Assertion Guided Abstraction: A Cooperative Optimization For Dynamic Partial Order Reduction

Markus Kusano Chao Wang

Virginia Tech

September 17, 2014

Assertion Guided Abstraction: A Cooperative Optimization For Dynamic Partial Order Reduction

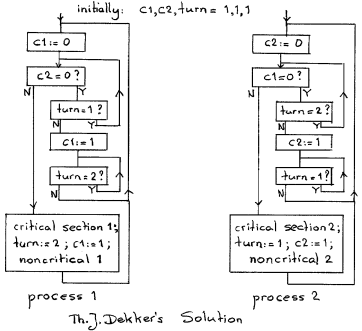
Markus Kusano Chao Wang

Virginia Tech

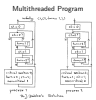
September 17, 2014

The Problem

Multithreaded Program



The Problem

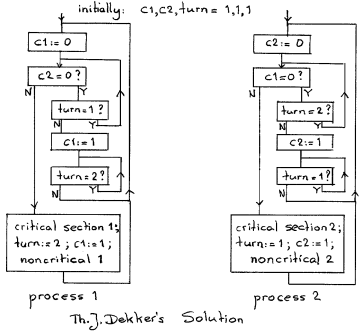


- There is a crisis in the development of multithreaded programs.
- First, on the design side, due to their astromical complexity, it is easy for the developer to insert Heisenbugs into the program.
- For example, data races and deadlocks are difficult to reproduce bugs which may rarely occur during traditional software testing. These bugs also often cause catastrophic system failure.
- The main cause of these bugs is that it is difficult for a human to reason about the complexity of a multithreaded program.
- As a result, it would be nice if we had tools to help developers write correct multithreaded programs.

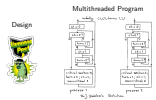
The Problem

Design

Multithreaded Program



The Problem

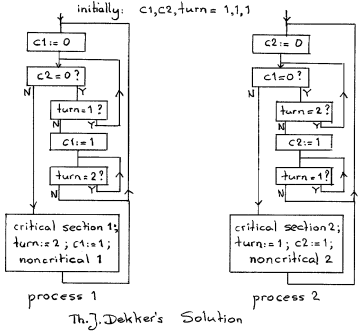


- There is a crisis in the development of multithreaded programs.
- First, on the design side, due to their astromical complexity, it is easy for the developer to insert Heisenbugs into the program.
- For example, data races and deadlocks are difficult to reproduce bugs which may rarely occur during traditional software testing. These bugs also often cause catastrophic system failure.
- The main cause of these bugs is that it is difficult for a human to reason about the complexity of a multithreaded program.
- As a result, it would be nice if we had tools to help developers write correct multithreaded programs.

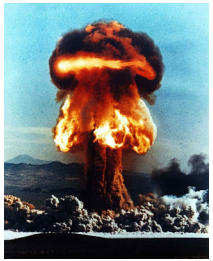
The Problem

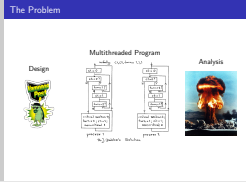
Design

Multithreaded Program



Analysis



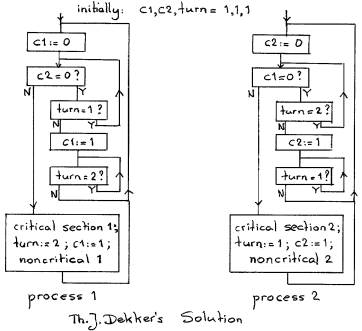


- However, concurrent program analysis suffers from the same problem of interleaving explosion. There are far too many interleavings for even a computer to reason about.
- This leaves us in a difficult situation: it is hard to write multithreaded programs and it is hard to analyze multithreaded programs
- This talk focuses on an optimization for multithreaded program analysis.

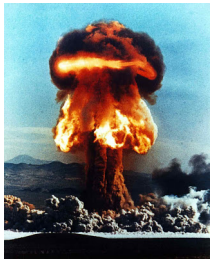
The Problem

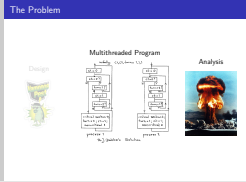
Design

Multithreaded Program



Analysis





- However, concurrent program analysis suffers from the same problem of interleaving explosion. There are far too many interleavings for even a computer to reason about.
- This leaves us in a difficult situation: it is hard to write multithreaded programs and it is hard to analyze multithreaded programs
- This talk focuses on an optimization for multithreaded program analysis.

