  49.44  24.49   0.00 | diff= 23.80
  0.00  37.08  67.67  87.10  93.34  87.02  70.89  48.90  24.62   0.00 | diff= 22.12
  0.00  34.88  63.89  82.62  89.06  83.67  68.87  48.09  24.48   0.00 | diff= 21.06
  0.00  32.89  60.40  78.44  85.03  80.45  66.81  47.10  24.17   0.00 | diff= 20.26
  0.00  31.07  57.19  74.55  81.23  77.35  64.72  45.98  23.73   0.00 | diff= 19.47
  0.00  29.39  54.21  70.92  77.63  74.36  62.62  44.77  23.21   0.00 | diff= 18.70
  0.00  27.84  51.46  67.52  74.23  71.47  60.52  43.49  22.64   0.00 | diff= 17.95
  0.00  26.41  48.89  64.34  71.00  68.67  58.43  42.17  22.02   0.00 | diff= 17.23
  0.00  25.07  46.50  61.35  67.94  65.97  56.37  40.84  21.38   0.00 | diff= 16.53
  0.00  23.83  44.26  58.54  65.02  63.36  54.34  39.49  20.72   0.00 | diff= 15.85
  0.00  22.68  42.17  55.88  62.24  60.85  52.34  38.14  20.05   0.00 | diff= 15.20
  0.00  21.59  40.20  53.38  59.60  58.42  50.39  36.81  19.38   0.00 | diff= 14.58
```



Decomposition and assignment

- Single Program Multiple Data (SPMD)
  - Decomposition: there are eight tasks to compute B[ ]
  - Assignment: the first four tasks for core 0, and the last four tasks for core 1

```
float A[N+2], B[N+2]; /* these are in shared memory */
float diff=0.0;       /* variable  in shared memory */


void solve_pp (int pid) {
    int i, done = 0;                    /* private variables */
    int mymin = (pid==0) ? 1 : 5;       /* private variable  */
    int mymax = (pid==0) ? 4 : 8;       /* private variable  */
    while (!done) {
        float mydiff = 0;
        for (i=mymin; i<=mymax; i++) {
            B[i] = 0.333 * (A[i-1] + A[i] + A[i+1]);
            mydiff = mydiff + fabsf(B[i] - A[i]);
        }
        diff = diff + mydiff;

        if (diff<TOL) done = 1;
        if (pid==1) diff = 0.0;
        for (i=mymin; i<=mymax; i++) A[i] = B[i];
    }
}

int main() { /* solve this using two cores */
    initialize shared data A and B;
    create thread1 and call solve_pp(0);
    create thread2 and call solve_pp(1);
}
```



Orchestration

- LOCK and UNLOCK around critical section
  - Lock provides exclusive access to the locked data.
  - Set of operations we want to execute atomically
- BARRIER ensures all reach here

```
float A[N+2], B[N+2]; /* these are in shared memory */
float diff=0.0;       /* variable  in shared memory */

pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_barrier_t barrier;
void solve_pp (int pid) {
    int i, done = 0;                    /* private variables */
    int mymin = (pid==0) ? 1 : 5;       /* private variable  */
    int mymax = (pid==0) ? 4 : 8;       /* private variable  */
    while (!done) {
        float mydiff = 0;
        for (i=mymin; i<=mymax; i++) {
            B[i] = 0.333 * (A[i-1] + A[i] + A[i+1]);
            mydiff = mydiff + fabsf(B[i] - A[i]);
        }
        pthread_mutex_lock(&m);
        diff = diff + mydiff;
        pthread_mutex_unlock(&m);

        pthread_barrier_wait(&barrier);  // Barrier 1
        if (diff <TOL) done = 1;
        pthread_barrier_wait(&barrier);  // Barrier 2
        if (pid==1) diff = 0.0;
        for (i=mymin; i<=mymax; i++) A[i] = B[i];
        pthread_barrier_wait(&barrier);  // Barrier 3
    }
}
```

These operations must be executed atomically

```
(1) load diff
(2) add
(3) store diff
```

After all cores update the diff, *if statement* must be executed.

```
if (diff <TOL) done = 1;
```

Exercise 1

- Are these three barriers necessary in the parallel program?
- What happens if we remove Barrier 1?
- What happens if we remove Barrier 2?
- What happens if we remove Barrier 3?

