Parallel Computing I

Parallel Program Designs
SMP: Massively Parallel Problems

A First Parallel Program

Primality tests via trial division

- `PrimeTesterSeq.java`
- `PrimeTesterSmp.java`

Parallel Programming

How do we *write* a program to make use of a parallel computer?

Use a standard programming language and generic OS kernel functions:

- SMP: C with `pthreads`, Java with `Thread` objects
- Cluster: C with sockets API, Java with socket classes

- Requires expertise in threads and/or sockets
- Much repetition accross parallel programs

Use a parallel programming library:

- OpenMP (SMP)
- MPI (Cluster)
- Parallel Java (SMP and Cluster)

Parallel Programming

How do we *design* a program to make use of a parallel computer?

Three patterns for designing parallel programs

- Result parallelism
- Agenda parallelism
- Specialist parallelism

Two additional patterns for implementing parallel programs

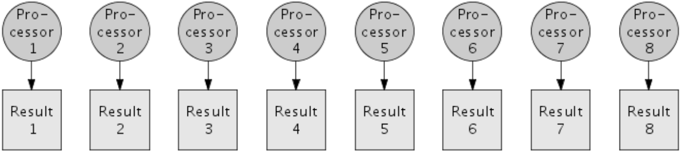
- Clumping (or slicing)
- Master-Worker

Steps for parallel program design

- Identify the pattern that best matches the problem.
- Take the pattern's suggested design as the starting point.
- Implement the design using the appropriate constructs.

Result Parallelism

- The result of the computation (a data structure) is divided into elements
- The elements are all computed simultaneously



Example: calculating pixels in the frames of a computer-animated film.

Important characteristic: no dependencies between individual results.

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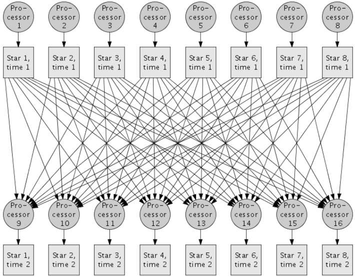
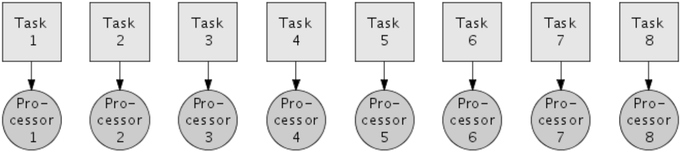


Example: calculating positions of stars in a cluster over time.

Important characteristic: some dependencies between individual results.

Agenda Parallelism

- The problem is divided into tasks (an "agenda")
- Multiple workers perform the tasks simultaneously
- Each worker is a "generalist" that can perform any task

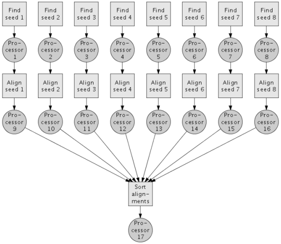


Example: querying a DNA sequence database.

Important characteristic: not really interested in individual results.

Agenda Parallelism with Reduction

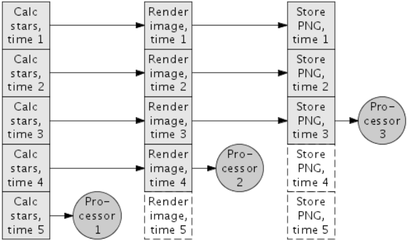
- The problem is divided into tasks (an "agenda")
- Multiple workers perform the tasks simultaneously
- Each worker is a "generalist" that can perform any task
- Output a single summary result (reduction) of individual tasks



Example: Basic Local Alignment Search Tool (BLAST)

Specialist parallelism

- The program is divided into sub-programs
- Each sub-program is a "specialist" that does a different thing
- All specialists run simultaneously



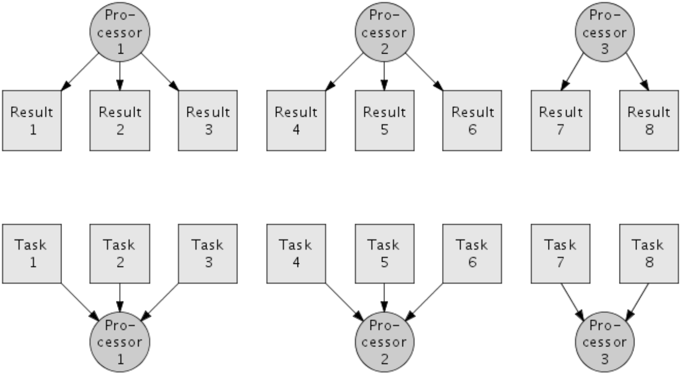
Example: animate positions of stars in a cluster over time

Important characteristic: sequential dependencies leads to pipelining
Important characteristic: independence leads to overlapping

Clumping (or Slicing)

Conceptually, every result/task assigned to a different processor.