The Problem: Non-deterministic Scheduler

- An operating system's scheduler is *non-deterministic*
- Sometimes bugs don't manifest for a long time
- How many schedules are there for a program with:

1. Two threads,
2. Each thread executing 100 instructions

The Problem: Non-deterministic Scheduler
- An operating system's scheduler is *non-deterministic*
- Sometimes bugs don't manifest for a long time
- How many schedules are there for a program with:

1. Two threads,
2. Each thread executing 100 instructions

- The root cause of the difficulty in both the design and analysis of multithreaded programs is the non-determinism in the thread scheduler.
- Depending on on the schedule of each thread the program may produce different results which may uncover hidden bugs.
- Consider the following: a simple program with two threads each executing only 100 instructions.
- Naively enumerating each thread schedule would require us to test just under 10^{60} thread schedules.

The Problem: Non-deterministic Scheduler

- An operating system's scheduler is *non-deterministic*
- Sometimes bugs don't manifest for a long time
- How many schedules are there for a program with:

1. Two threads,
2. Each thread executing 100 instructions

$$90{,}548{,}514{,}656{,}103{,}281{,}165{,}404{,}177{,}077{,}484{,}163{,}874{,}504{,}589{,}675{,}$$
$$413{,}336{,}841{,}320$$
$$\approx 10^{60}$$

The Problem: Non-deterministic Scheduler
- An operating system's scheduler is *non-deterministic*
- Sometimes bugs don't manifest for a long time
- How many schedules are there for a program with:

1. Two threads,
2. Each thread executing 100 instructions

$90{,}548{,}514{,}656{,}103{,}281{,}165{,}404{,}177{,}077{,}484{,}163{,}874{,}504{,}589{,}675{,}$ $413{,}336{,}841{,}320$ $\approx 10^{60}$

- The root cause of the difficulty in both the design and analysis of multithreaded programs is the non-determinism in the thread scheduler.
- Depending on on the schedule of each thread the program may produce different results which may uncover hidden bugs.
- Consider the following: a simple program with two threads each executing only 100 instructions.
- Naively enumerating each thread schedule would require us to test just under 10^{60} thread schedules.

The Problem: Program Analysis

Fact: Multithreaded bugs are a real pest
Solutions:

1. Dynamic analysis [God96, FG05, AAJS14]
2. Static analysis [CE82, CGP99, FK12]

The Problem: Program Analysis
Fact: Multithreaded bugs are a real pest
Solutions:
1. Dynamic analysis [God96, FG05, AAJS14]
2. Static analysis [CE82, CGP99, FK12]

- The fact is that finding, reproducing, and analyzing multithreaded bugs is a challenge.
- Currently, there are largely two techniques: static, or dynamic program analysis.
- Static analysis analyzes the source code of the program while dynamic analysis analyzes the runtime behavior of the program.
- Both of these techniques have their advantages and disadvantages.
- However, neither static nor dynamic analysis methods provide an ideal solution.

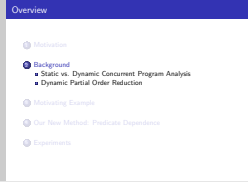
Contribution

- We present a static–dynamic concurrent program analysis
- Supplement static analysis with runtime information
- We prove our method is sound
- Experimentally, we show our method scales to verify previously intractable programs

Contribution
- We present a static-dynamic concurrent program analysis
- Supplement static analysis with runtime information
- We prove our method is sound
- Experimentally, we show our method scales to verify previously intractable programs

- This brings us to our contribution.
- We present a cooperative static and dynamic analysis method.
- We allow the static and dynamic analyses to communicate with each other.
- Our goal is to get the best of both worlds from both analyses.
- We prove our method is sound in that it will not miss any bugs
- And, we show using experiments that our method can verify some intractable programs

Overview



- Next I will go over a comparison of concurrent static and dynamic program analysis techniques.

Dynamic Concurrent Program Analysis

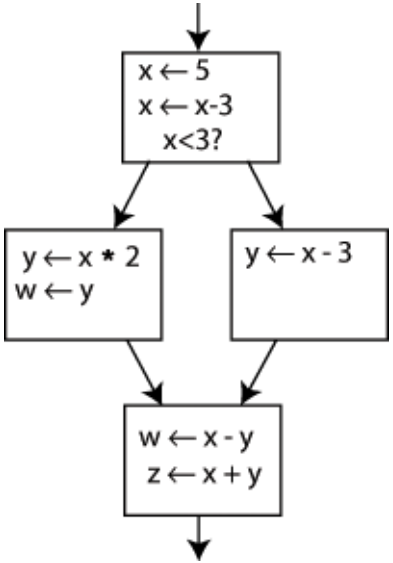
- Stateless model checking + partial order reduction addresses two issues:
  1. Too many states to hold in memory
  2. Often schedules are *equivalent*
- Dynamic analysis is *accurate*
- But, still doesn't scale
- Too many thread schedules

