Programming Practice

Fall 2011

Parallelism

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Outline

- Types of parallelism
  - Task-parallelism
  - Data-parallelism
  - Stream-parallelism
- Examples

Example: preparing a salad


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Tasks to do:

- tear leaves
- wash leaves
- chop leaves

- wash
- slice

- apply dressing
- mix

Single Chef Salad (sequential)

execution time (seconds)

tear leaves T1

20

wash leaves T2

40

chop leaves T3

60

wash tomatoes T4

80

slice tomatoes T5

100

apply dressing T6

120

mix T7

140

- Preparing a salad consists of 7 tasks (T1-T7).
- A single chef prepares a salad in processing the 7 tasks **sequentially** (one after the other).
- It takes a single chef 142 seconds to prepare a salad.
- We can speed up the process by making the chef work **faster**.

Fast Single Chef Salad (sequential)

execution time (seconds)

tear leaves T1

20

wash leaves T2

40

chop leaves T3

wash tomatoes T4

60

slice tomatoes T5

80

apply dressing T6

100

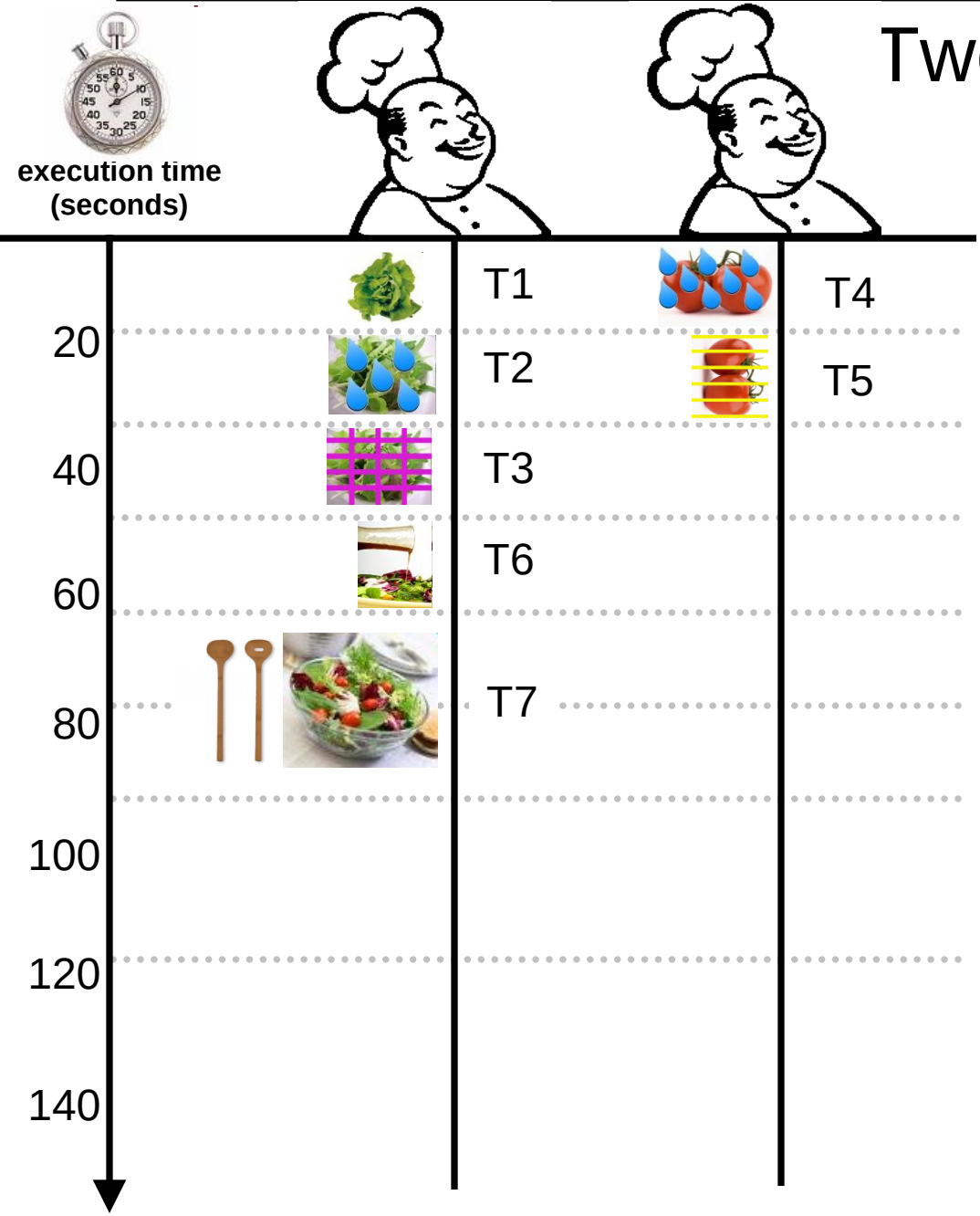
mix T7

120

140

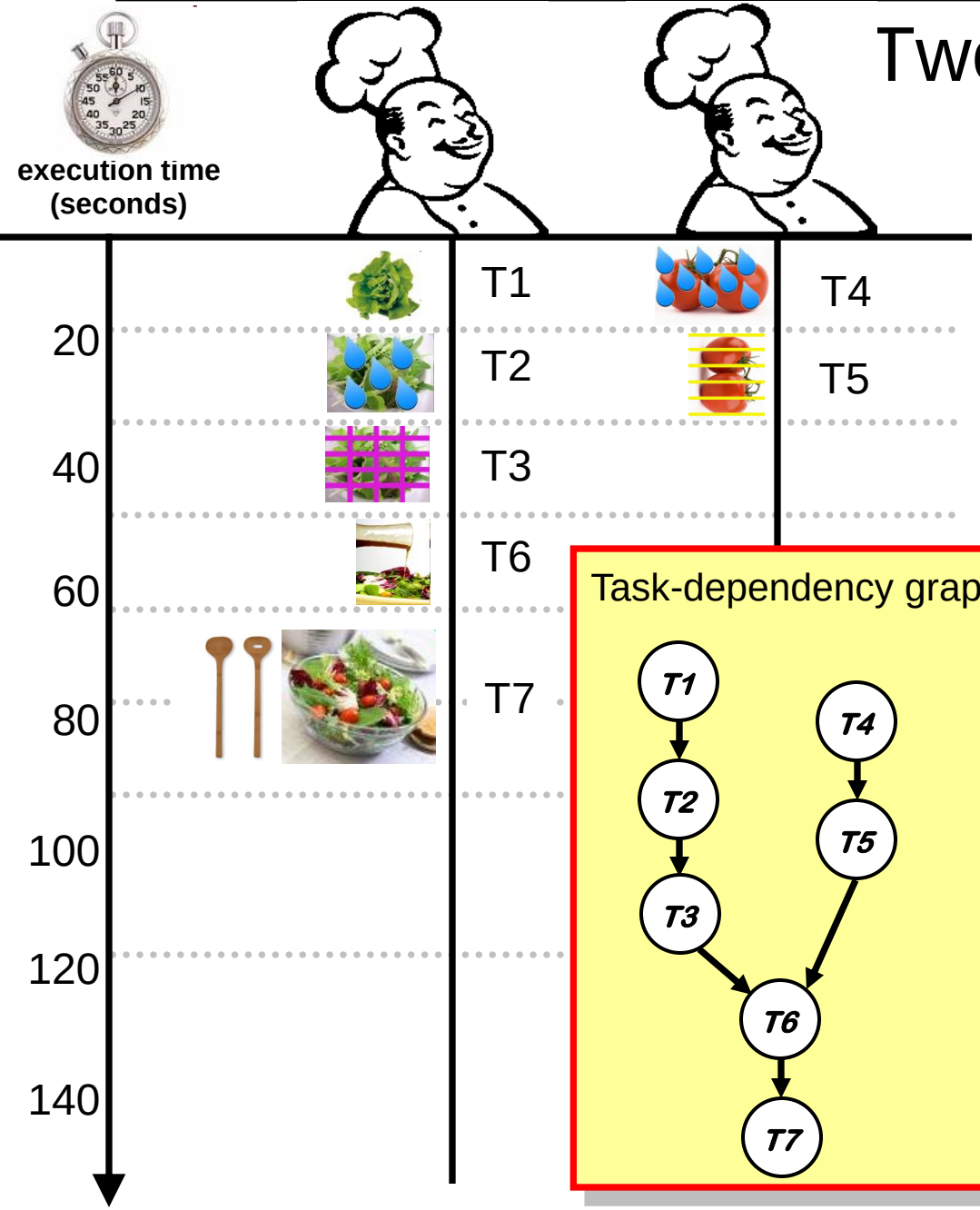
- If we can convince the Chef to finish every task in 18 instead of 20 seconds, we will reduce the process to 7x18=126 seconds.
- The chef agrees for Tasks T1-T6.
- However, he cannot speed up Task T7 without spoiling the entire kitchen.
- He refuses to work any faster than that.
- We can speed up the process by bringing in an additional Chef that works **in parallel** to Chef 1.

Two Chefs in Parallel Salad



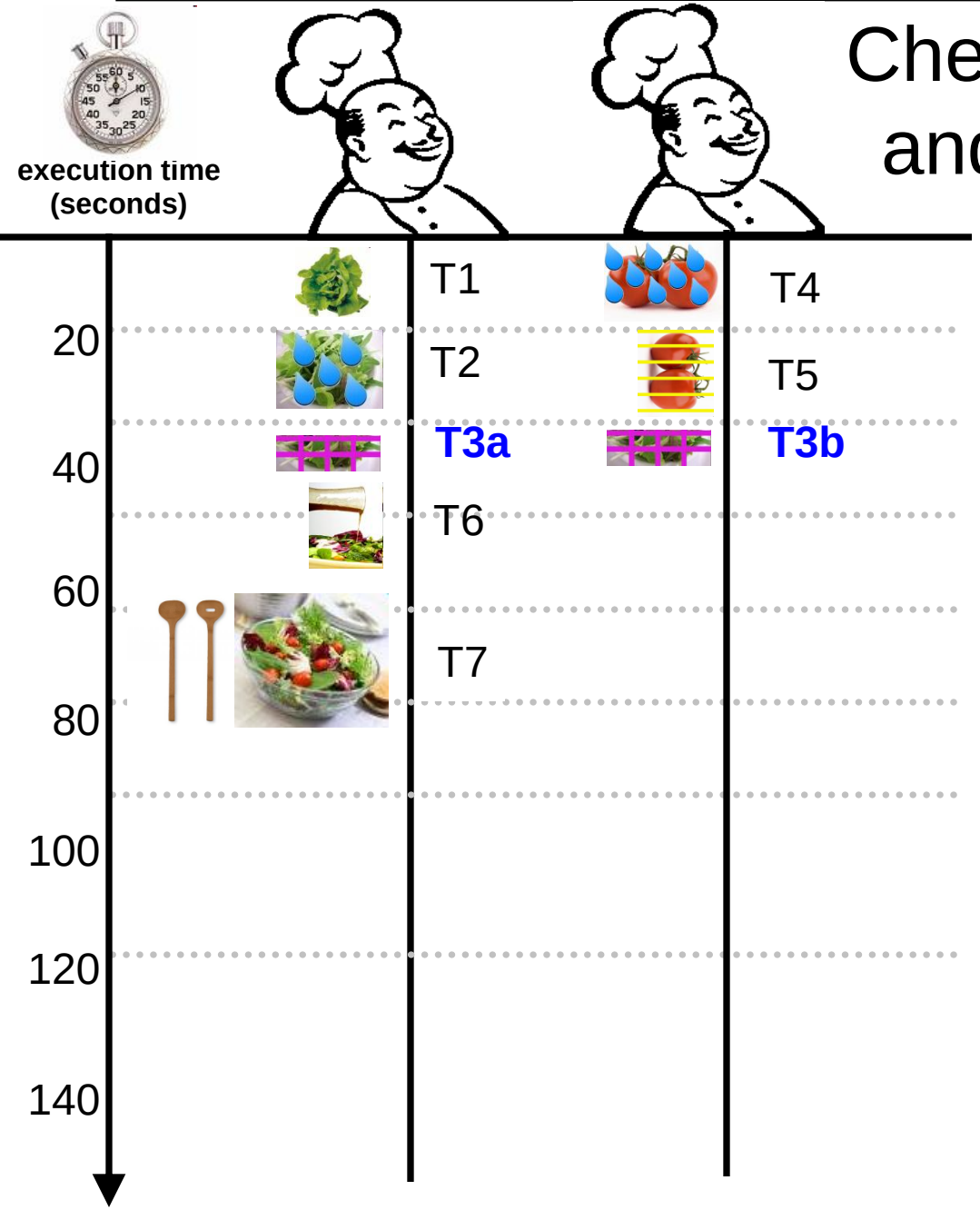
- Chef 2 washes the tomatoes (Task T4) while Chef 1 tears the lettuce (Task T1).
- Task T1 is processed in parallel to Task T4. Processing tasks in parallel is called **task-parallelism**.
- Another form of task-parallelism occurs between tasks T2 and T5.
- There exist **dependencies** between tasks:
  - Vegetables must be washed *before* they are chopped/sliced.
  - Mixing (T7) can only be done *after* the dressing has been applied (T6).

