# Preventing Races and Deadlocks in Concurrent Programs: The SHIM Approach

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# The Data Race Problem

- In general, concurrent programming languages are non-deterministic
- Example of non-determinism in C

```
int x = 1;
void* bar(void* args) {
        x = x*2;
}
void foo() {
        pthread_create(&thread, NULL, bar, NULL);
        x++;
        printf("%d", x);
}
```

# The Data Race Problem

- Ensure atomicity by using locks

```
int x = 1;
void* bar(void* args) {
        pthread_mutex_lock(&mutex);
        x = x*2;
        pthread_mutex_unlock(&mutex);
}
void foo() {
        pthread_create(&thread, NULL, bar, NULL);
        pthread_mutex_lock(&mutex);
        x++;
        pthread_mutex_unlock(&mutex);
        printf("%d", x);
}
```

# The Data Race Problem

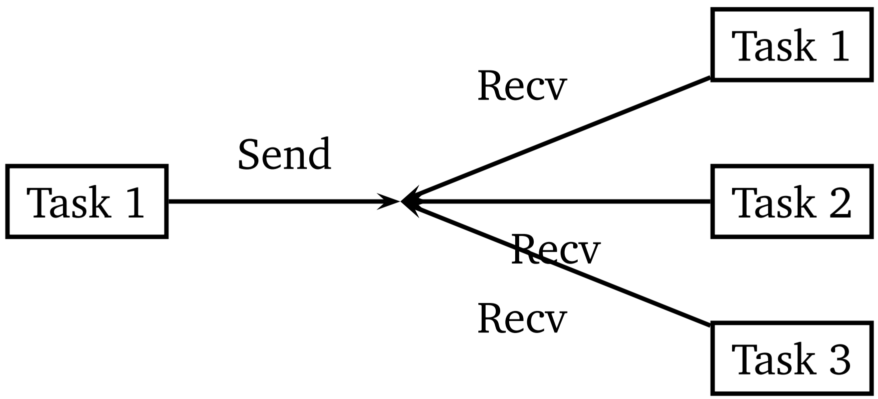
```
int x = 1;
void* bar(void* args) {
        pthread_mutex_lock(&mutex);
        x = x*2;
        pthread_mutex_unlock(&mutex);
}
void foo() {
        pthread_create(&thread, NULL, bar, NULL);
        pthread_mutex_lock(&mutex);
        x++;
        pthread_mutex_unlock(&mutex);
        printf("%d", x);
}
```

Output: 3 or 4

| | |
|---|---|
| x = 1 | x = 1 |
| bar: x = 1 * 2 = 2 | foo: x = 2 |
| foo: x = 3 | bar: x = 2*2 = 4 |

# The SHIM Model

- Stands for *Software Hardware Integration Medium*
- Race free, scheduling independent, concurrent model
- Blocking synchronous rendezvous communication



# The SHIM Language

An imperative language with familiar C/Java-like syntax

```
int32 gcd(int32 a, int32 b)
{
  while (a != b) {
    if (a > b)
      a -= b;
    else
      b -= a;
  }
  return a;
}
```

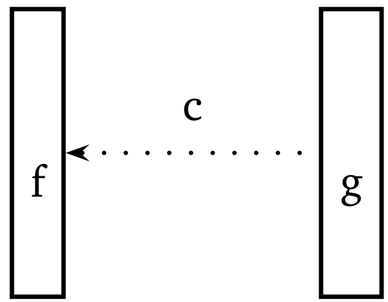
# Additional Constructs

| | |
|---|---|
| $stmt_1$ *par* $stmt_2$ | Run $stmt_1$ and $stmt_2$ concurrently |
| *send var* | Send on channel *var* |
| *recv var* | Receive on channel *var* |

# Communication

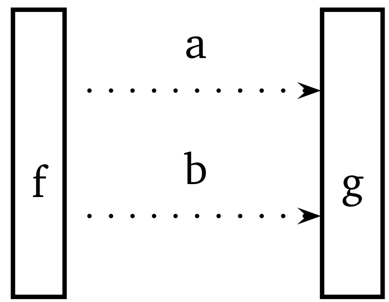
- Blocking: wait for all processes connected to *c*

```
void f(chan int a) { // a is a copy of c
  a = 3; // change local copy
  recv a; // receive (wait for g)
  // a now 5
}
void g(chan int &b) { // b is an alias of c
   b = 5; // sets c
   send b; // send (wait for f)
  // b now 5
}
void main() {
  chan int c = 0;
  f(c); par g(c);
  c = c * 2;
}
```