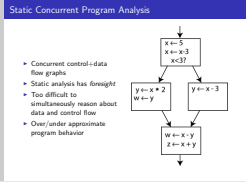
Dynamic Concurrent Program Analysis
- Stateless model checking + partial order reduction addresses two issues:
  1. Too many states to hold in memory
  2. Often schedules are equivalent
- Dynamic analysis is accurate
- But, still doesn't scale
- Too many thread schedules

- One current state-of-the-art dynamic method to verify concurrernt programs is stateless model checking coupled with partial order reduction.
- This method addresses two issues: first, often there are too many states in a concurrent program to store in memory, and second often many of the thread schedules are equivalent.
- Dynamic analysis in general has the benefit that it is accurate. Since we are actually running the program, we will never have any false positives.
- However, dynamic analysis still is not perfect. It still suffers from the interleaving explosion problem. There simply are too many thread schedules.

Static Concurrent Program Analysis

- Concurrent control+data flow graphs
- Static analysis has *foresight*
- Too difficult to simultaneously reason about data and control flow
- Over/under approximate program behavior





- On the other hand, a purely static method at verifying multithreaded programs is to use concurrent control and data flow graphs.
- Static analysis has the benefit of having foresight.
- Consider the control flow graph on the right: static analysis can simultaneously view all possible branches of the program. Dynamic analysis, on the other hand, can only view the executed branch.
- While the extra information is often useful, it also comes as a burden: it is often too difficult to simultaneously reason about all control and data flow information.
- As a result, static analyses often over- or under-approximate program behavior

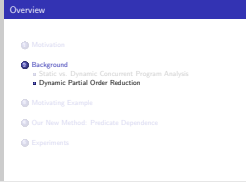
Current State of Concurrent Program Analysis

- Dynamic analysis doesn't scale
- Static analysis isn't accurate

Current State of Concurrent Program Analysis
Dynamic analysis doesn't scale
Static analysis isn't accurate

- This leaves us at the current and sad situation for concurrent program analysis: dynamic analysis doesn't scale and static analysis isn't accurate.
- Our contribution is to combine the two to get the best of both worlds.

Overview

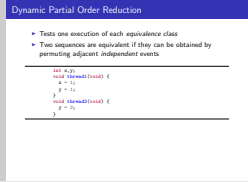


- Next, I will provide a brief background to Dynamic Partial Order Reduction.

Dynamic Partial Order Reduction

- Tests one execution of each *equivalence class*
- Two sequences are equivalent if they can be obtained by permuting adjacent *independent* events

```
int x,y;
void thread1(void) {
  x = 1;
  y = 1;
}
void thread2(void) {
  y = 2;
}
```

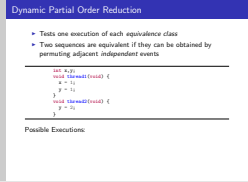
- At the center of dynamic partial order reduction is the notion of dependence between events in the program.
- Based on the definition of dependence, different sequences of events can be grouped into equivalance classes
- After grouping the events into equivalance classes, DPOR simply tests one representative sequence from each equivalance class.
- Consider the following program. There are three possible thread schedules
- First: thread one executes until completion followed by thread two
- Second: Thread one exeuctes one statement, followed by thread two, and then thread one executes
- And, finally: thread two executes first followed by thread one
- Dynamic Partial Order Reduction tries to answer the following question: Are any of these sequences redundant?

Dynamic Partial Order Reduction

- Tests one execution of each *equivalence class*
- Two sequences are equivalent if they can be obtained by permuting adjacent *independent* events

```
int x,y;
void thread1(void) {
  x = 1;
  y = 1;
}
void thread2(void) {
  y = 2;
}
```

Possible Executions:



- At the center of dynamic partial order reduction is the notion of dependence between events in the program.
- Based on the definition of dependence, different sequences of events can be grouped into equivalance classes
- After grouping the events into equivalance classes, DPOR simply tests one representative sequence from each equivalance class.
- Consider the following program. There are three possible thread schedules
- First: thread one executes until completion followed by thread two
- Second: Thread one exeuctes one statement, followed by thread two, and then thread one executes
- And, finally: thread two executes first followed by thread one
- Dynamic Partial Order Reduction tries to answer the following question: Are any of these sequences redundant?

