Compile-Time Analysis and Specialization of Clocks in Concurrent Programs

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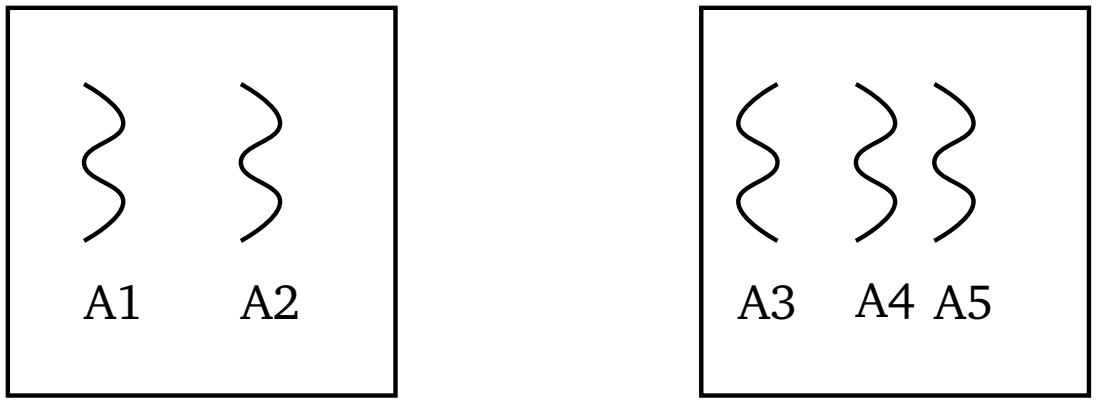
Background

The X10 Programming Language

- Concurrent programming model
- Activities are light weight threads
- Places are distributed memory locations



The X10 Programming Language

- Activities created using *async*

```
async {
/* Body of async
executed locally */
}
```

```
async (p2) {
/* Body of async
executed at p2 */
}
```

- Synchronization between activities through
  - *finish*
  - *atomic*
  - clocks

Clocks in X10

- Barriers in X10

```
final clock c = clock.factory.clock();
async clocked (c) {
    ..
    c.next();
    ..
    c.next();
}
async clocked (c) {
    ..
    c.next();
    ..
}
c.next();
..
c.next();
```

Clocks in X10

- Barriers in X10

```
final clock c = clock.factory.clock();
async clocked (c) {
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async clocked (c) {
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c.next();
```

Declare a clock

Clocks in X10

- Barriers in X10

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final clock c = clock.factory.clock();
async clocked (c) {
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    c.next();
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async clocked (c) {
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c.next();
..
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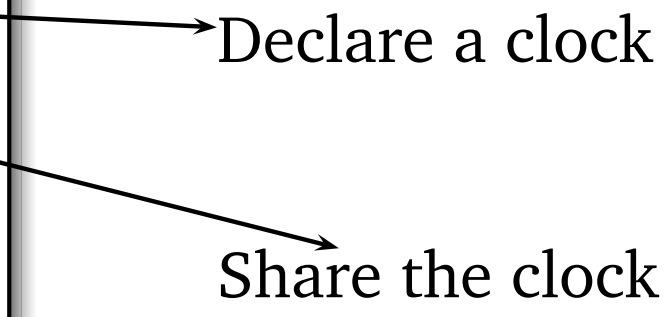
```



Clocks in X10

- Barriers in X10

```
final clock c = clock.factory.clock();
async clocked (c) {
    ..
    c.next();
    ..
    c.next();
}
async clocked (c) {
    ..
    c.next();
    ..
}
c.next();
..
c.next();
```

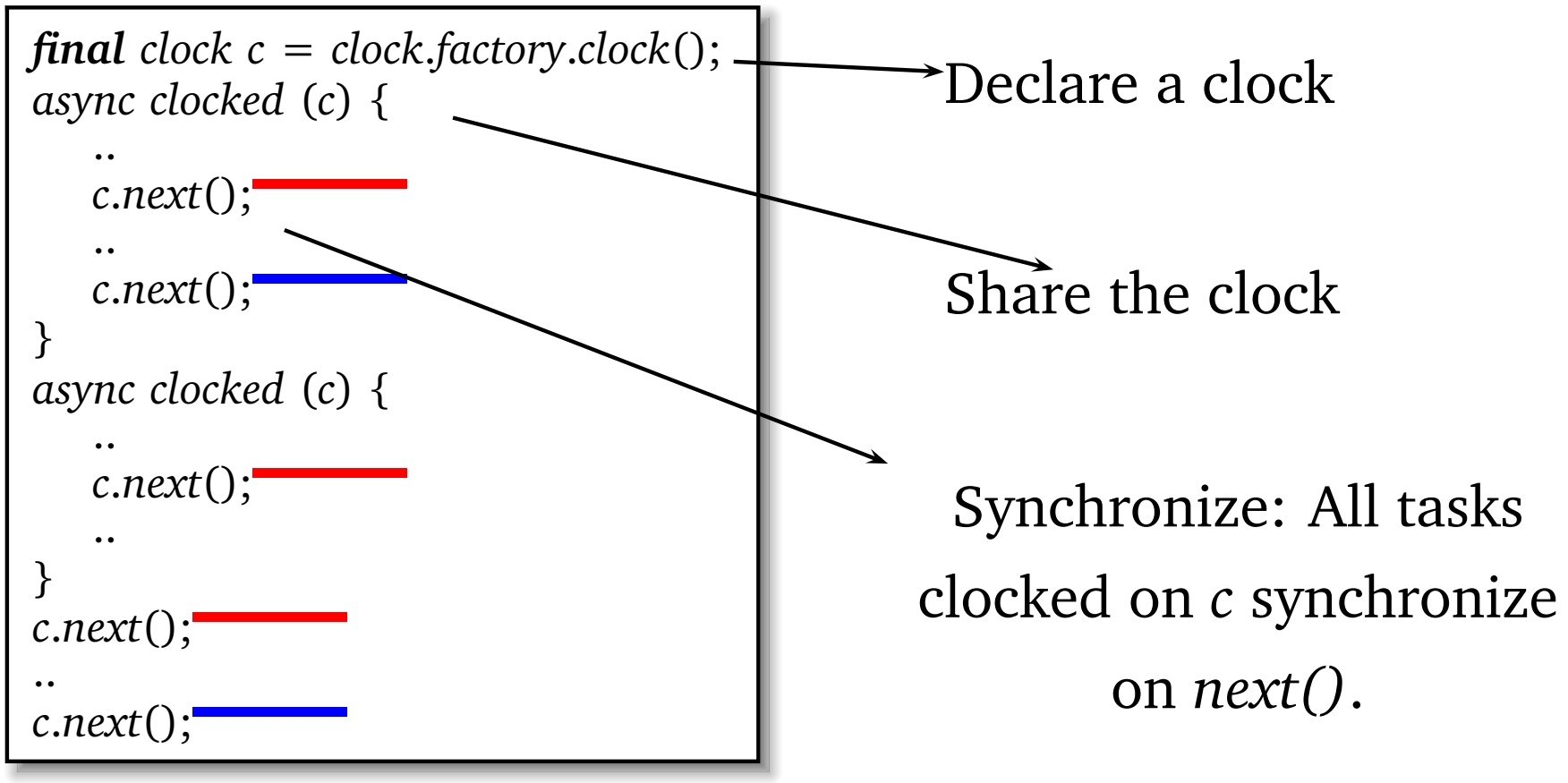
Declare a clock

Share the clock

Synchronize: All tasks clocked on *c* synchronize on *next()*.

Clocks in X10

- Barriers in X10



More about Clocks

- *next()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
   c.next();
   ..
   ..
   ..
   c.next();
   ..
}
   ..
   c.next();
   ..
   c.next();
```