Two Chefs in Parallel Salad



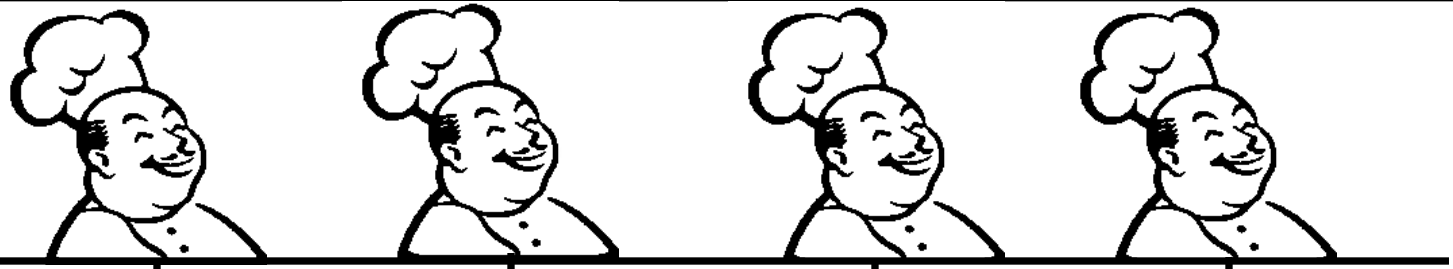
- Dependencies between tasks do not allow further task-parallelism with this example.
- A **task-dependency graph** shows dependencies between tasks.
  - directed acyclic graph (DAG)
  - graph nodes represent tasks
  - directed edge $T_a \rightarrow T_b$ indicates that T_b can only be processed after T_a has completed.
  - See example graph to the left.

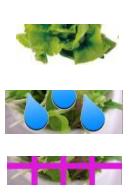
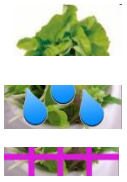
Chefs in Parallel (task and data parallelism)



- Dependencies between tasks do not allow further task-parallelism with this example.
- However, we can have several Chefs work in parallel on the “data” of a task.
- This form of parallelism is called **data-parallelism.**
  - Example1: Chef 1 and Chef 2 chop one half of the lettuce each (Tasks **T3a** and **T3b**).
  - Example2: On the next slide more data-parallelism is introduced.

execution time (seconds)








T1a T2a T3a T1b T2b T3b T4a T5a T3c T4b T5b T3d

T6

T7

20 40 60 80 100 120 140

T1 || T4 means: Task T1 executes in parallel to Task T4.

The final outcome:

- Task parallelism: T1 || T4, T2 || T5
- Data parallelism: T2a || T2b, T5a || T5b, T3a||T3b||T3c||T3d
  - We can still increase data parallelism with the lettuce by bringing in more Chefs. What about limits?

Definitions

Task: a computation that consists of a sequence of instructions. The computation is a *distinct* part of a program or algorithm. (That is, programs and algorithms can be de-composed into tasks).

Examples: “washing lettuce”, “initialize data-structures”, “sort array”, ...

Task-parallelism: parallelism achieved from executing different tasks at the same time (i.e., in parallel).

Data-parallelism: performing the same task to different data-items at the same time.

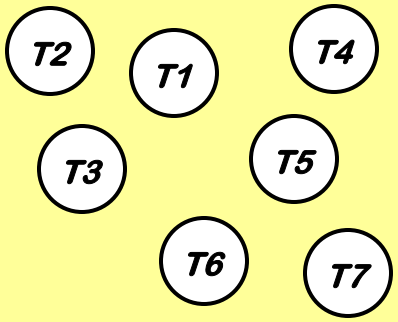
Example: 2 Chefs slicing 1 tomato each. (tomato = data, slicing ~ task).

Definitions (cont.)