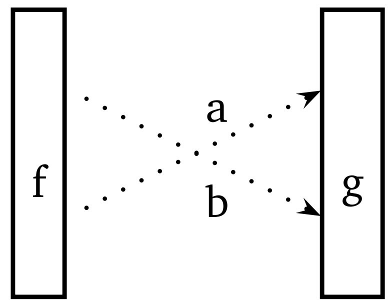
# Another Example

```
void main() {
 chan int a, b;
 {
     // Task 1
     a = 15, b = 10;
     send a;
     send b;
 } par {
     // Task 2
     int c;
     recv a;
     recv b;
     c = a + b;
  }
}
```



# The Problem

```
void main() {
 chan int a, b;
 {
     // Task 1
     a = 15, b = 10;
     send a;
     send b;
 } par {
     // Task 2
     int c;
     recv b;
     recv a;
     c = a + b;
  }
}
```

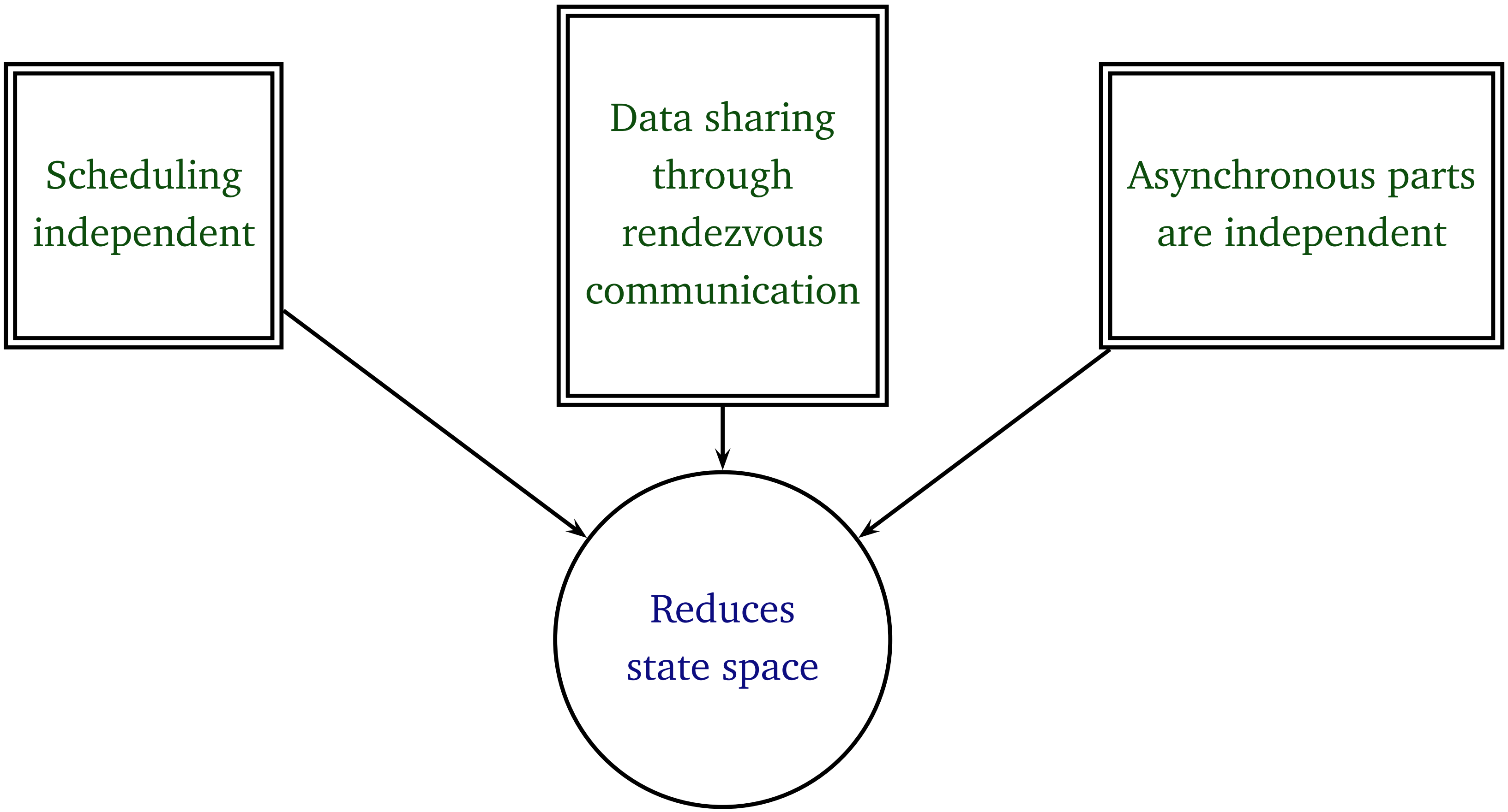


# The Deadlock Problem

- Why SHIM? No data races.
- Deadlocks in SHIM are deterministic (always reproducible).
- SHIM's philosophy: It prefers deadlocks to races. Can be detected at run-time.