More about Clocks

- *next()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
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   ..
}
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   c.next();
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   c.next();
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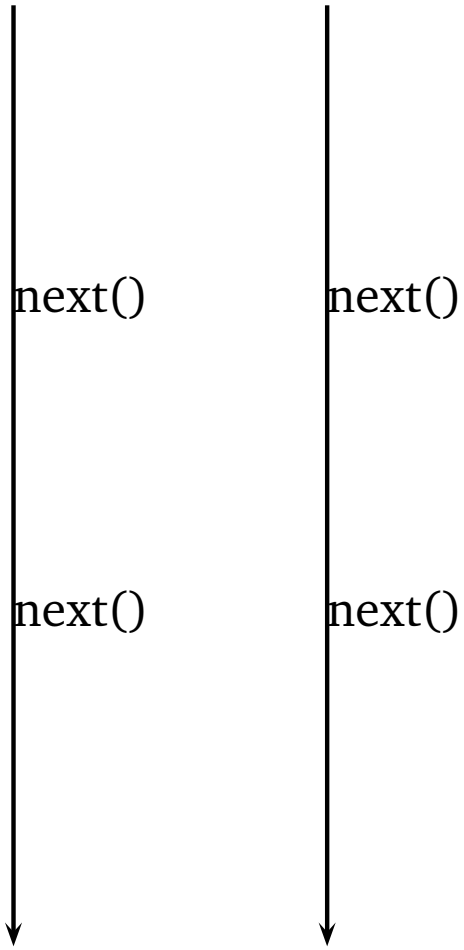

More about Clocks

- *next()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
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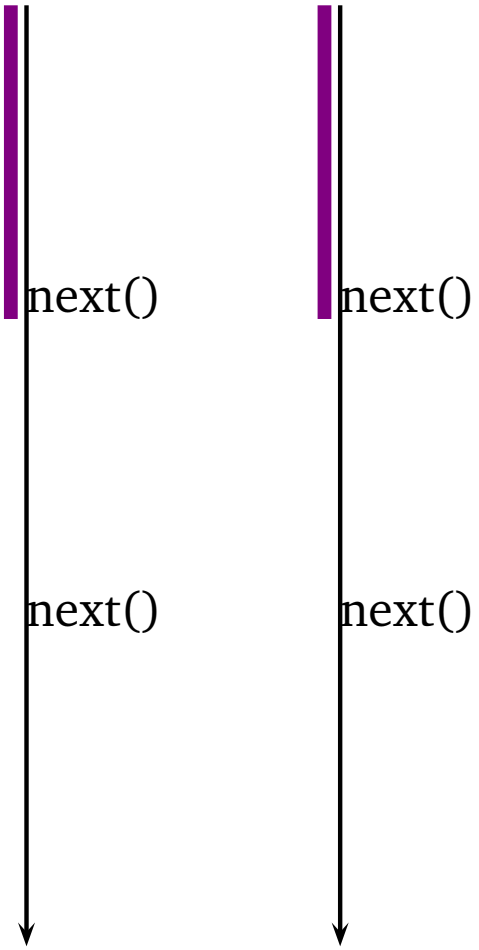
   c.next();
```



More about Clocks

- *next()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
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   ..
   c.next();
   ..
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   c.next();
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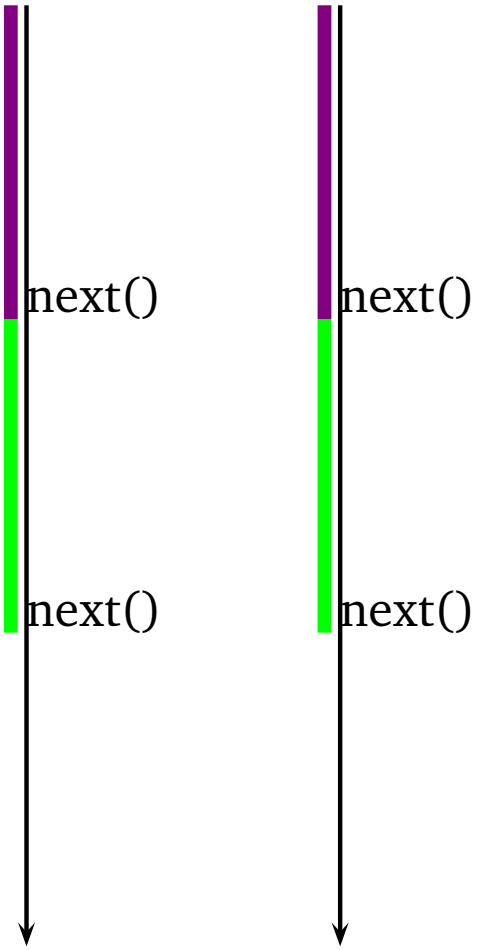
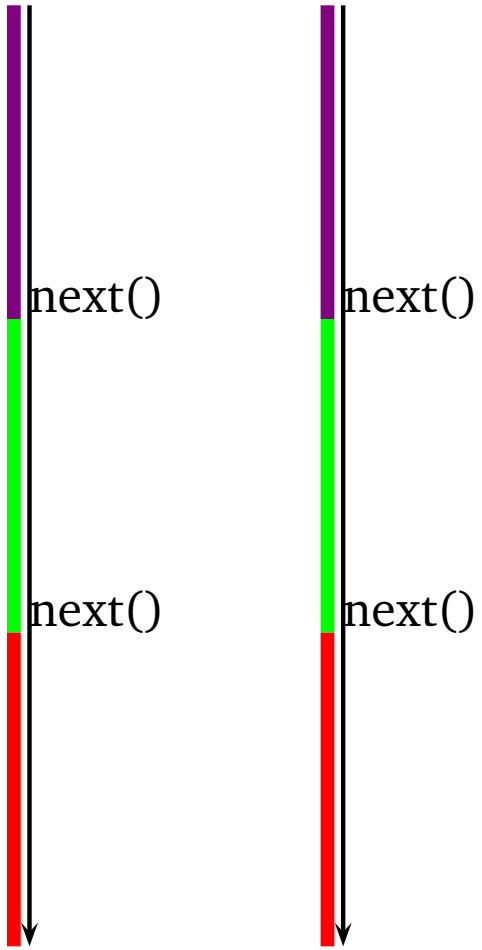
   c.next();
```



More about Clocks

- *next()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
   c.next();
   ..
   ..
   ..
   c.next();
   ..
}
   ..
   c.next();
   ..
   c.next();
```



More about Clocks

- *resume()*

```
final clock c = clock.factory.clock();
async clocked (c) {
    ..
    c.next();
    ..
    c.resume();
    ..
    c.next();
    ..
}
    ..
    c.next();
    ..
    c.next();
```

More about Clocks

- *resume()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
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   ..
}
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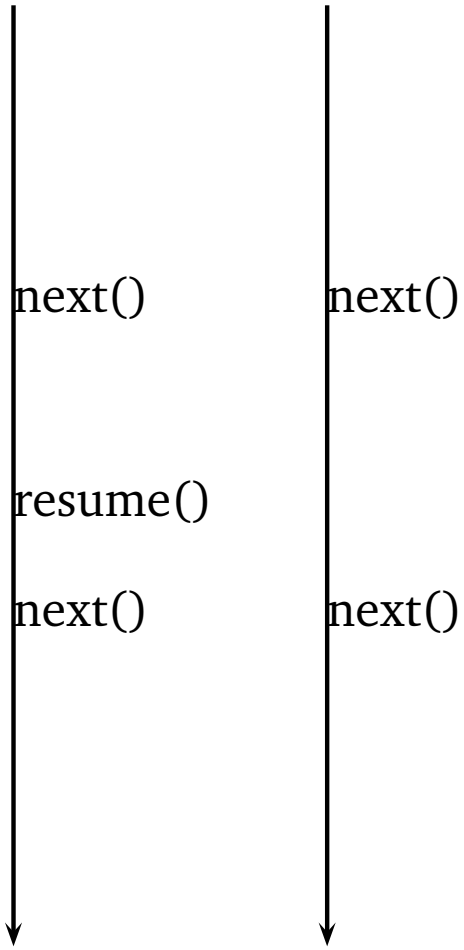
```