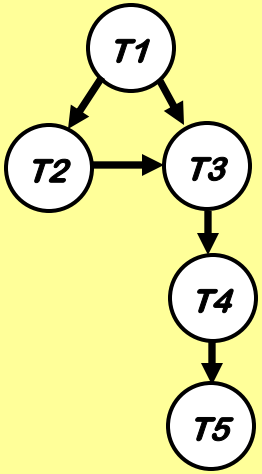
Dependencies: an execution order between two tasks Ta and Tb. Ta must complete before Tb can execute. Notation: Ta → Tb. Dependencies limit the amount of parallelism in an application.

Example task dependency graphs:

no dependencies, maximum parallelism:



dependencies, no parallelism possible:

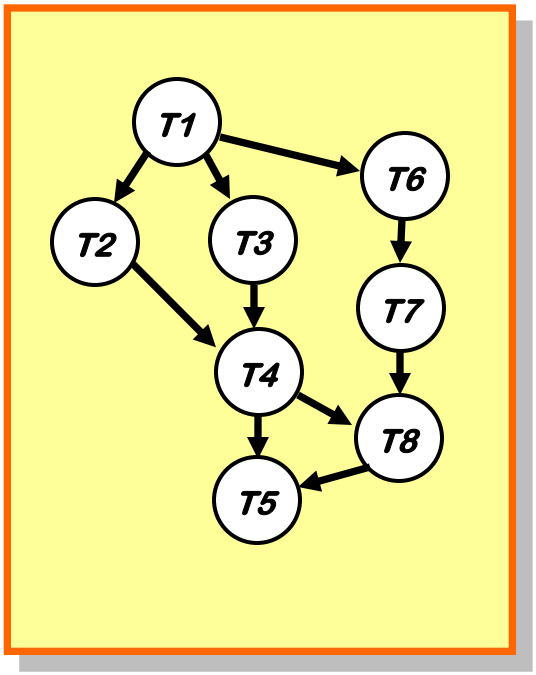


Definitions (cont. cont.)

Dependencies impose a **partial ordering** on the tasks:

Two tasks Ta and Tb can execute in parallel iff

1) there is no path in the dependence graph from Ta to Tb
2) there is no path in the dependence graph from Tb to Ta

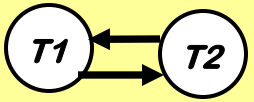


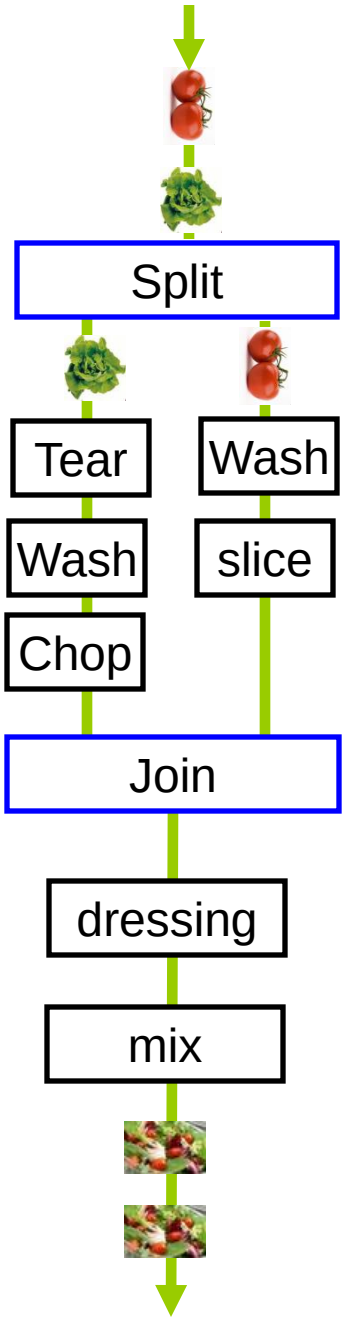
Dependency is transitive:

Ta→Tb and Tb→Tc implies Ta→Tc

Say: Ta has to complete befor Tb, and Tb has to complete before Tc, therefore Ta has to complete before Tc.

What about this?



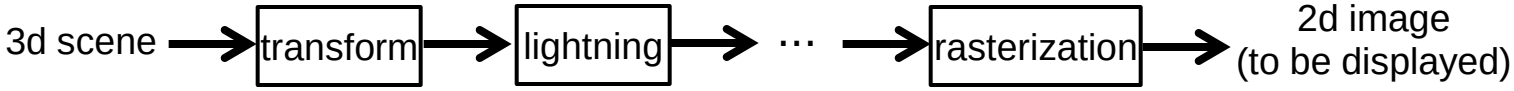


Stream Parallelism

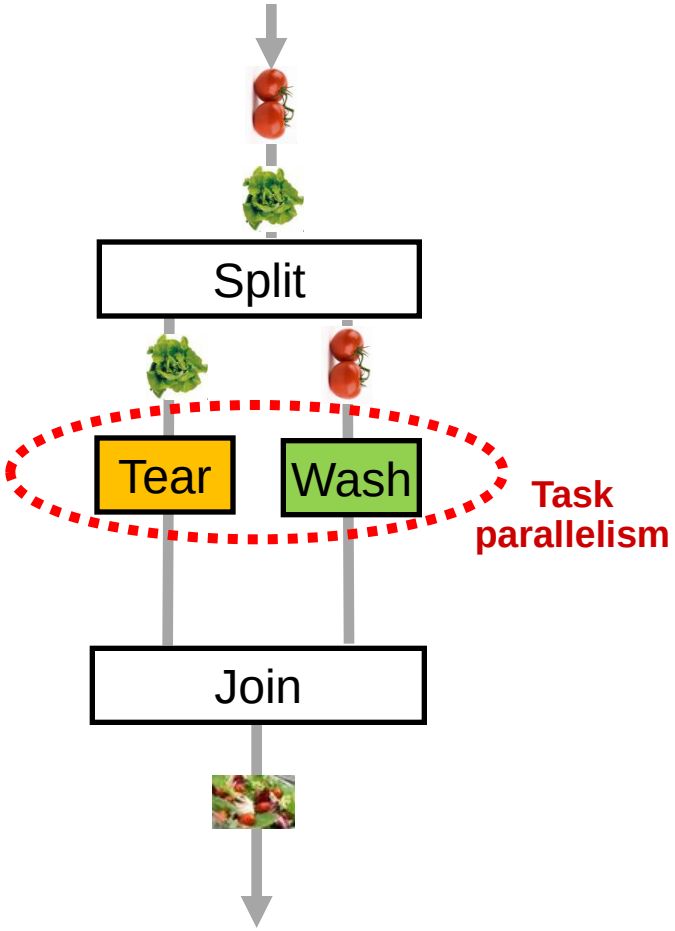
- Some programs work on streams of data (audio, video, ...)
  - Examples: audio and video encoders/decoders, cell phone base stations.
- Tasks depicted as rectangles
  - operate in parallel -> task parallelism
  - data parallelism also easy to model (using split and join)
- "Split" divides a stream
- "Join" merges a stream
- For regular and repeating computations.
- We will discuss programming of streams with the StreamIt programming language.