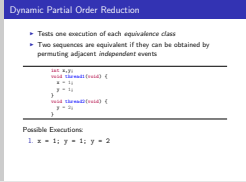
Dynamic Partial Order Reduction

- Tests one execution of each *equivalence class*
- Two sequences are equivalent if they can be obtained by permuting adjacent *independent* events

```
int x,y;
void thread1(void) {
  x = 1;
  y = 1;
}
void thread2(void) {
  y = 2;
}
```

Possible Executions:

1. `x = 1; y = 1; y = 2`



- At the center of dynamic partial order reduction is the notion of dependence between events in the program.
- Based on the definition of dependence, different sequences of events can be grouped into equivalance classes
- After grouping the events into equivalance classes, DPOR simply tests one representative sequence from each equivalance class.
- Consider the following program. There are three possible thread schedules
- First: thread one executes until completion followed by thread two
- Second: Thread one exeuctes one statement, followed by thread two, and then thread one executes
- And, finally: thread two executes first followed by thread one
- Dynamic Partial Order Reduction tries to answer the following question: Are any of these sequences redundant?

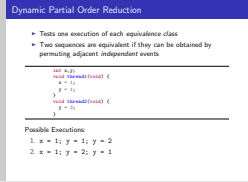
Dynamic Partial Order Reduction

- Tests one execution of each *equivalence class*
- Two sequences are equivalent if they can be obtained by permuting adjacent *independent* events

```
int x,y;
void thread1(void) {
  x = 1;
  y = 1;
}
void thread2(void) {
  y = 2;
}
```

Possible Executions:

1. `x = 1; y = 1; y = 2`
2. `x = 1; y = 2; y = 1`



- At the center of dynamic partial order reduction is the notion of dependence between events in the program.
- Based on the definition of dependence, different sequences of events can be grouped into equivalance classes
- After grouping the events into equivalance classes, DPOR simply tests one representative sequence from each equivalance class.
- Consider the following program. There are three possible thread schedules
- First: thread one executes until completion followed by thread two
- Second: Thread one exeuctes one statement, followed by thread two, and then thread one executes
- And, finally: thread two executes first followed by thread one
- Dynamic Partial Order Reduction tries to answer the following question: Are any of these sequences redundant?

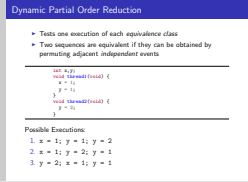
Dynamic Partial Order Reduction

- Tests one execution of each *equivalence class*
- Two sequences are equivalent if they can be obtained by permuting adjacent *independent* events

```
int x,y;
void thread1(void) {
  x = 1;
  y = 1;
}
void thread2(void) {
  y = 2;
}
```

Possible Executions:

1. `x = 1; y = 1; y = 2`
2. `x = 1; y = 2; y = 1`
3. `y = 2; x = 1; y = 1`



- At the center of dynamic partial order reduction is the notion of dependence between events in the program.
- Based on the definition of dependence, different sequences of events can be grouped into equivalance classes
- After grouping the events into equivalance classes, DPOR simply tests one representative sequence from each equivalance class.
- Consider the following program. There are three possible thread schedules
- First: thread one executes until completion followed by thread two
- Second: Thread one exeuctes one statement, followed by thread two, and then thread one executes
- And, finally: thread two executes first followed by thread one
- Dynamic Partial Order Reduction tries to answer the following question: Are any of these sequences redundant?

Conflict Dependence

Conflict Dependence: Statements are dependent if:

1. Accessing the same memory location,
2. different threads, and
3. at least one is a write.

1. `x = 1; y = 1; y = 2`
2. `x = 1; y = 2; y = 1`
3. `y = 2; x = 1; y = 1`

Conflict Dependence
Conflict Dependence: Statements are dependent if:
1. Accessing the same memory location,
2. different threads, and
3. at least one is a write.
1. x = 1; y = 1; y = 2
2. x = 1; y = 2; y = 1
3. y = 2; x = 1; y = 1

- The simplest, and often used, definition of dependence is conflict dependence.
- Conflict dependence considers statements to be dependent if they are accessing the same memory location, from two different threads, and atleast one is a write.
- If we examine the same set of executions using conflict dependence we can see that two are in the same equivalance class
- The first two events in sequences two and three are independent as defined by conflict dependence.
- They are from two different threads, accessing different locations in memory.
- We can see this reflected in the final states: for the last two sequences the final state of the program is the same.
- Partial order methods make use of this concept: out of the last two sequences, only one needs to be tested