More about Clocks

- *resume()*

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
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   c.next();
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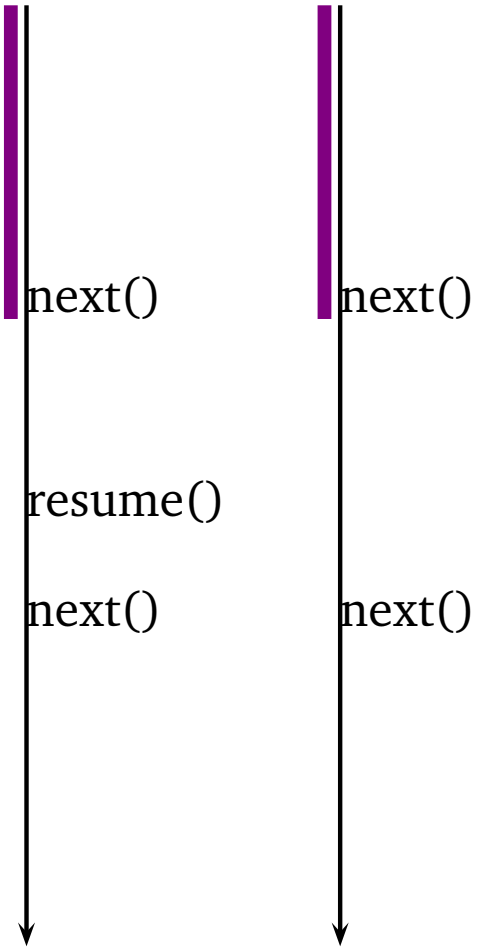

More about Clocks

- *resume()*

```
final clock c = clock.factory.clock();
async clocked (c) {
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   ..
}
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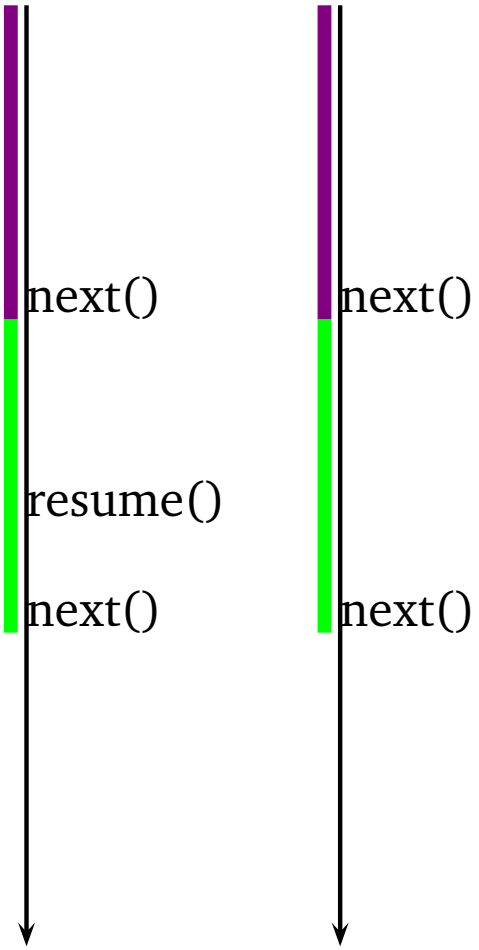

More about Clocks

- *resume()*

```
final clock c = clock.factory.clock();
async clocked (c) {
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   c.next();
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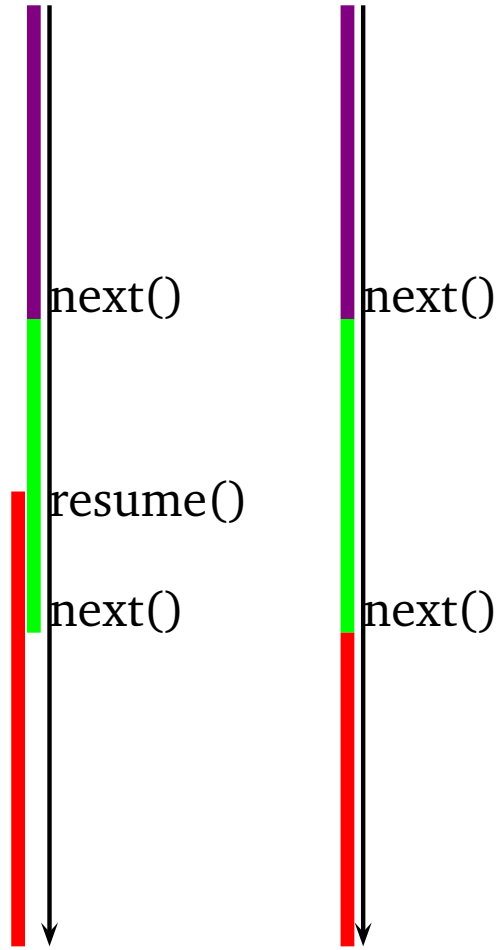
   c.next();
   ..
}
   ..
   c.next();
   ..
   c.next();
```



More about Clocks

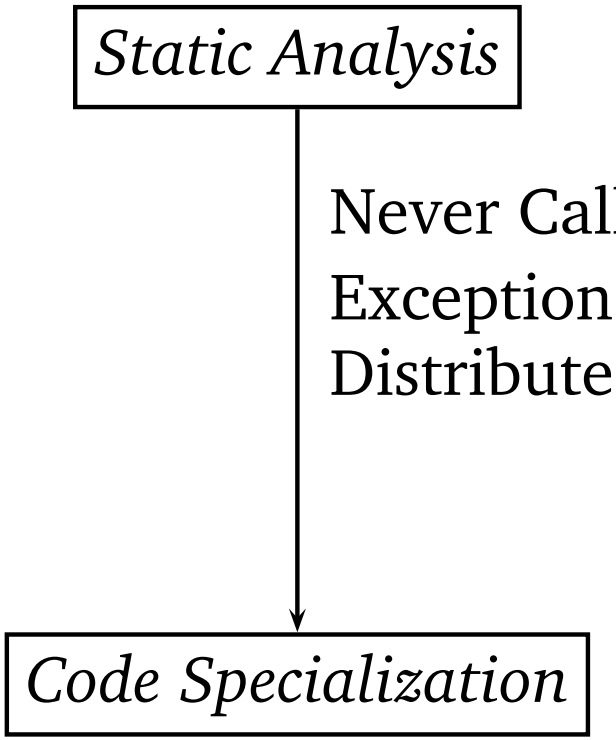
- *drop()*
  - Explicitly drop the clock
  - Task does not have to synchronize anymore