In practice, a single processor works on multiple results/tasks.



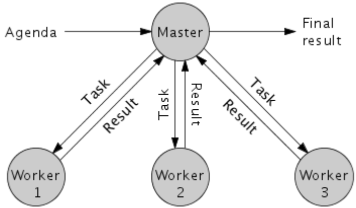
Fits well with Result and Agenda parallelism.

Master-Worker

Conceptually, every result/task assigned to a different processor.

In practice, a single processor works on multiple results/tasks.

- Master: Send task to a worker; Receive task result from any worker; Record task result; Loop.
- Worker: Receive task from the master; Compute task results; Send results to the master; Loop.



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Other Patterns

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Certainly!

One missing aspect of the above patterns: dynamic creation of tasks.

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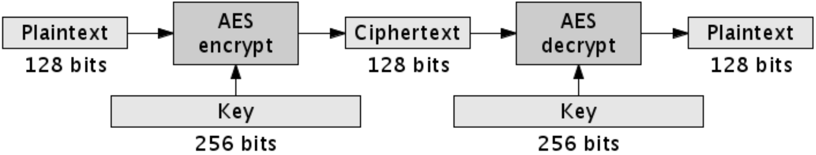
Yet another missing aspect: problems combine multiple patterns.

Arguably: Agenda parallelism with Master-Worker pattern is most general.

AES Encryption

Consider AES encryption:



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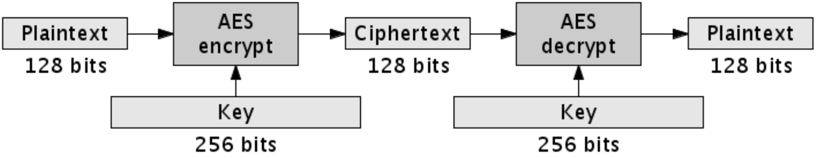

How can we "crack" AES encryption?

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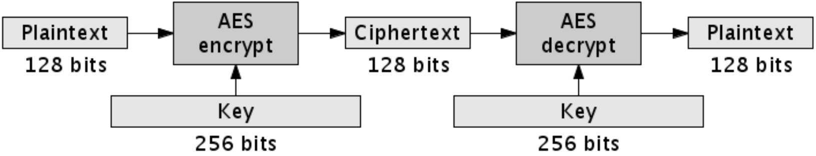

How can we "crack" AES encryption?

Attack the encryption with a known plaintext (using exhaustive search)!

- We (somehow) obtain a plaintext block and the ciphertext block
- We (exhaustively) try `key` equal to $0, 1, \ldots, 2^{256} - 1$:
  - With each trial key, encrypt the plaintext and compare to the ciphertext.
  - (Alt: decrypt the ciphertext and compare to the plaintext.)
    - (Might not even need plaintext, if we know it when we see it.)

AES Key Search

How much computation does this plaintext attack take?

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- On the order of $\mathbf{2^{256}}$ (or $\mathbf{10^{77}}$) encryptions.
- Universe will end before finding key,
  even if we use all computers on Earth in parallel.
- (Good for encryption!)

But what if we knew **232** bits of the **256**-bit key?

- On the order of $\mathbf{2^{24}}$ (or $\mathbf{1.67 \times 10^{7}}$) encryptions.
- Feasible to crack in minutes on one computer
- Feasible to crack in seconds on parallel computer

AES Partial Key Search:

- Inputs: a plaintext block `p`, a ciphertext block `c`, a partial key `k'` with $\mathbf{256 - n}$ bits of the `k` (which produced `c` from `p`)
- Outputs: the complete key `k` (which produced `c` from `p`)
- Algorithm: exhaustive search

AES Partial Key Search

Preparing the input:

Generate a random 256-bit key:

```
[mtf@fenrir code]$ java edu.rit.smp.keysearch.MakeKey
3f5f5a45d429feff41bf957ed46d69f7df8323926ad32fe9eb0dd07bb7cfe5b6
```

Encrypt a message and mask key:

```
[mtf@fenrir code]$ java edu.rit.smp.keysearch.Encrypt 'Hello, PC1!'\
3f5f5a45d429feff41bf957ed46d69f7df8323926ad32fe9eb0dd07bb7cfe5b6 24
48656c6c6f2c20504331210000000000
ea482cc8278b57cba021228877e6627b
3f5f5a45d429feff41bf957ed46d69f7df8323926ad32fe9eb0dd07bb7000000
24
```

See textbook for more details.

