Advantages of concurrent programs

- Reactive programming
  - User can interact with applications while tasks are running, e.g., stopping the transfer of a big file in a web browser.
- Availability of services
  - Long-running tasks need not delay short-running ones, e.g., a web server can serve an entry page while at the same time processing a complex query.
- Parallelism
  - Complex programs can make better use of multiple resources in new multi-core processor architectures, SMPs, LANs or WANs, e.g., scientific/engineering applications, simulations, games, etc.
- Controllability
  - Tasks requiring certain preconditions can suspend and wait until the preconditions hold, then resume execution transparently.

Disadvantages of concurrent programs

- Safety
  - “Nothing bad ever happens”
  - Concurrent tasks should not corrupt consistent state of program
- Live-lock
  - “Nothing ever happens at all”
  - Tasks should not suspend and indefinitely wait for each other (deadlock).
- Non-determinism
  - Mastering exponential number of interleavings due to different schedules.
- Resource consumption
  - Threads can be expensive. Overhead of scheduling, context-switching, and synchronization.
  - Concurrent programs can run slower than their sequential counterparts even with multiple CPUs!

Overview of concurrent programming

- There are four basic approaches:
  - Sequential programming (no concurrency)
  - Declarative concurrency (streams in a functional language)
  - Message passing with active objects (Erlang, SALSA)
  - Atomic actions on shared state (Java)
- The atomic action approach is the most difficult, yet it is the one you will probably be most exposed to!
- But, if you have the choice, which approach to use?
  - Use the simplest approach that does the job: sequential if that is ok, else declarative concurrency if there is no observable nondeterminism, else message passing if you can get away with it.

Actors/SALSA

- Actor Model
  - A reasoning framework to model concurrent computations
  - Programming abstractions for distributed open systems
- SALSA
  - Simple Actor Language System and Architectures
  - An actor-oriented language for mobile and internet computing
  - Programming abstractions for internet-based concurrency, distribution, mobility, and coordination

SALSA and Java

- SALSA source files are compiled into Java source files before being compiled into Java byte code.
- SALSA programs may take full advantage of the Java API.
Hello World Example

```java
module examples.helloworld;

behavior HelloWorld {
    void act(String[] args) {
        standardOutput <- print("Hello") @
        standardOutput <- println("World!");
    }
}
```

The `act(String[] args)` message handler is similar to the `main(...)` method in Java and is used to bootstrap SALSA programs.

When a SALSA program is executed, an actor of the given behavior is created and an `act(args)` message is sent to this actor with any given command-line arguments.

References to `standardOutput`, `standardInput` and `standardError` actors are available to all SALSA actors.

SALSA Support for Actors

- Programmers define behaviors for actors.
- Messages are sent asynchronously.
- State is modeled as encapsulated objects/primitive types.
- Messages are modeled as potential method invocations.
- Continuation primitives are used for coordination.

Reference Cell Example

```java
module examples.cell;

behavior Cell {
    Object content;

    Cell(Object initialContent) {
        content = initialContent;
    }

    Object get() { return content; }

    void set(Object newContent) {
        content = newContent;
    }
}
```

Actor Creation

- To create an actor:
  ```java
  TravelAgent a = new TravelAgent();
  ```

Message Sending

- To create an actor:
  ```java
  TravelAgent a = new TravelAgent();
  ```
- To send a message:
  ```java
  a <- book(flight);
  ```
Causal order

- In a sequential program all execution states are totally ordered.
- In a concurrent program all execution states of a given actor are totally ordered.
- The execution state of the concurrent program as a whole is partially ordered.

Total order

- In a sequential program all execution states are totally ordered.

Causal order in the actor model

- In a concurrent program all execution states of a given actor are totally ordered.
- The execution state of the concurrent program is partially ordered.

Non-determinism

- An execution is non-deterministic if there is a computation step in which there is a choice of what to do next.
- Non-determinism appears naturally when there is asynchronous message passing:
  - Messages can arrive or be processed in an order different from the sending order.

Example of non-determinism

Actor \( a \) can receive messages \( m_1() \) and \( m_2() \) in any order.

Coordination Primitives

- SALSA provides three main coordination constructs:
  - Token-passing continuations:
    - To synchronize concurrent activities
    - To notify completion of message processing
    - Named tokens enable arbitrary synchronization (data-flow)
  - Join blocks:
    - Used for barrier synchronization for multiple concurrent activities
    - To obtain results from otherwise independent concurrent processes
  - First-class continuations:
    - To delegate producing a result to a third-party actor
Token Passing Continuations

- Ensures that each message in the continuation expression is sent after the previous message has been processed. It also enables the use of a message handler return value as an argument for a later message (through the token keyword).

  - Example:
    
    \[ a_1 \leftarrow \text{m}_1(); \]
    
    \[ a_2 \leftarrow \text{m}_2(\text{token}); \]
    
    Send \text{m}_1 to \text{a}_1 asking \text{a}_1 to forward the result of processing \text{m}_1 to \text{a}_2 (as the argument of message \text{m}_2).