```
final clock c = clock.factory.clock();
async clocked (c) {
   ..
   c.next();
   ..
   c.drop();
   ..
}
   ..
   c.next();
   ..
   c.next();
```

Motivation

- Default implementation handles all cases
- Protocol violation is handled by exceptions
  - Example: call *next()* after *drop()*
- We can generate more efficient code if
  - Activity never violates the protocol
  - Activity never calls *resume()* on clock c

Design Overview



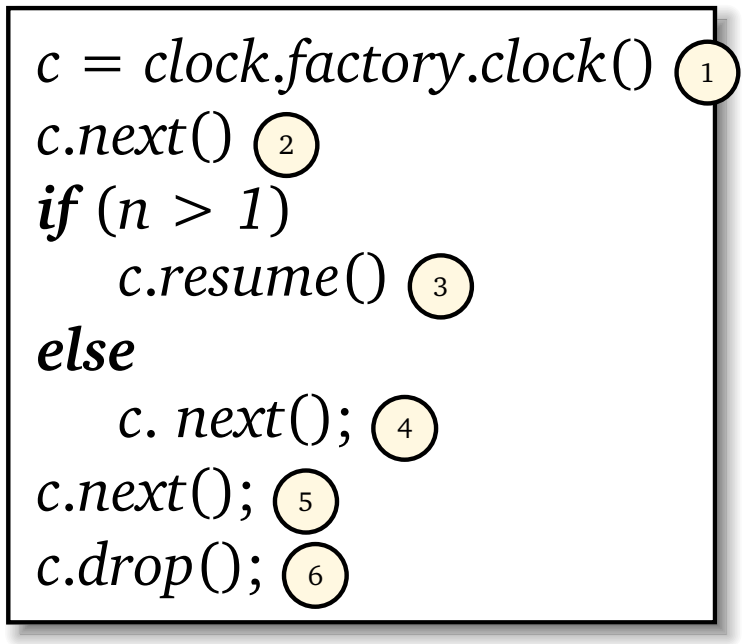
- Extract model from IR
- One automaton per clock
- Use NuSMV

- X10 compiler plug-in to choose clock implementation based on analysis result
- Each clock specialized independently

Building the Automaton

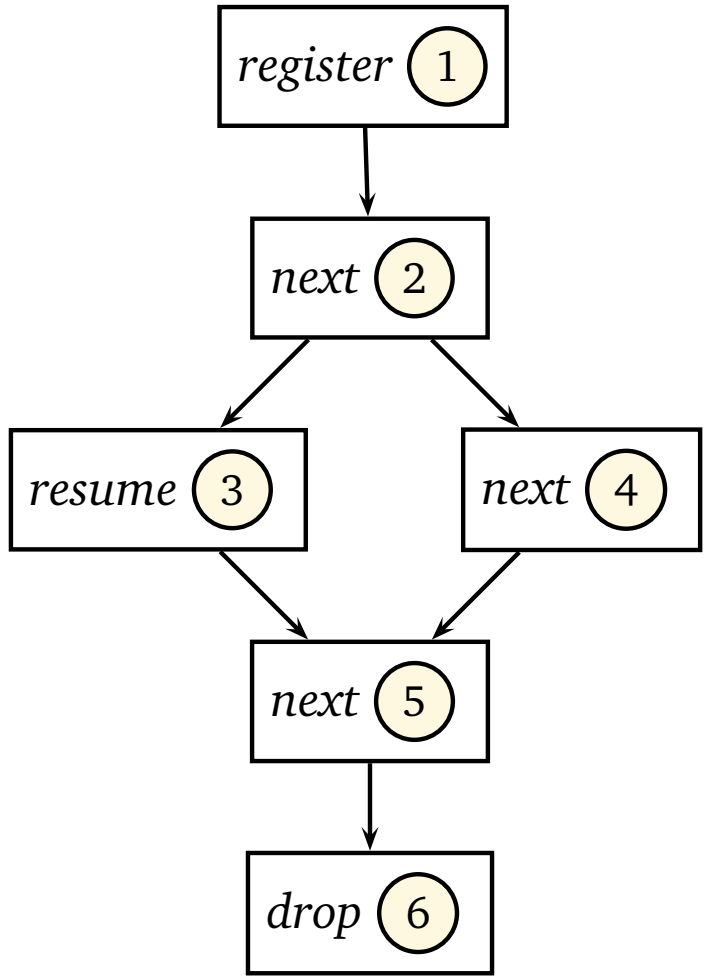
```
c = clock.factory.clock()
c.next()
if (n > 1)
    c.resume()
else
    c. next();
c.next();
c.drop();
```

Building the Automaton



Building the Automaton

```
c = clock.factory.clock()  1
c.next()  2
if (n > 1)
    c.resume()  3
else
    c. next();  4
c.next();  5
c.drop();  6
```



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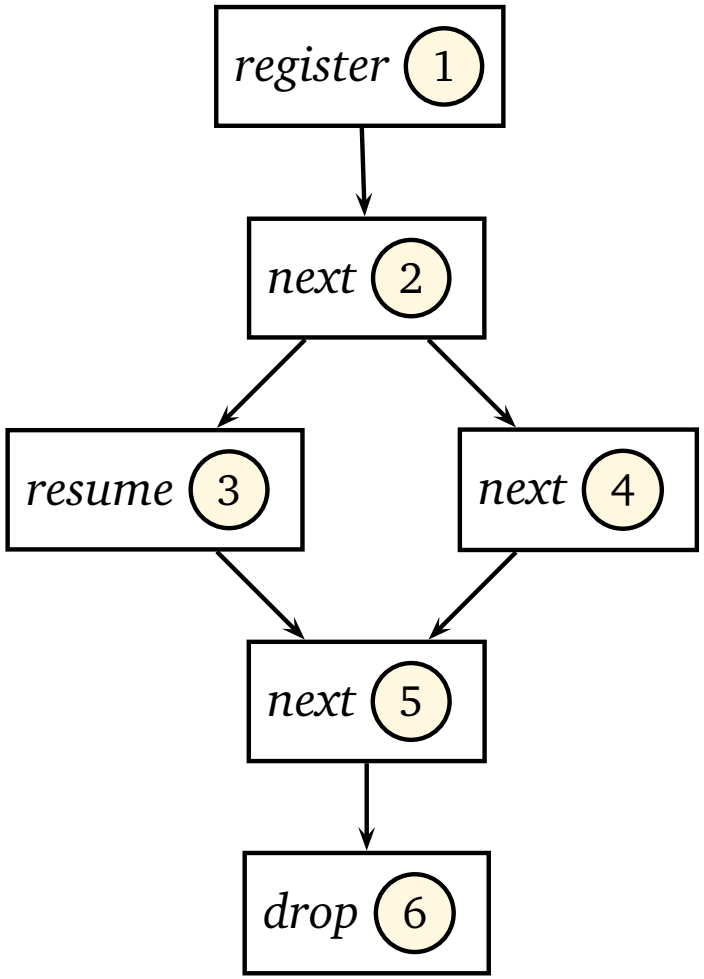
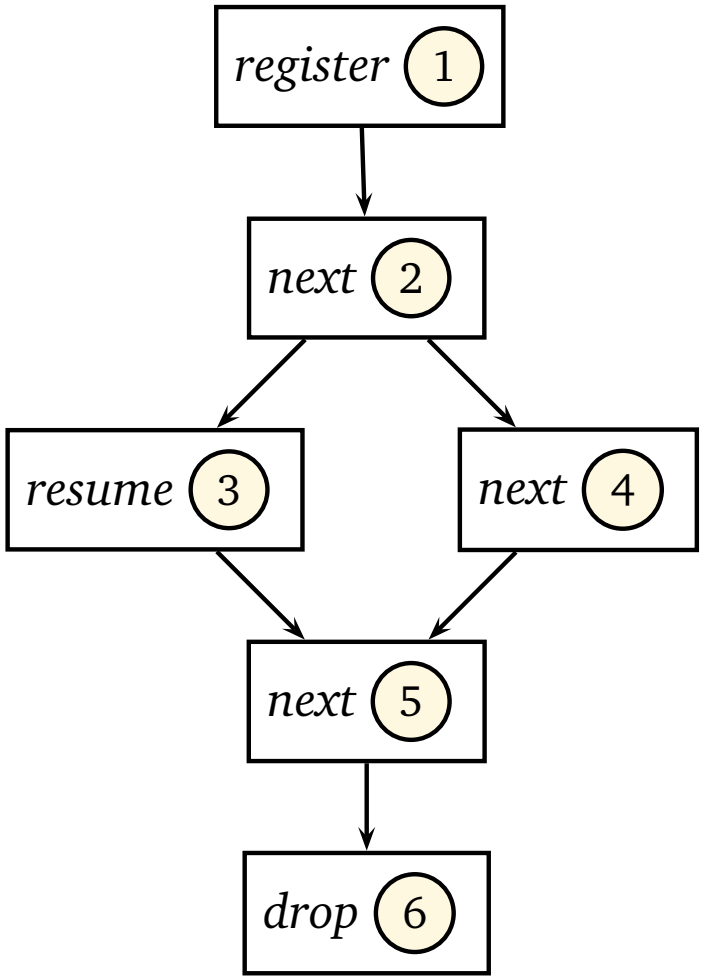
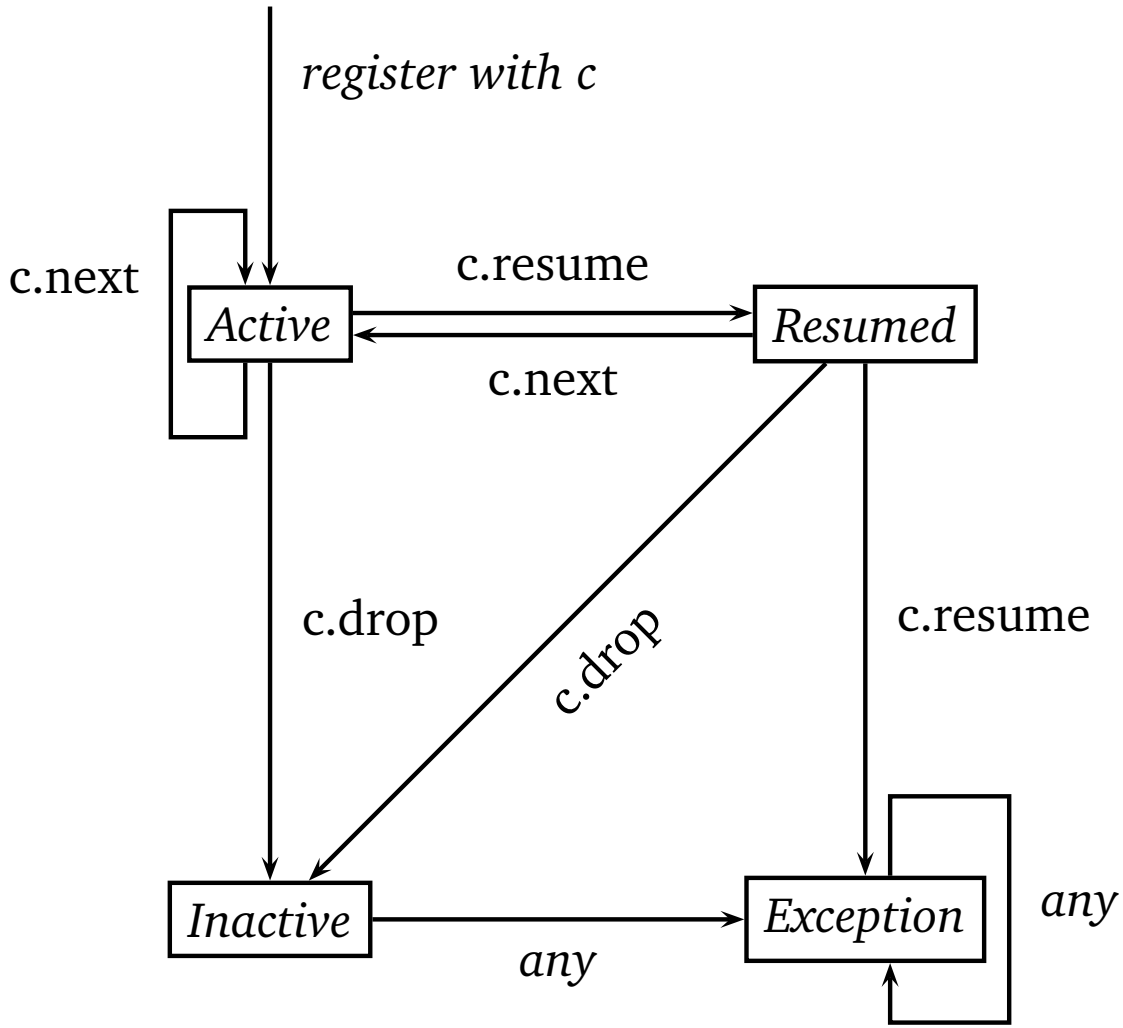


Building the Automaton