Sequential AES Partial Key Search

`FindKeySeq.java`

Parallel AES Partial Key Search

How do we convert the sequential key search program to a parallel key search program?

- What pattern does the AES partial key search use?
- Are there any sequential dependencies?
- If we have 2^n processors, then how should we divide the problem and how long should it take?

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- What pattern does the AES partial key search use?
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- If we have 2^n processors, then how should we divide the problem and how long should it take?

This type of problem is called a *massively parallel problem* or *embarrassingly parallel problem*!

Massively Parallel Problems

Some problems require many, many independent computations.
These independent computations can be done in parallel.

For the Parallel AES Partial Key Search,
if we use K threads on K processors,
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For the Parallel AES Partial Key Search,
if we use K threads on K processors,
then how do we partition the problem?

Each partition handles $2^n/K$ computations.

For example, if $n = 24$ and $K = 8$,
then each thread/processor handles approx. 2097152 computations.

Next task is to convert the sequential program
to a parallal program using Parallel Java.

SMP Parallel Programming with PJ

- Parallel Team
- Parallel Region
- Parallel For Loop
- Variables

Parallel Team

An SMP parallel program (in PJ) has the following structure:

- Initial setup
- Create a parallel team
- Have the parallel team execute the computation
- Clean up

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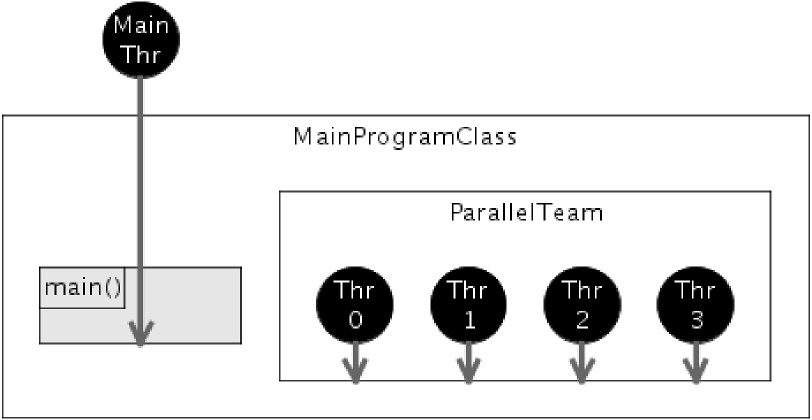
Creating parallel teams:

- `new ParallelTeam(4);`
  - create a team of four threads
- `new ParallelTeam();`
  - create a team of #processors threads (recommended)
- `$ java -Dpj.nt=8`
  - specify the number of threads

Parallel Team

Creating a parallel team introduces K new threads, in addition to the main thread.



Parallel Region

A parallel team represents the threads
that will carry out the program's computation.

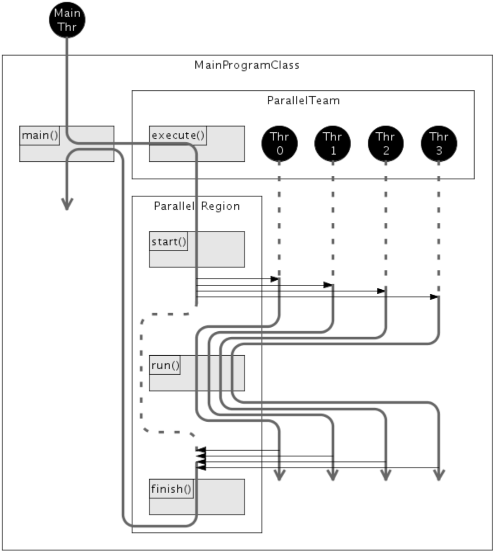
A parallel region (passed to the parallel team's `execute` method)
represents the code for the program's computation.

```
new ParallelTeam().execute(new ParallelRegion() {
  public void start() {
    // Initialization code
  }
  public void run() {
    // Parallel computation code
  }
  public void finish() {
    // Finalization code
  }
}
```

Note: convenient with an anonymous inner class.

Parallel Region

The methods of `ParallelRegion` are executed by different threads.



Parallel For Loop

The program's computation is often a loop of (independent) iterations.

```
new ParallelTeam().execute(new ParallelRegion() {
  public void run() {
    execute(0,1023,new IntegerForLoop() {
      public void start() {
        // Per-thread per-loop initialization code
      }
      public void run(int first, int last) {
        // Loop computation code
      }
      public void finish() {
        // Per-thread per-loop finalization code
      }
    });
  }
}
```

Note: convenient with an anonymous inner class.