Pipeline Parallelism with Stream Programs

- Pipeline: sequence of actors
  - producer-consumer relationship between actors:
    - actor reads input from upstream data-channel
    - actor writes output to downstream data-channel
- Actors of pipeline operate in parallel on different data items
  - much like a factory assembly line
  - Example: while one actor tears the lettuce leaves, another actor washes torn lettuce lives that it received from the upstream actor.
- Pipeline parallelism very popular with graphics pipelines of GPUs:
  - http://en.wikipedia.org/wiki/Graphics_pipeline

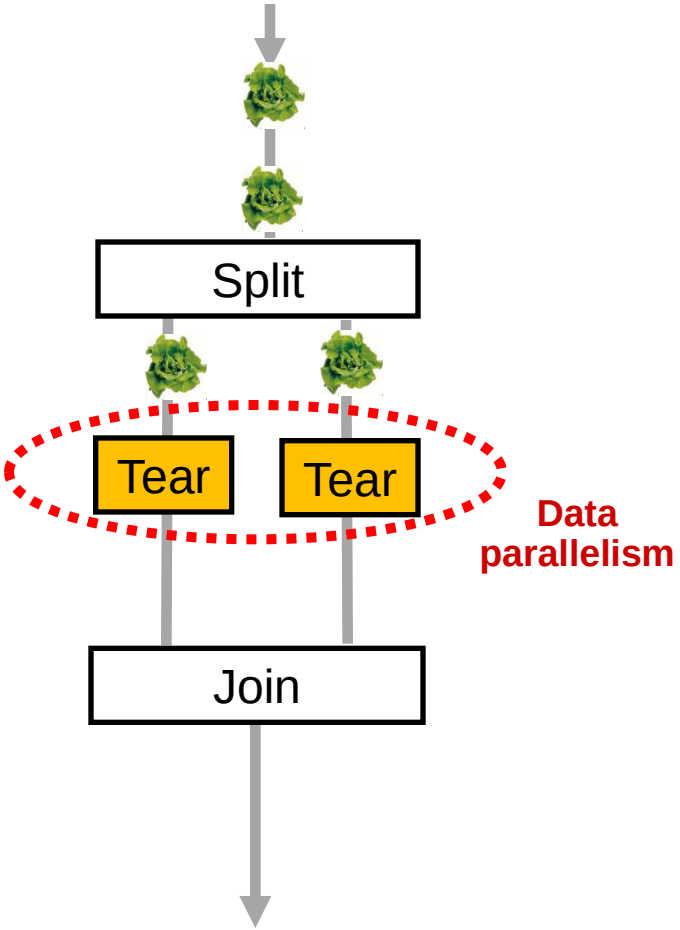


Task Parallelism with Stream Programs



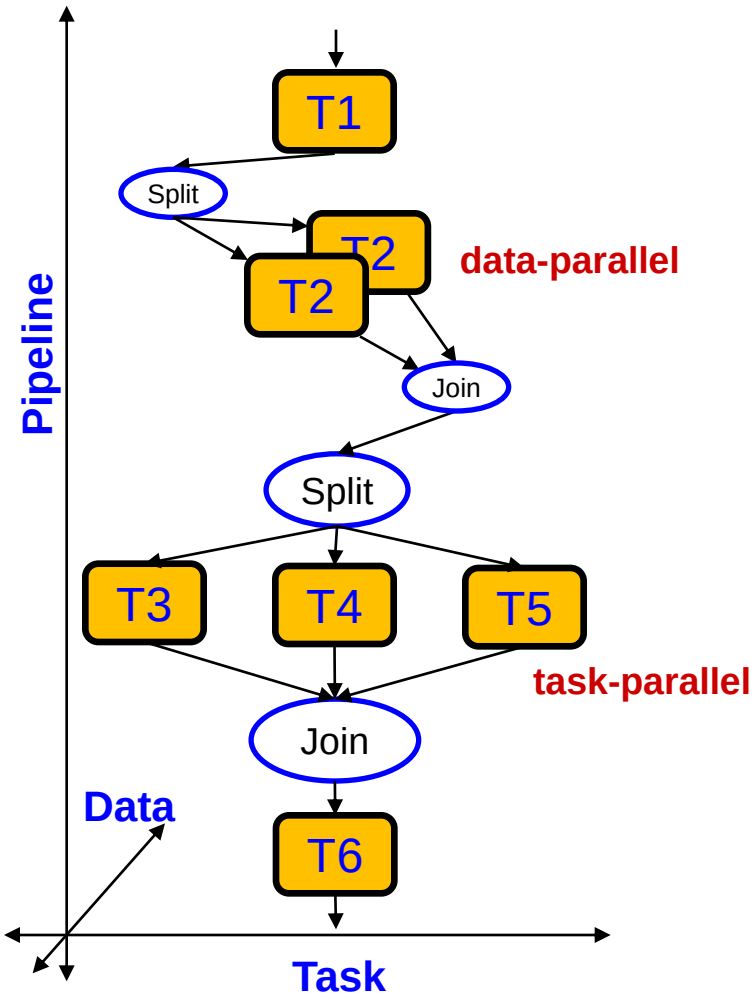
- Parallel execution of different tasks that don't have producer-consumer relationship.
- Enabled by Split and Join