Can we statically detect deadlocks in a program?

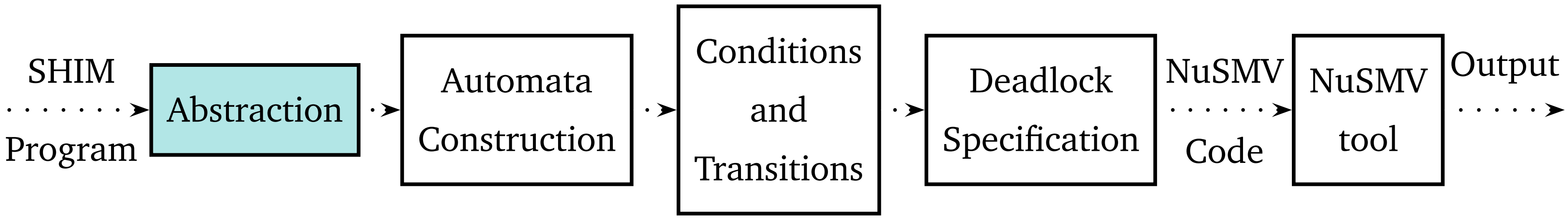
# SHIM design for static analysis



# Assumptions

- All functions are known at compile time.
- Recursion is statically bounded.
- Channel connections are known at static time.

# The Deadlock Detection Algorithm



# Abstraction

```
void main() {
 chan int a, b;
 {
     // Task 1
     a = 15, b = 10;
     send a;
     send b;
 } par {
     // Task 2
     int c;
     recv b;
     recv a;
     c = a + b;

  }
}
```

# Abstraction

```
void main() {
 chan int a, b;
 {
     // Task 1
     a = 15, b = 10;
     send a;
     send b;
 } par {
     // Task 2
     int c;
     recv b;
     recv a;
     c = a + b;

  }
}
```

⟹

```
void main() {

 {
     // Task 1
     wait a;
     wait b;
 } par {
     // Task 2

     wait b;
     wait a;

  }
}
```

# Abstraction

```
void main() {
  chan int a, b;
  {
      // Task 1
      a = 15, b = 10;
      send a;
      send b;
  } par {
      // Task 2
      int c;
      recv b;
      recv a;
      c = a + b;

   }
}
```

⇒

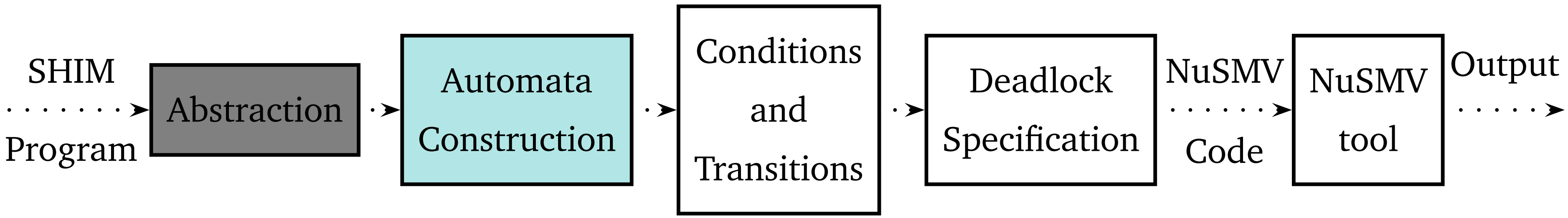
```
void main() {

  {
      // Task 1
      wait a;  (1)
      wait b;  (2)
  } par {  (1)
      // Task 2

      wait b;  (1)
      wait a;  (2)

   }
}
```