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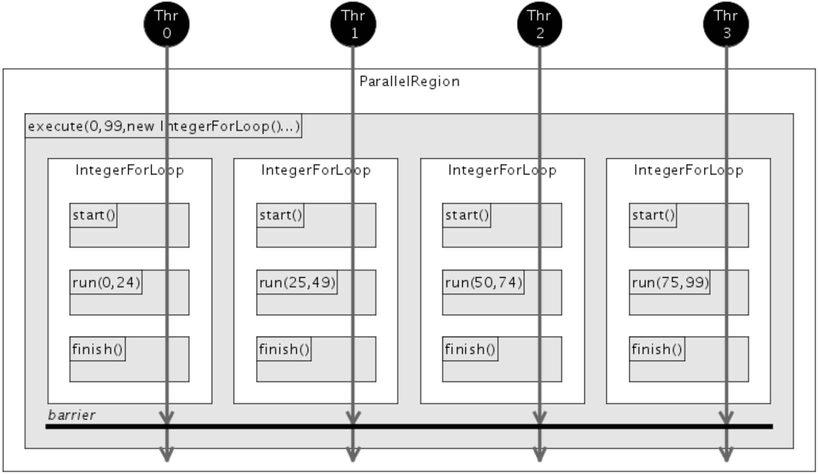


Parallel For Loop

In more detail, execution proceeds as follows:

1. Each thread creates an instance of the `IntegerForLoop` subclass
2. Each thread calls the `execute()` method with the lower and upper index bounds.
3. The `execute()` method partitions the index range into K chunks (where K is the number of threads in the parallel team)
4. Each thread calls the `start()`, `run()`, and `finish()` methods, where the `run()` method receives a different index range

On a parallel computer with K processors, this program runs faster, because each thread executes only $1/K$ of the loop iterations.

Variables in a Parallel Java Program

A key decision in writing a parallel program is deciding where to declare variables.

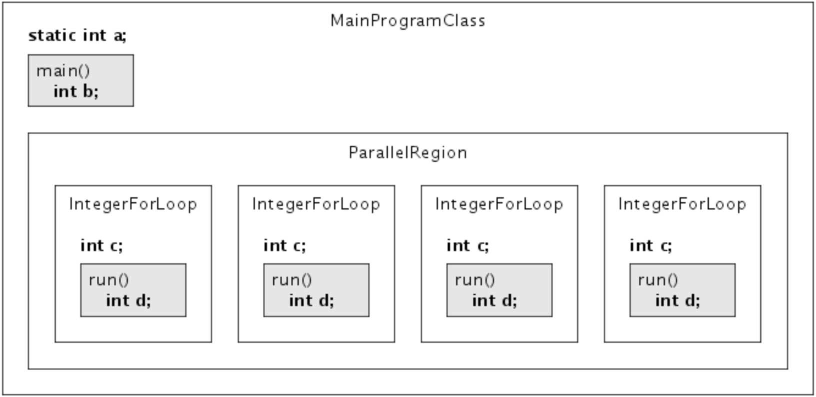
- Shared (global) variables
- Per-thread variables
- Loop local variables
- Main program local variables

Which code can access which variables?

Variables in a Parallel Java Program

```
public class MainProgramClass {
  // Shared (global) varriable declarations
  static int a;

  public static void main(String[] args) {
    // Main program local variable declarations (incl. args)
    int b;

    new ParallelTeam().execute(new ParallelRegion() {
      public void run() {
        execute(0,1023,new IntegerForLoop() {
          // Per-thread variable declarations
          int c;

          public void run(int first, int last) {
            // Loop local variable declarations (incl. i)
            int d;

            for (int i = first; i <= last; i++) {
              // Code for loop iteration i
            }
          }
        })
      }
    })
  }
}
```

Parallel Variables



Shared Memory

An SMP parallel program is organized around data structures located in shared memory.

- In a result parallel program, the shared data structure may contain all the results.
- In an agenda parallel program, the shared data structure may contain the agenda items and their results.
- In a specialist parallel program, the shared data structure may contain outputs and inputs.

In Java, shared (global) variables are located in shared memory; hence, use shared (global) variables to reference the shared data structures.

Shared Memory

Pro: a shared variable can be accessed by all threads.
Con: a shared variable can be accessed by all threads.

When multiple threads access the same shared variable, conflicts may arise:

- read-write conflict: one thread reads a variable at the same time as another thread writes the variable.
- write-write conflict: one thread writes a variable at the same time as another thread writes the variable.

Synchronize threads to avoid conflicts.

- Force a specific ordering of thread accesses

Synchronization adds overhead, so synchronize only when necessary.

SMP Parallel AES Partial Key Search

`FindKeySmp.java`