Named Tokens

- Tokens can be named to enable more loosely-coupled synchronization

  - Example:
    
    \[
    \begin{align*}
    \text{token } t_1 &= \text{a}_1 \leftarrow \text{m}_1(); \\
    \text{token } t_2 &= \text{a}_2 \leftarrow \text{m}_2(); \\
    \text{token } t_3 &= \text{a}_3 \leftarrow \text{m}_3( t_1 ); \\
    \text{token } t_4 &= \text{a}_4 \leftarrow \text{m}_4( t_2 ); \\
    a &\leftarrow ( t_3, t_2, t_4 );
    \end{align*}
    \]
    
    Sending \text{n}(\ldots) to a will be delayed until messages \text{m}_1(); \ldots \text{m}_4(); have been processed. \text{m}_2() can proceed concurrently with \text{m}_1().

Cell Tester Example

```java
module examples.cell;

behavior CellTester {
  void act(String[] args) {
    Cell c = new Cell(”Hello”);
    standardOutput <− print(”Initial Value:” @ c);
    c <− get() @ standardOutput <− println(token @ c <− set(”World” @ standardOutput <− print(”New Value:” @ c <− get() @ standardOutput <− println(token));
  }
}
```

Join Blocks

- Provide a mechanism for synchronizing the processing of a set of messages.
- Set of results is sent along as a token containing an array of results.

  - Example:
    
    ```java
    Actor[] actors = { searcher0, searcher1, searcher2, searcher3 };
    join { for (int i=0; i < actors.length; i++){
      actors[i] <− find( phrase );
    } }
    resultActor <− output( token );
    ```
    
    Send the \text{find}(\text{phrase}) message to each actor in \text{actors[\ldots]} then after all have completed send the result to \text{resultActor} as the argument of an \text{output}(\ldots) message.

Example: Acknowledged Multicast

```java
join{ a1 <− n(); a2 <− m2; an <− m(n()); } @ cust <− n(token);
```
First Class Continuations

- Enable actors to delegate computation to a third party independently of the processing context.

- For example:

```java
int m(...)
   b <- n(...) @ currentContinuation;
   ask (delegate) actor b to respond to this message n on behalf of current actor (m(...)) by processing its own message n.
```

Delegate Example

```java
module examples.fibonacci;
behavior Calculator {
    int fib(int n) {
        Fibonacci f = new Fibonacci(n);
        f <- compute() @ currentContinuation;
    }
    int add(int n1, int n2) (return n1+n2);
}
void act(String args[]) {
    fib(10) @ standardOutput <- println(token);
    fib(8) @ add(token,3) @ standardOutput <- println(token);
}
}
```

Fibonacci Example

```java
module examples.fibonacci;
behavior Fibonacci {
    int n;
    Fibonacci(int n) {
        this.n = n;
    }
    int add(int x, int y) {
        return x + y;
    }
    int compute(int n) {
        if (n == 0) return 0;
        else if (n <= 2) return 1;
        else {
            Fibonacci fib1 = new Fibonacci(n-1);
            Fibonacci fib2 = new Fibonacci(n-2);
            token x = fib1.compute();
            token y = fib2.compute();
            add(x,y) @ currentContinuation;
        }
    }
    void act(String args[]) {
        n = Integer.parseInt(args[0]);
        compute(n) @ standardOutput <- println(token);
    }
}
```

Fibonacci Example 2

```java
module examples.fibonacci2;
behavior Fibonacci {
    int add(int x, int y) { return x + y; }
    int compute(int n) {
        if (n == 0) return 0;
        else if (n <= 2) return 1;
        else {
            Fibonacci fib = new Fibonacci();
            token x = fib.compute(n-1);
            compute(n-2) @ add(x,token) @ currentContinuation;
        }
    }
    void act(String args[]) {
        n = Integer.parseInt(args[0]);
        compute(n) @ standardOutput <- println(token);
    }
}
```

Execution of salsa Fibonacci 6

Create new actor
Synchronize on result
Non-blocked actor
Scheduling

- The choice of which actor gets to execute next and for how long is done by a part of the system called the scheduler.
- An actor is non-blocked if it is processing a message or if its mailbox is not empty, otherwise the actor is blocked.
- A scheduler is fair if it does not starve a non-blocked actor, i.e. all non-blocked actors eventually execute.
- Fair scheduling makes it easier to reason about programs and program composition.
  - Otherwise some correct program (in isolation) may never get processing time when composed with other programs.

Message Properties

- SALSA provides message properties to control message sending behavior:
  - priority
    - To send messages with priority to an actor
  - delay
    - To delay sending a message to an actor for a given time
  - waitfor
    - To delay sending a message to an actor until a token is available.

Priority Message Sending

- To (asynchronously) send a message with high priority:
  \[ a \leftarrow \text{book(flight)}:\text{priority}; \]
  
  Message is placed at the beginning of the actor’s mail queue.

Delayed Message Sending

- To (asynchronously) send a message after a given delay in milliseconds:
  \[ a \leftarrow \text{book(flight)}:\text{delay(1000)}; \]
  
  Message is sent after one second has passed.

Synchronized Message Sending

- To (asynchronously) send a message after another message has been processed:
  \[
  \text{token fundsOk = bank} \leftarrow \text{checkBalance}();
  a \leftarrow \text{book(flight)}:\text{waitfor(fundsOk)};
  \]
  
  Message is sent after token has been produced.

Exercises

63. How would you implement the join continuation linguistic abstraction in terms of message passing?
64. Download and execute the CellTester.salsa example.
65. *Write a solution to the Flavius Josephus problem in SALSA. A description of the problem is at VRH Section 7.8.3 (page 558).