```
init (clock) = register;
next(clock) :=
case
   (clock = register) : next_2;
   (clock = next_2) : {resume_3, next_4};
   (clock = resume_3) : next_5;
   (clock = next_4) : next_5;
   (clock = next_5) : drop_6;
   1: clock;
esac;
DEFINE clock_next = clock in
                        {next_2, next_4, next_5}
DEFINE clock_resume = clock in {resume_3}
..
```

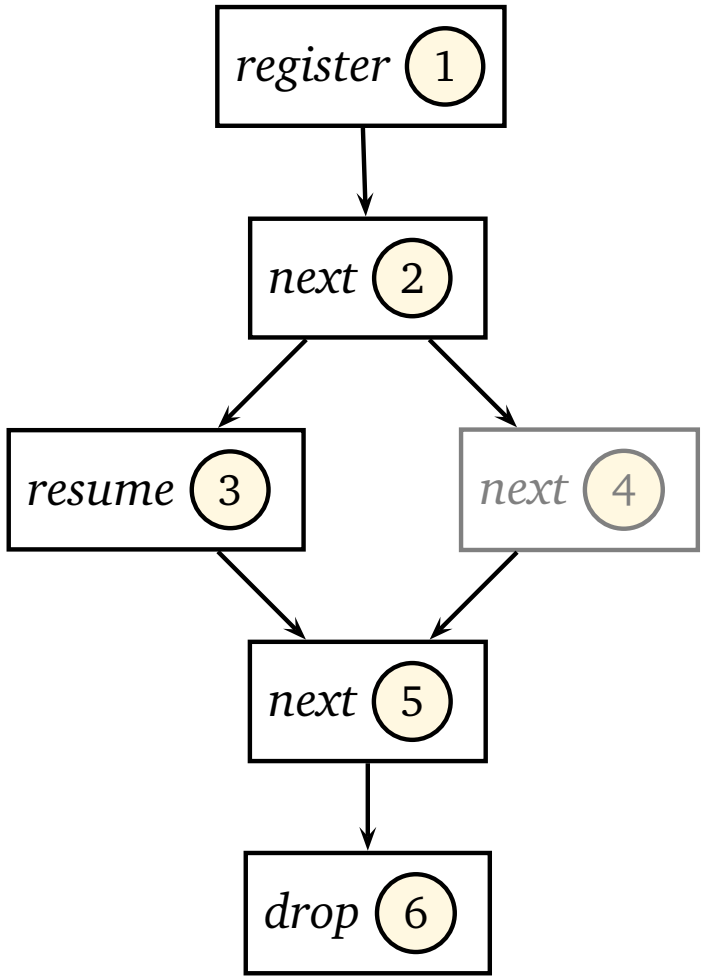
The Protocol



The Monitor

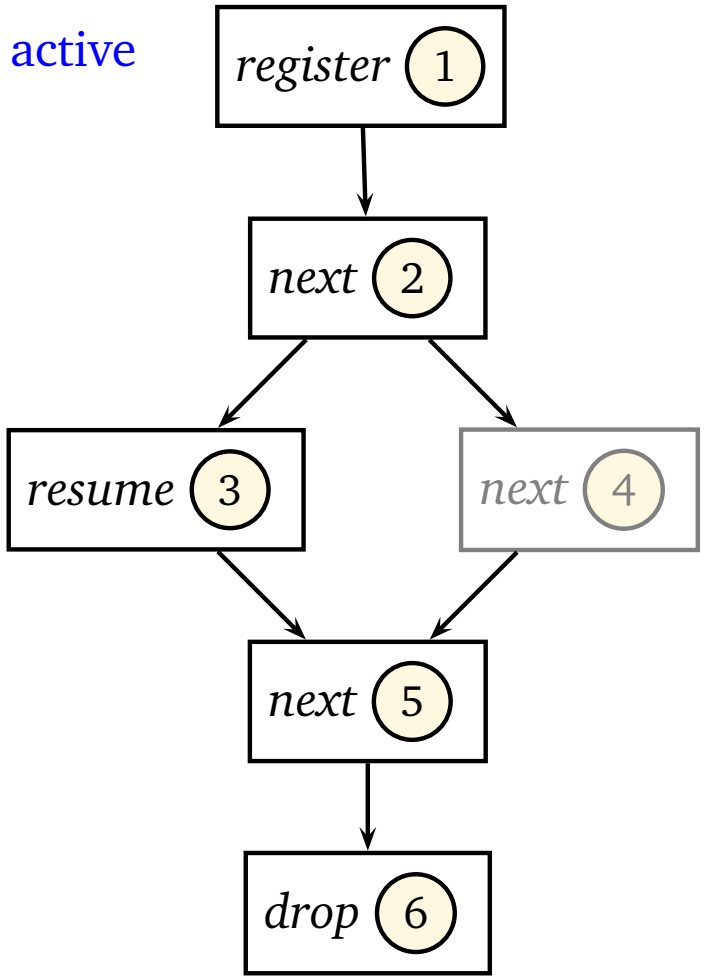
```
init (state) = inactive;
next(state) :=
case
   (state = inactive) & (clock_register) : active;