# The Deadlock Detection Algorithm

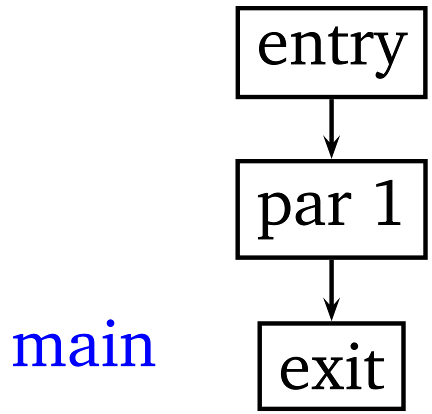


# Automata

```
void main() {
  {
      // Task 1
      wait a;  1
      wait b;  2
  } par {  1
      // Task 2
      wait b;  1
      wait a;  2
   }
}
```

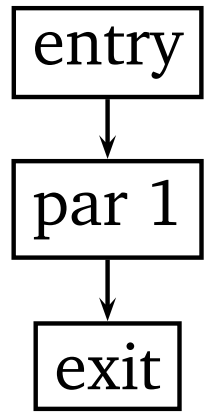
# Automata

```
void main() {
 {
    // Task 1
    wait a; 1
    wait b; 2
 } par { 1
    // Task 2
    wait b; 1
    wait a; 2
  }
}
```

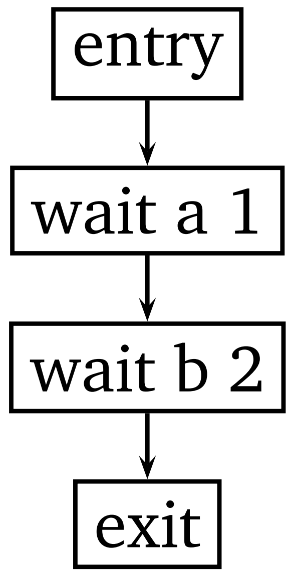


# Automata

```
void main() {
  {
      // Task 1
      wait a; (1)
      wait b; (2)
  } par { (1)
      // Task 2
      wait b; (1)
      wait a; (2)
    }
}
```