Data Parallelism with Stream Programs



- Parallel execution of the same task on different data items.
- Enabled by Split and Join
  - similar to task-parallelism
- Example: in the graph on the previous slide, we can data-parallelize the lettuce 'Tear' task as shown to the left.
  - more than 2 data-parallel instances of the 'Tear' task possible!
- Not possible with stateful actors
  - a stateful actor remembers information between executions
  - Example: actor that computes the maximum over the complete data-stream
  - More on that in a latter part of the lecture...

Stream Programs: Task+Data+Pipeline Parallelism



Data Parallelism

- For *stateless* actors
- Actor duplicated within split/join pair (*actor fission*)
- Example: 2 instances of task T2

Task Parallelism

- Between actors *without* producer/consumer relationship
  - Example: T3 || T4 || T5

Pipeline Parallelism

- Between producers and consumers
- *Stateful* actors can be parallelized

Outline

- Types of parallelism ✓
  - Task-parallelism ✓
  - Data-parallelism ✓
  - Stream-parallelism ✓
- Examples

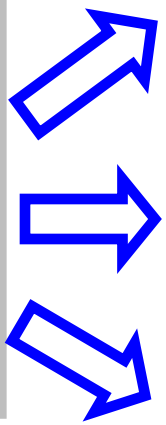
Task Parallelism Example

Example: Assume we have a large data-set in an array and the task is to compute the minimum, average and maximum value. This task can be decomposed into 3 tasks: computing minimum (T1), average (T2), and maximum value (T3).

```
#define maxN 1000000000

int m[maxN];
int i;
int min = m[0];
int max = m[0];
double avrg = m[0];

for(i=1; i < maxN; i++) {
   if(m[i] < min)
     min = m[i];
   avrg = avrg + m[i];
   if(m[i] > max)
     max = m[i];
}
avrg = avrg / maxN;
```



```
#define maxN 1000000000
int m[maxN];

int i; int min = m[0];
for(i=1; i < maxN; i++) {
   if(m[i] < min)
     min = m[i];
}

int j;
double avrg = m[0];
for(j=1; j < maxN; j++) {
   avrg = avrg + m[j];
}
avrg = avrg / maxN;

int k; int max = m[0];
for(k=1; k < maxN; k++) {
   if(m[k] > max)
     max = m[k];
}
```

T1

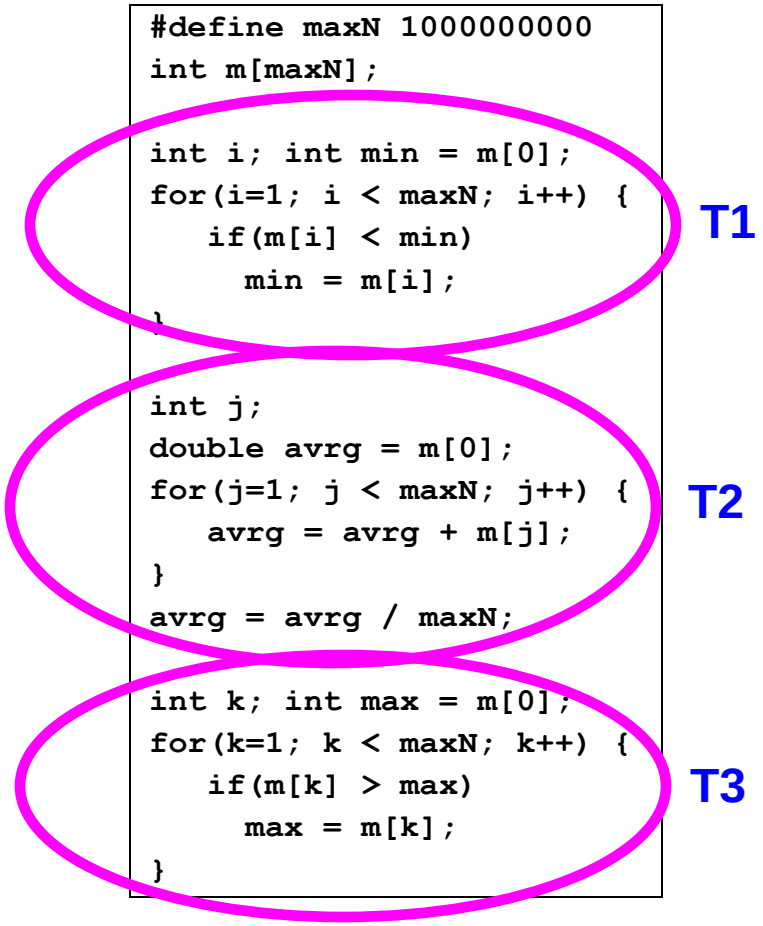
T2

T3

Dependence graph:

Note: if T1 – T3 should execute in parallel, then each task needs its own loop index variable (i, j, k)!

Task Parallelism Example (cont.)



- The problem is now decomposed into three tasks T1, T2, T3.
- However: still sequential
  - T1, then T2 then T3
- Need a way to tell the compiler that tasks T1, T2 and T3 shall be executed in parallel.
- We will use POSIX threads to do that.
  - Our next lecture will be on POSIX threads.
- We will discuss other ways to express task parallelism in later parts of the lecture.