   (state = active) & (clock_drop) : inactive;
   (state = active) & (clock_resume): resumed;
   (state = resumed) & (clock_next): active;
   ..
-- Exception cases
   (state = resumed) & (clock_resume): exception;
   (state = inactive) & (clock_next) : exception;
```

The Monitor

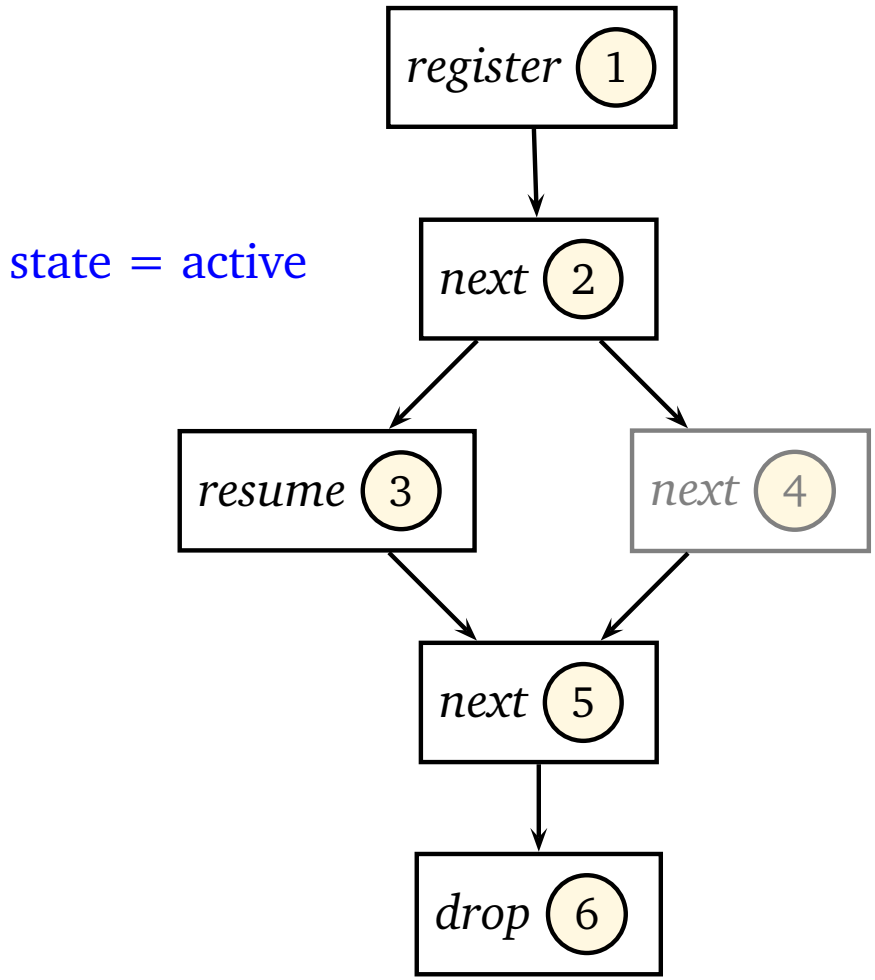


The Monitor

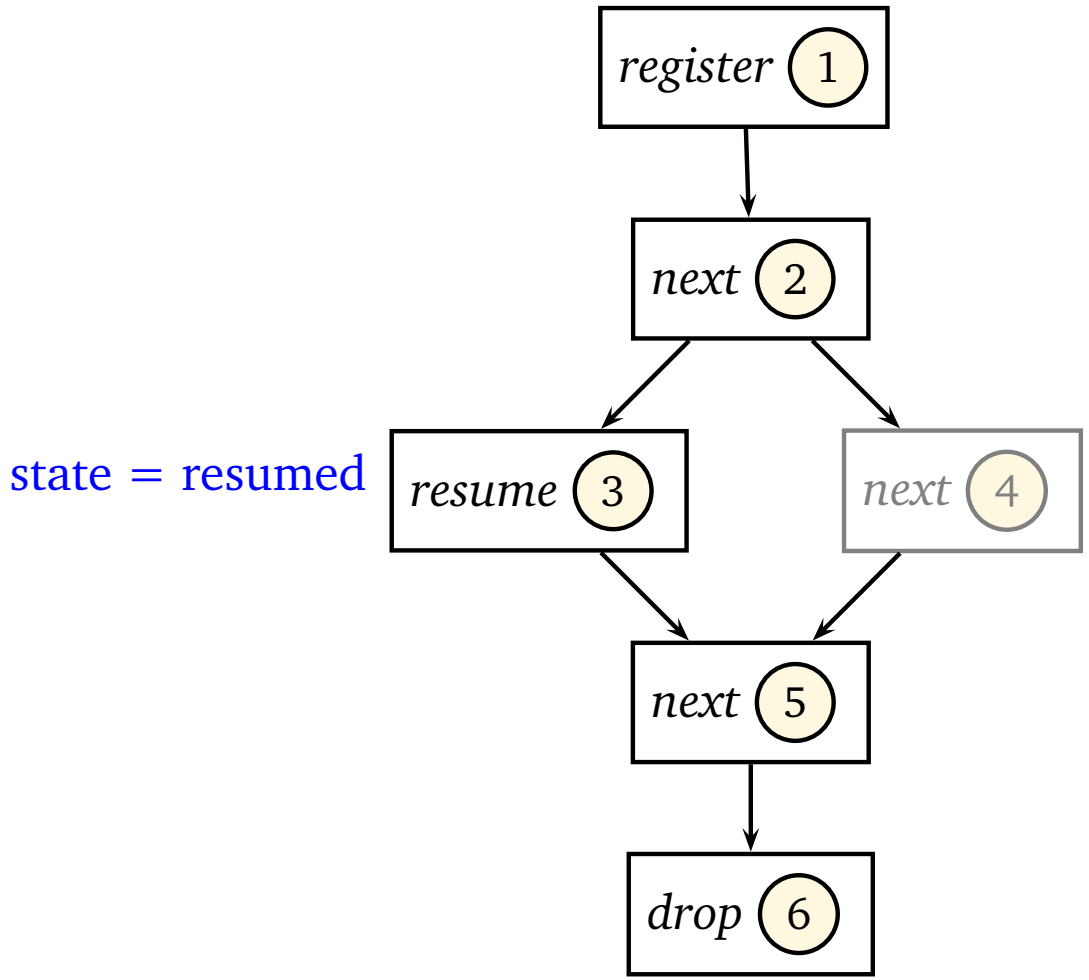
state = active



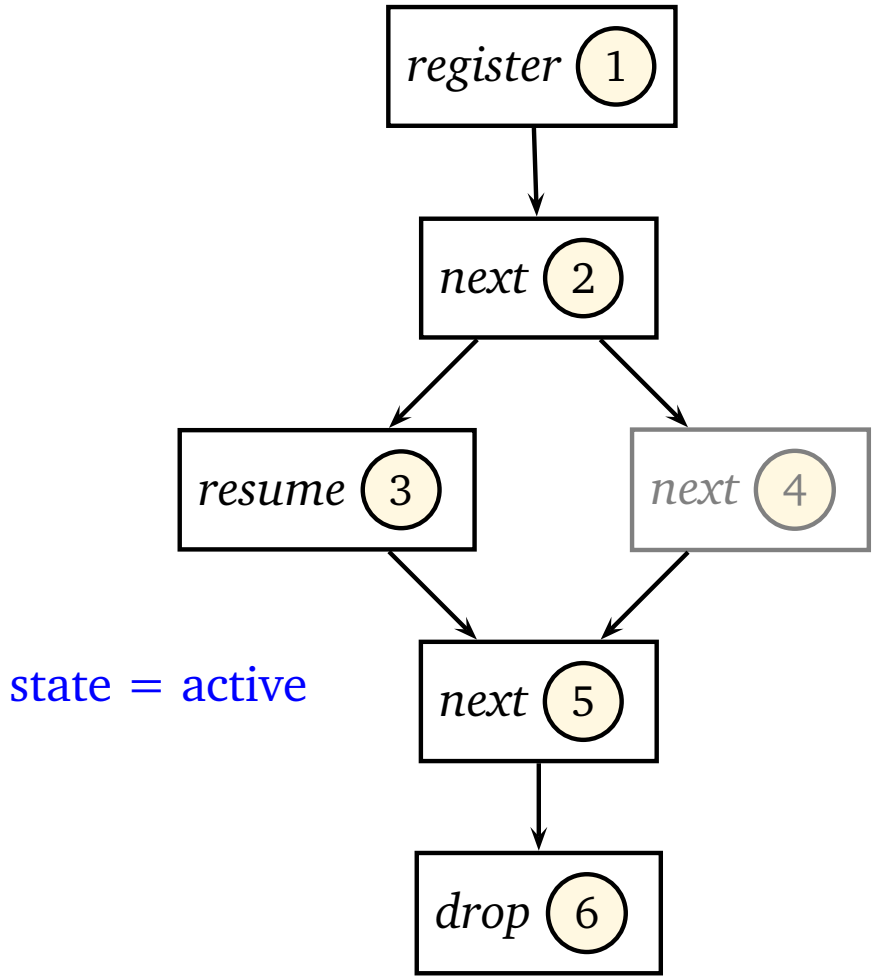
The Monitor



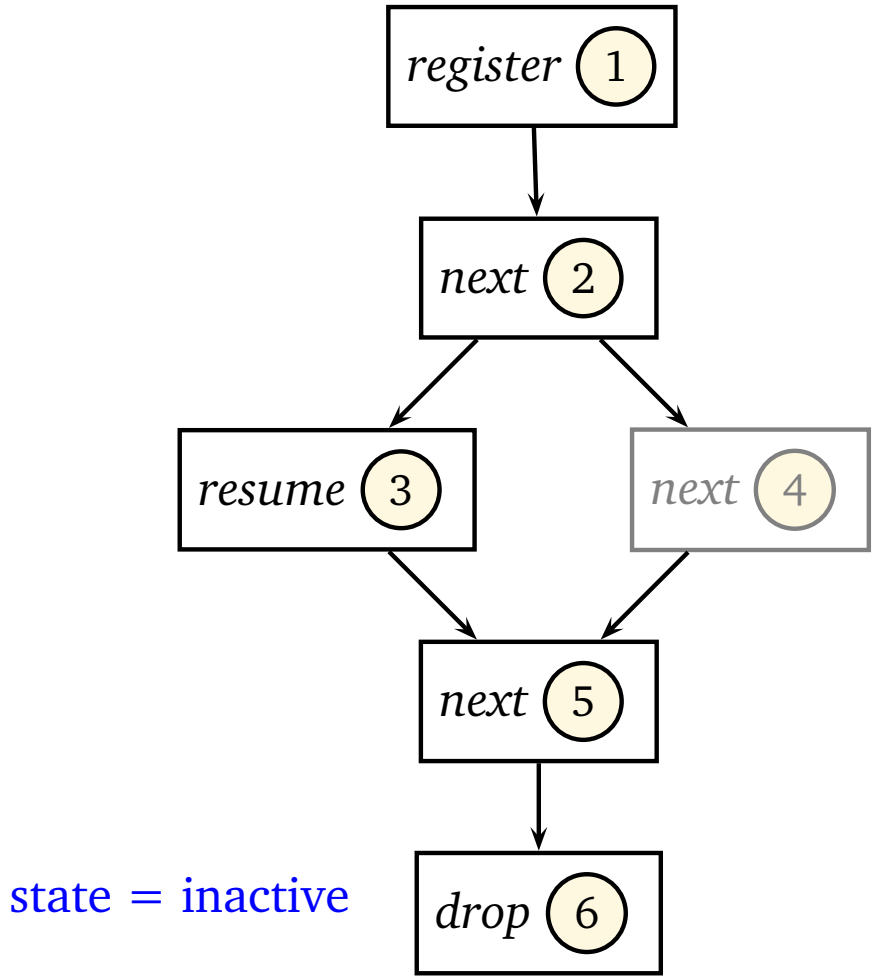
The Monitor



The Monitor



The Monitor



Dealing with *async*