```
float A[N+2], B[N+2]; /* these are in shared memory */
float diff=0.0;       /* variable  in shared memory */

pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_barrier_t barrier;
void solve_pp (int pid) {
    int i, done = 0;                    /* private variables */
    int mymin = (pid==0) ? 1 : 5;       /* private variable  */
    int mymax = (pid==0) ? 4 : 8;       /* private variable  */
    while (!done) {
        float mydiff = 0;
        for (i=mymin; i<=mymax; i++) {
            B[i] = 0.333 * (A[i-1] + A[i] + A[i+1]);
            mydiff = mydiff + fabsf(B[i] - A[i]);
        }
        pthread_mutex_lock(&m);
        diff = diff + mydiff;
        pthread_mutex_unlock(&m);

        pthread_barrier_wait(&barrier);  // Barrier 1
        if (diff <TOL) done = 1;
        pthread_barrier_wait(&barrier);  // Barrier 2
        if (pid==1) diff = 0.0;
        for (i=mymin; i<=mymax; i++) A[i] = B[i];
        pthread_barrier_wait(&barrier);  // Barrier 3
    }
}
```

Parallel program after orchestration

```
% gcc main7.c -O0 -lpthread -lm -o a.out7
```

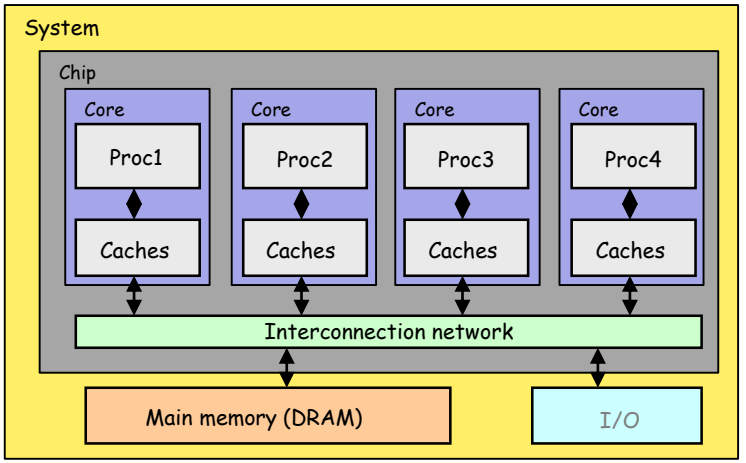
```
#include <stdio.h>
#include <math.h>
#include <pthread.h>
#define N 8           /* the number of grids */
#define TOL 15.0      /* tolerance parameter */

float A[N+2], B[N+2]; /* these are in shared memory */
float diff=0.0;       /* variable  in shared memory */
int ncores = 2;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_barrier_t barrier;

int main(){
    pthread_t t1, t2;
    int pid0 = 0;
    int pid1 = 1;
    for (int i=1; i<N-1; i++) A[i] = 100+i*i;

    pthread_barrier_init(&barrier, NULL, ncores);
    pthread_create(&t1, NULL, (void *)solve_pp, (void*)&pid0);
    pthread_create(&t2, NULL, (void *)solve_pp, (void*)&pid1);

    pthread_join(t1, NULL);
    pthread_join(t2, NULL);

    for (int i=0; i<=N+1; i++) printf("%6.2f ", B[i]);
    printf("¥n");
    return 0;
}
```

```
void solve_pp (void *p) {
    int pid = *(int *)p;
    int i, done = 0;                    /* private variables */
    int mymin = 1 + (pid * N/ncores);   /* private variable  */
    int mymax = mymin + N/ncores - 1;   /* private variable  */
    while (!done) {
        float mydiff = 0.0;
        for (i=mymin; i<=mymax; i++) {
            B[i] = 0.333 * (A[i-1] + A[i] + A[i+1]);
            mydiff = mydiff + fabsf(B[i] - A[i]);
        }
        pthread_mutex_lock(&m);
        diff = diff + mydiff;
        pthread_mutex_unlock(&m);

        pthread_barrier_wait(&barrier);
        if (diff <TOL) done = 1;
        pthread_barrier_wait(&barrier);
        if (pid==1) diff = 0.0;
        for (i=mymin; i<=mymax; i++) A[i] = B[i];
        pthread_barrier_wait(&barrier);
    }
}
```

main7.c parallel program

Key components of many-core processors

- Interconnection network
  - connecting many modules on a chip achieving high throughput and low latency
- Main memory and caches
  - Caches are used to reduce latency and to lower network traffic
  - A parallel program has private data and shared data
  - New issues are cache coherence and memory consistency
- Core
  - High-performance superscalar processor providing a hardware mechanism to support thread synchronization (lock, unlock, barrier)



Shared memory many-core architecture