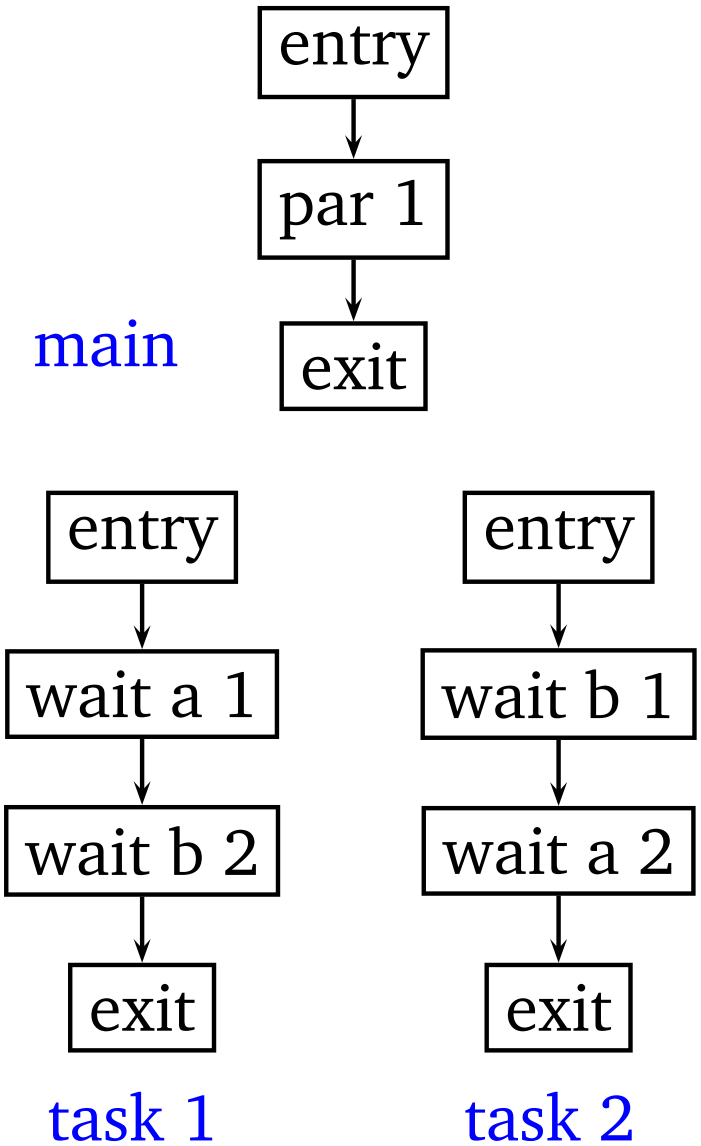

main




task 1

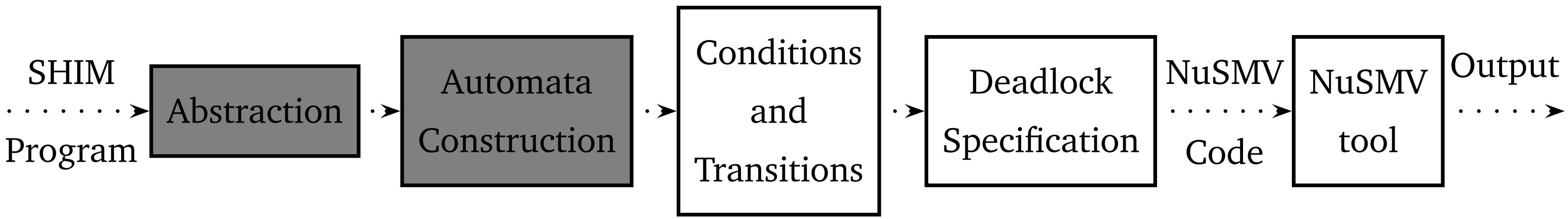
# Automata

```
void main() {
  {
      // Task 1
      wait a; (1)
      wait b; (2)
  } par { (1)
      // Task 2
      wait b; (1)
      wait a; (2)
   }
}
```

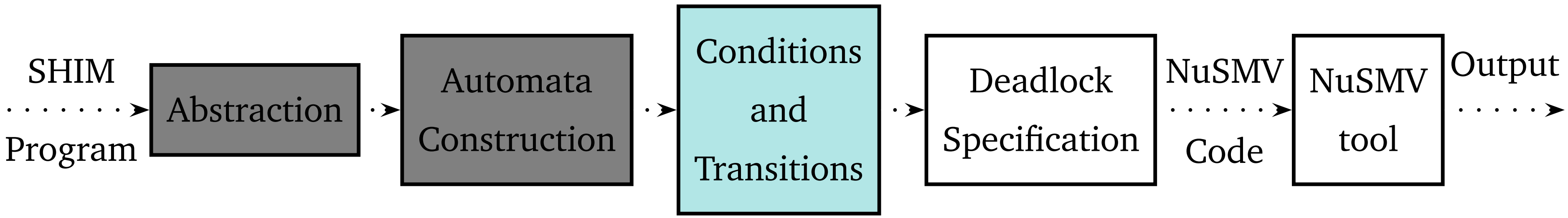


# NuSMV

- A BDD and SAT based model checker.
- Conditions for transitions expressed as Boolean functions.
- Specifications can be expressed in Temporal Logic.
- We translate SHIM to NuSMV.



# The Deadlock Detection Algorithm



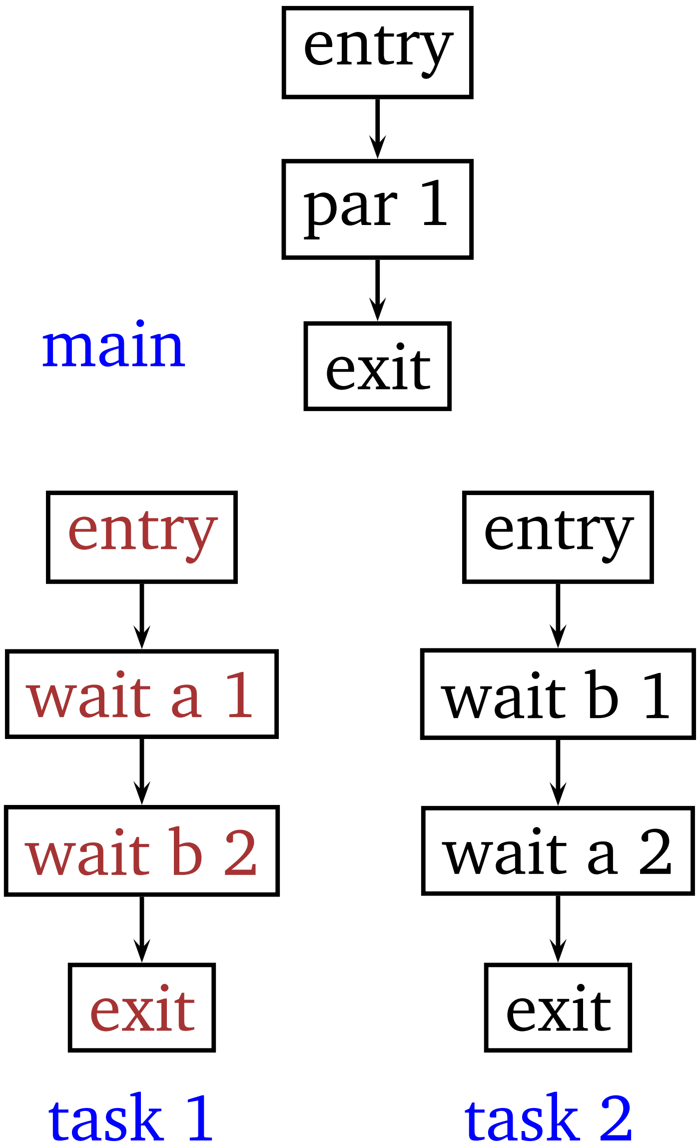
# Rendezvous Conditions

```
void main() {
  {
     // Task 1
     wait a;  (1)
     wait b;  (2)
  } par {  (1)
     // Task 2
     wait b;  (1)
     wait a;  (2)
  }
}
```