```
c = clock.factory.clock()  1
c.next();  2

async clocked (c) {  3
    c.resume();  4
}
c.next();  5
c.drop();  6
```

Dealing with *async*

```
c = clock.factory.clock()  1
c.next();  2

async clocked (c) {  3
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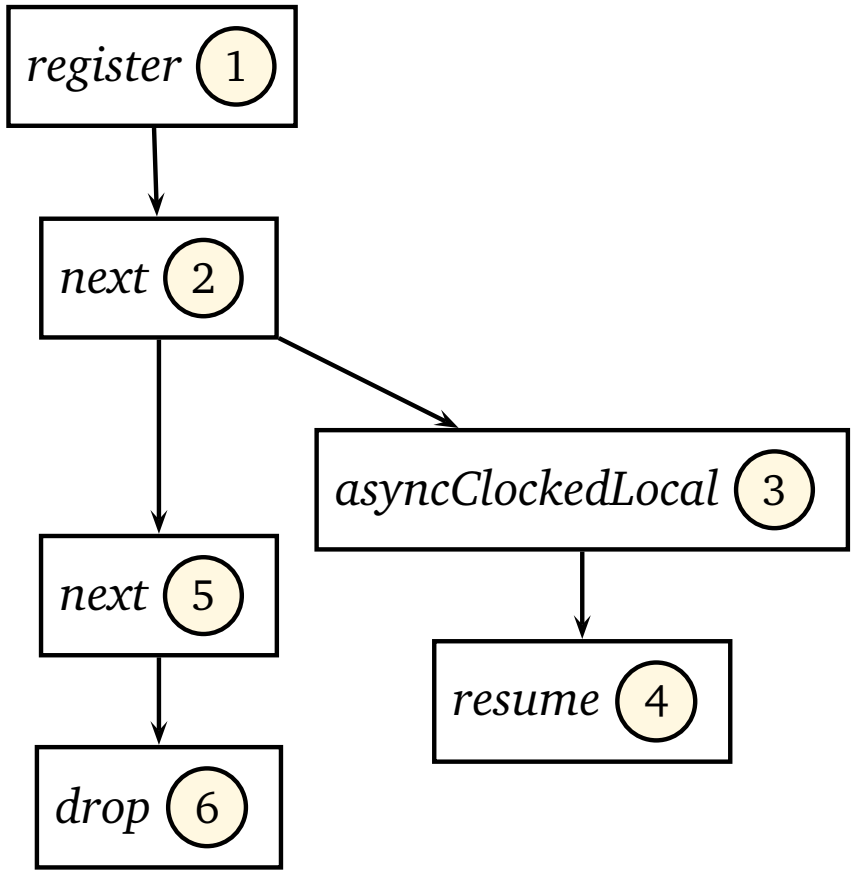
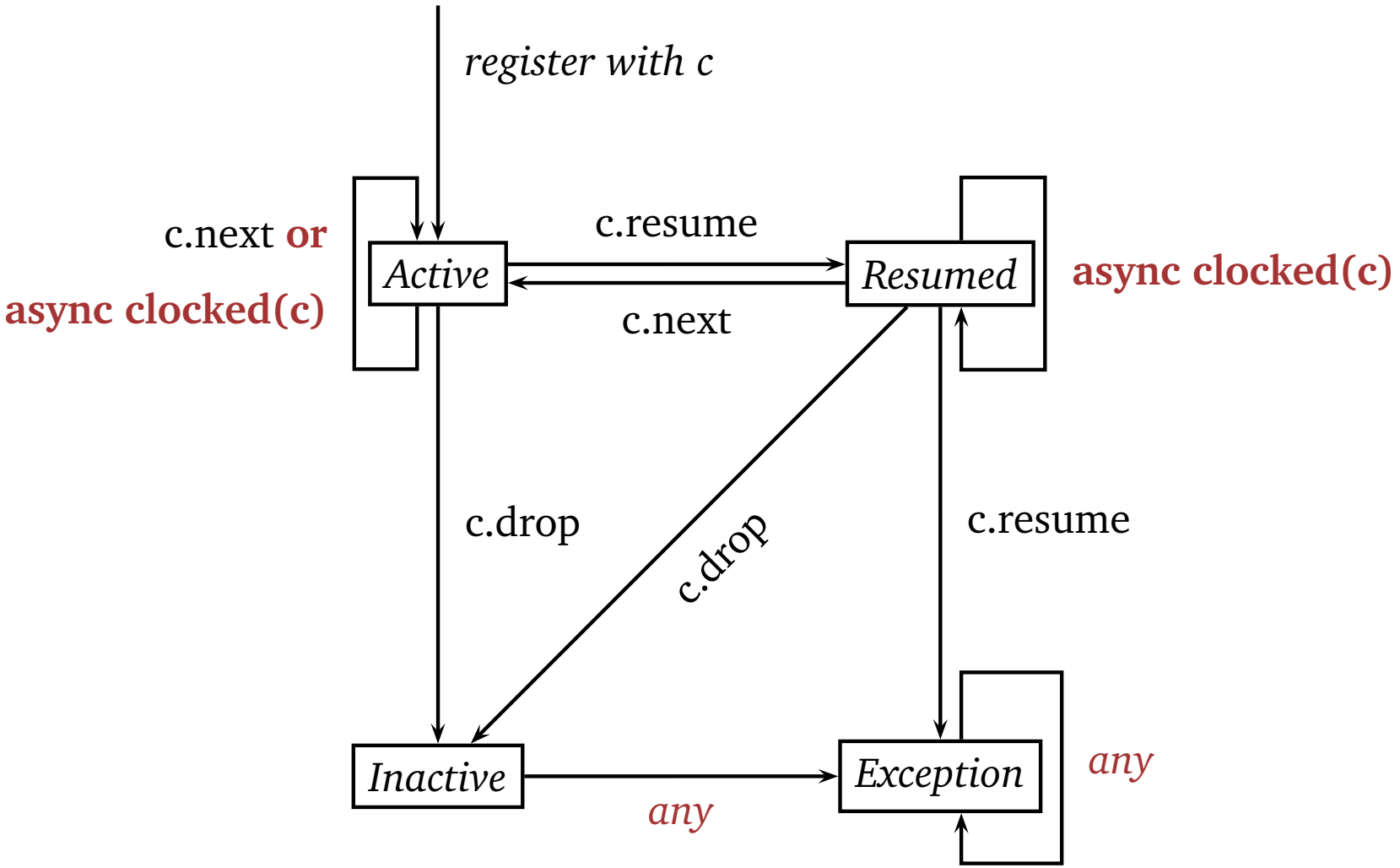