Data Parallelism Example

Example 1: parallel sum computation on array (Lecture L00).

Example 2: vector operations:

```
int a[4] = {1,2,3,4};
int b[4] = {1,2,3,4};
int c[4];
int i;

for(i=0; i < 4; i++) {
   c[i] = a[i] + b[i];
}
```

- Assume two arrays of integers, compute the pair-wise sum.
- A sequential version uses a for-loop to compute the sum.
  - Requires one loop iteration per array index.
  - 4 add operations in total
- Using SSE on the Intel IA32 architecture, this sum operation can be computed in one step.
  - See example on next slides.
  - The Intel AVX instructions of the new Sandy Bridge architecture supports vectors of 8 ints.

SIMD Vectorization

- To sum the values of 2 arrays, a conventional CPU needs one add operation (“+”) per array index:

```
int a[4] = {1,2,3,4};
int b[4] = {1,2,3,4};
int c[4];

c[0] = a[0] + b[0];
c[1] = a[1] + b[1];
c[2] = a[2] + b[2];
c[3] = a[3] + b[3];
```

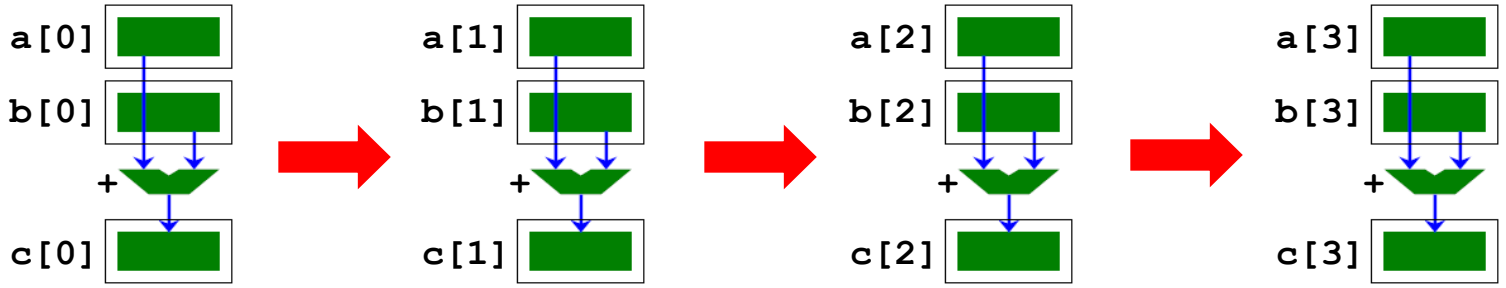
sequential array sum

```
int a[4] = {1,2,3,4};
int b[4] = {1,2,3,4};
int c[4];
int i;

for(i=0; i < 4; i++) {
   c[i] = a[i] + b[i];
}
```

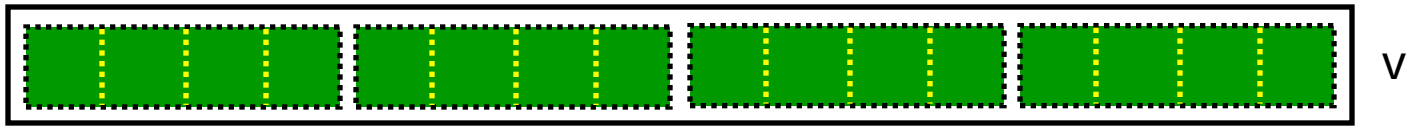
array sum using loop

- Reason: a register of a conventional CPU can only hold only 1 data item at a time (such a register is called a **scalar register**):



Data Parallelism Example (cont.)

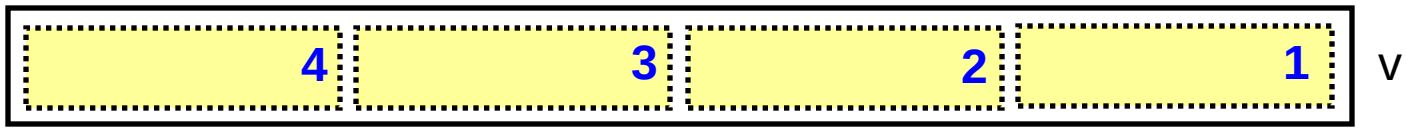
- Vector processors have large registers that can hold *multiple* values of the *same* data type (vector register).
- The SSE registers of the Intel x86 are 128 bit wide.
  - `__m128i v;` declares vector v, which consists of four 4-byte integers:



  - The **`__m128i`** vector data type is provided in header file emmintrin.h.
  - Other provided types: 64-bit int, 64-bit float, 32-bit float, 16-bit int, 8-bit int.

```
__m128i v = _mm_set_epi32(1, 2, 3, 4);
```

assigns values to the **elements** of v.