- $a$ is connected to main, task_1, task_2;

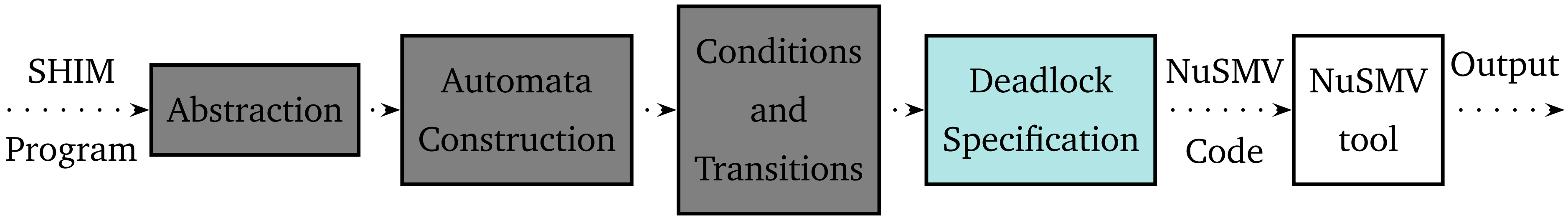
$$ready\_a := \quad main = par\_1 \;\&\; task\_1 = wait\_a\_1 \;\&\; task\_2 = wait\_a\_2$$

# Transitions




***next***(*task_1*) :=
 ***case***
  (*task_1* = *entry*) & (*main* = *par_1*): *wait_a_1*;
  (*task_1* = *wait_a_1*) & *ready_a*: *wait_b_2*;
  (*task_1* = *wait_b_2*) & *ready_b*: *exit*;
  (*task_1* = *exit*) & (*task_2* = *exit*): *entry* ;
  *1*: *task_1*;
 ***esac***;

# The Deadlock Detection Algorithm



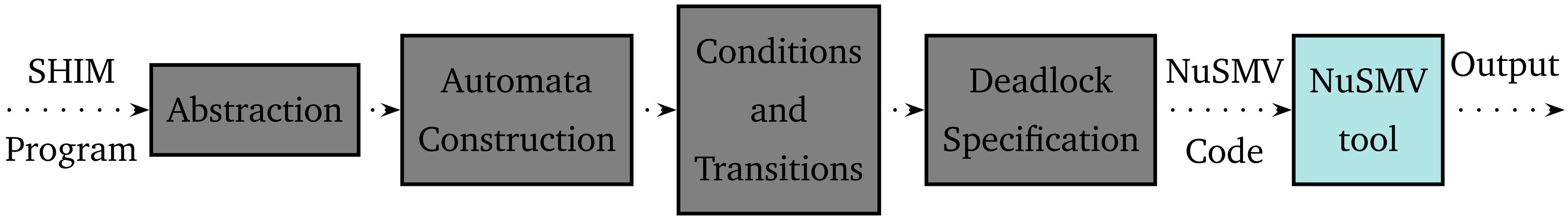
# Deadlock states

- Maintain a progress bit for each task.
- If no task makes any progress, then the program is in the deadlock state.

$$\textbf{\textit{SPEC AG}}((main != exit) -> \\ (progress\_main = yes \mid \\ progress\_task\_1 = yes \mid \\ progress\_task\_2 = yes))$$

- Checking for absence of deadlock.