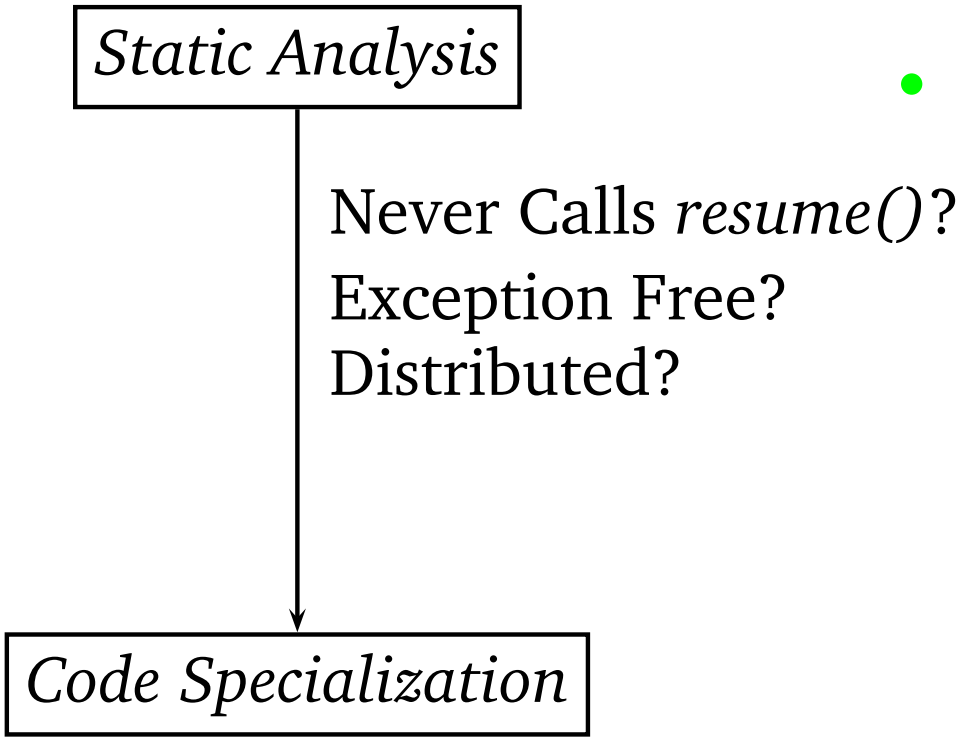
The Protocol



Checking for properties

- Is the clock protocol violation free?
  AG (!($state = exception$))
- Does the clock ever call resume()?
  AG (!($state = resumed$))
- Is the clock used in multiple places?
  AG(!$clock\_asyncClockedRemote$)
- Do the spawned activities ever call next?
  G($clock\_next- >$
  H(!($clock\_asyncClockedLocal|clock\_asyncClockedRemote$)))

Code Specialization



- We generate different code for each clock
- For eg., we remove run-time exception checks for exception free clocks

Experimental Results

Example	Clocks	Lines	Result	Speed Up	Analysis Time Base	Analysis Time NuSMV
Linear Search	1	35	EF, NR, L	35.2%	33.5s	0.4s
Relaxation	1	55	EF, NR, L	87.6	6.7	0.3
All Reduction Barrier	1	65	EF, NR	1.5	27.2	0.1
Pascal's Triangle	1	60	EF, L	20.5	25.8	0.4
Prime Number Sieve	1	95	NR, L	213.9	34.7	0.4
N-Queens	1	155	EF, NR, ON, L	1.3	24.3	0.5
LU Factorization	1	210	EF, NR	5.7	20.6	0.9
MolDyn JGF Bench.	1	930	NR	2.3	35.1	0.5
Pipeline	2	55	Clock 1: EF, NR, L Clock 2: EF, NR, L	31.4	7.5	0.5
Edmiston	2	205	Clock 1: NR, L Clock 2: NR, L	14.2	29.9	0.5

EF: No ClockUseException
NR: No Resume
ON: Only the activity that created the clock calls *next* on it
L: Clocked used locally (in a single place)

Conclusion

- Sequential analysis for concurrency optimization
- Our analysis is safe
- Combined with alias analysis
- Future work
  - Modular techniques
  - Inter-activity analysis
  - Refining alias analysis using clock information

Beginning of Research

Combining with Alias Analysis

```
final clock c = clock.factory.clock();
final clock d = clock.factory.clock();
final clock x = (n > 1)? c: d;
x.next();
x.resume();
```

Combining with Alias Analysis

```
final clock c = clock.factory.clock();
final clock d = clock.factory.clock();
final clock x = (n > 1)? c: d;
x.next();
x.resume();
```

```
final clock c = clock.factory.clock();
final clock d = clock.factory.clock();
if (*) {
    c.next();
    c.resume();
} else {
    d.next();
    d.resume();
}
```

Combining with Alias Analysis

```
final clock c = clock.factory.clock();
final clock d = clock.factory.clock();
final clock x = (n > 1)? c: d;
x.next();
x.resume();
```

```
final clock c = clock.factory.clock();
final clock d = clock.factory.clock();
if (*)
    c.next();
else
    d.next();
if (*)
    c.resume();
else
    d.resume();
}
```

Related Work

- Typestate analysis
- Model checking concurrent programs
- Code specialization
  - Specialization of CML message-passing techniques [Reppy 2007]
- Analysis of X10 programs
  - May-happen-in-parallel analysis [Agarwal 2007]