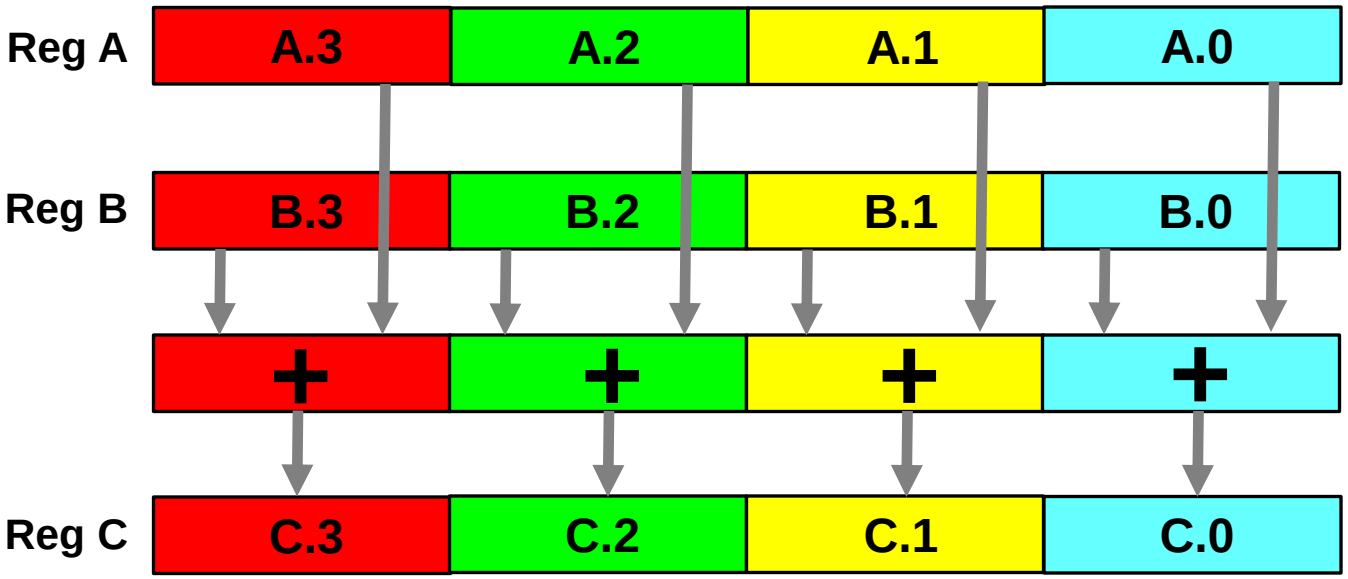
- SSE instructions will apply an operation to all elements of a vector **at once**.
  - See example on next slide.

Data Parallelism Example (cont.)

- Example: adding two vectors of integers in one step.

```
__m128i A, B, C; // declare 3 vectors A, B, C of type __m128i

C = _mm_add_epi32(A, B);
```



Data Parallelism Example (cont.)

```
#include <smmintrin.h>
#include <emmintrin.h>
#include <stdio.h>

int main(void) {

   __m128i A = _mm_set_epi32(4, 3, 2, 1);
   __m128i B = _mm_set_epi32(2, 2, 2, 2);
   __m128i C = _mm_add_epi32(A, B); //add vectors A and B

   int res = _mm_extract_epi32(C, 3); //extract element
                                      //at index 3

   printf("Result: %d\n", res); // ....... ?

   return 0;
}
```

Note: This program is available in YSCEC.
Log in on elc1, compile & run:

$ gcc -msse4.1 sse_int.c

Data Parallelism Example (cont.)

- The header files **`smmintrin.h`** and **`emmintrin.h`** contain the C language extensions for the example's SSE parts.
  - Must be included to use _mm_add_epi32() aso.
  - Further header files exist, to cover various SSE generations:
    - for SSE, SSE2, SSSE3, SSE4_1, SSE4_2, AVX

- _mm_add_epi32() is called an **intrinsic**. An intrinsic is a procedure provided by the compiler. The compiler will replace the intrinsic with one or more assembly instructions.

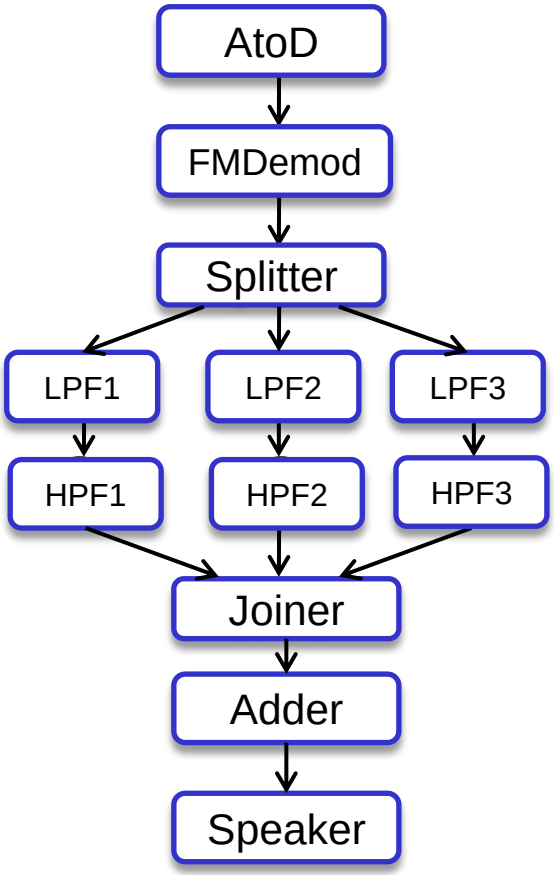
- Note:
  - Intel issued successive generations of SSE extensions with their line of x86 processors: SSE, SSE2, SSSe3, SSE4_1, SSE4_2, AVX
  - Older processors will only support the earlier versions (SSE, SSE2, ...)
    - Running machine-code with SSE instructions on CPU that does not support it will result in an 'illegal instruction' exception followed by program termination.
  - Sometimes SSE is also referred to as MMX (multimedia extensions).
    - MMX was the name of the first generation of SSE extensions.

Data Parallelism Example (cont.)

- Many of today's mainstream CPU architectures support vector instructions.
  - Architecture-specific
  - Intel x86: SSE and AVX extensions
  - AMD: 3DNow! for floating-point numbers
  - PowerPC: AltiVec

Stream Parallelism Example

- We will discuss StreamIT
- For programs based on streams of data
  - Audio, video, DSP, networking, cryptographic processing kernels
  - Examples: HDTV editing, radar tracking, cell phone base stations, computer graphics
- Properties of streams:
  - Regular and repeating computation
  - Independent filters (aka ‘actors’) with explicit communication
  - Task, data, and stream parallelism can be expressed



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