# The Deadlock Detection Algorithm



# NuSMV output

```
void main() {
 chan int a, b;
 {
    // Task 1
    a = 15, b = 10;
    send a;
    send b;
 } par {
    // Task 2
    int c;
    recv b;
    recv a;
    c = a + b;

  }
}
```

```
-- specification AG (main != exit ->
     ( progress_main = yes)
     | progress_task_1 = yes)
     | progress_task_2 = yes) is false
 ..
 ..
-> State: 1.2 <-
  progress_main = no
  task_2 = wait_b_1
  task_1 = wait_a_1
-> Input: 1.3 <-
-> State: 1.3 <-
  progress_task_2 = no
  progress_task_1 = no
```

# Conditional Statements

```
{
    // Task 1
    if (n)
      send a;   1
    else
      recv b;   2
    recv b;   3
}
```

# Conditional Statements

```
{
    // Task 1
    if (n)
        send a;   (1)
    else
        recv b;   (2)
    recv b;       (3)
}
```

→

```
{
    // Task 1
    if (_)
        wait a;   (1)
    else
        wait b;   (2)
    wait b;       (3)
}
```

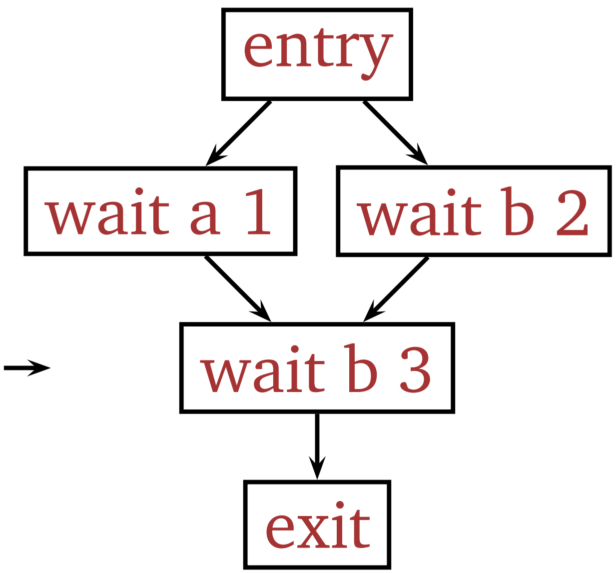
# Conditional Statements

```
{
    // Task 1
    if (n)
        send a;   ①
    else
        recv b;   ②
    recv b;   ③
}
```

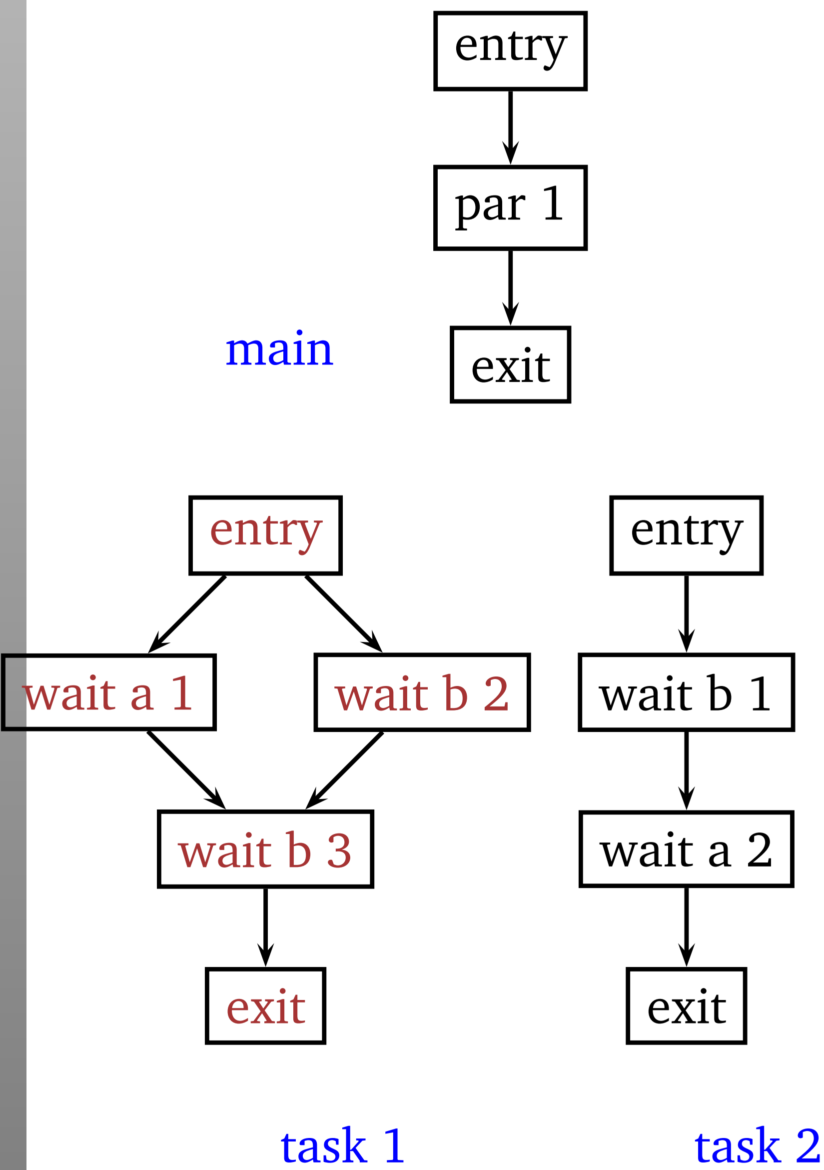
→

```
{
    // Task 1
    if (_)
        wait a;   ①
    else
        wait b;   ②
    wait b;   ③
}
```

→



# Conditional Statements




***next***(*task_1*) :=

  ***case***

    (*task_1* = *entry*) & (*main* = *par_1*): {*wait_a_1*, *wait_b_2*};

    (*task_1* = *wait_a_1*) & *ready_a*: *wait_b_3*;

    (*task_1* = *wait_b_2*) & *ready_b*: *wait_b_3*;

    ..

    ..

  ***esac***;

# Checking for deadlock

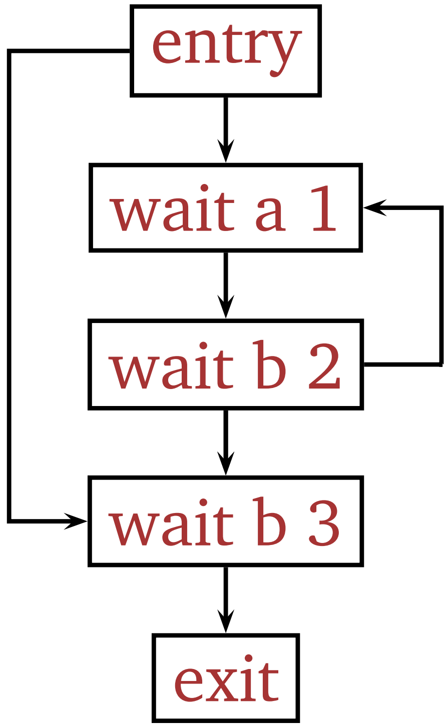
- Reports error if any path in the program deadlocks.

  $$\textbf{\textit{SPEC AG}}((main != exit) \; -> \; (\; progress\_main = yes \mid progress\_task\_1 = yes \mid progress\_task\_2 = yes \;))$$

  Reports possibility of deadlock.
- May generate false-positives.

# Loops

```
{
    // Task 1
    for(i = 0; i < n; i++ ) {
        send a; (1)
        recv b; (2)
    }
    recv b; (3)
}
```



# Results

| Example | Lines | Channels | Tasks | Result | Runtime | Memory |
|---|---|---|---|---|---|---|
| Source-Sink | 35 | 2 | 11 | No Deadlock | 0.2 s | 3.9 MB |
| Pipeline | 30 | 7 | 13 | No Deadlock | 0.1 | 2.0 |
| Prime Sieve | 35 | 51 | 45 | No Deadlock | 1.7 | 25.4 |
| Berkeley | 40 | 3 | 11 | No Deadlock | 0.2 | 7.2 |
| FIR Filter | 100 | 28 | 28 | No Deadlock | 0.4 | 13.4 |
| Bitonic Sort | 130 | 65 | 167 | No Deadlock | 8.5 | 63.8 |
| Framebuffer | 220 | 11 | 12 | No Deadlock | 1.7 | 11.6 |
| JPEG Decoder | 1020 | 7 | 15 | May Deadlock | 0.9 | 85.6 |
| JPEG Decoder Modified | 1025 | 7 | 15 | No Deadlock | 0.9 | 85.6 |

# Conclusions

- SHIM: A deterministic concurrent model
- We can statically detect deadlocks
  - Using synchronous methodologies to verify asynchronous systems.
- Future Work
  - Increase channel buffer size to increase performance and avoid deadlocks
  - Convince the world: SHIM's philosophy- Deadlocks are better than data races