Conflict Dependence

Conflict Dependence: Statements are dependent if:

1. Accessing the same memory location,
2. different threads, and
3. at least one is a write.

1. `x = 1; y = 1; y = 2`
2. `x = 1; y = 2; y = 1`
3. `y = 2; x = 1; y = 1`

Conflict Dependence
Conflict Dependence: Statements are dependent if:
1. Accessing the same memory location,
2. different threads, and
3. at least one is a write.
1. x = 1; y = 1; y = 2
2. x = 1; y = 2; y = 1
3. y = 2; x = 1; y = 1

- The simplest, and often used, definition of dependence is conflict dependence.
- Conflict dependence considers statements to be dependent if they are accessing the same memory location, from two different threads, and atleast one is a write.
- If we examine the same set of executions using conflict dependence we can see that two are in the same equivalance class
- The first two events in sequences two and three are independent as defined by conflict dependence.
- They are from two different threads, accessing different locations in memory.
- We can see this reflected in the final states: for the last two sequences the final state of the program is the same.
- Partial order methods make use of this concept: out of the last two sequences, only one needs to be tested

Conflict Dependence

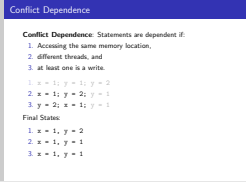
Conflict Dependence: Statements are dependent if:

1. Accessing the same memory location,
2. different threads, and
3. at least one is a write.

1. `x = 1; y = 1; y = 2`
2. `x = 1; y = 2; y = 1`
3. `y = 2; x = 1; y = 1`

Final States:

1. `x = 1, y = 2`
2. `x = 1, y = 1`
3. `x = 1, y = 1`



- The simplest, and often used, definition of dependence is conflict dependence.
- Conflict dependence considers statements to be dependent if they are accessing the same memory location, from two different threads, and atleast one is a write.
- If we examine the same set of executions using conflict dependence we can see that two are in the same equivalance class
- The first two events in sequences two and three are independent as defined by conflict dependence.
- They are from two different threads, accessing different locations in memory.
- We can see this reflected in the final states: for the last two sequences the final state of the program is the same.
- Partial order methods make use of this concept: out of the last two sequences, only one needs to be tested

Background: Where does conflict dependence fail?

```
int x, y;
void thread1(void) {
  x = 10;
  // ...
}
void thread2(void) {
  x = 10;
  // ...
}
```

- **View Dependence**: Only reorder transitions if they change the program state

Background: Where does conflict dependence fail?
int x, y;
void thread1(void) {
x = 10;
// ...
}
void thread2(void) {
x = 10;
// ...
}
- View Dependence: Only reorder transitions if they change the program state

- But, conflict dependence is not perfect.
- Researchers improved on the idea by defining view dependence.
- View dependence considers two statements to be dependent if their order can change program state.
- Consider the following program: both threads set the shared variable x to 10.
- These two statements are conflict dependent since they are from two different threads, accessing the same memory location, and they are both writes.
- However, regardless of their order, the state of the program remains the same.
- As a result, using view dependence results in fewer thread schedules required to be tested.
- This is the starting point for our contribution. We wondered if we could come up with an even more precise definition of dependence.
- A more precise the dependence defintiion results in fewer transitions to test, resulting in faster runtime.

Background: Where does conflict dependence fail?

```
int x, y;
void thread1(void) {
  x = 10;
  // ...
}
void thread2(void) {
  x = 10;
  // ...
}
```

- **View Dependence**: Only reorder transitions if they change the program state

Background: Where does conflict dependence fail?
int x, y;
void thread1(void) {
x = 10;
// ...
}
void thread2(void) {
x = 10;
// ...
}
- View Dependence: Only reorder transitions if they change the program state

- But, conflict dependence is not perfect.
- Researchers improved on the idea by defining view dependence.
- View dependence considers two statements to be dependent if their order can change program state.
- Consider the following program: both threads set the shared variable x to 10.
- These two statements are conflict dependent since they are from two different threads, accessing the same memory location, and they are both writes.
- However, regardless of their order, the state of the program remains the same.
- As a result, using view dependence results in fewer thread schedules required to be tested.
- This is the starting point for our contribution. We wondered if we could come up with an even more precise definition of dependence.
- A more precise the dependence defintiion results in fewer transitions to test, resulting in faster runtime.

Background: Where does conflict dependence fail?

```
int x, y;
void thread1(void) {
  x = 10;
  // ...
}
void thread2(void) {
  x = 10;
  // ...
}
```

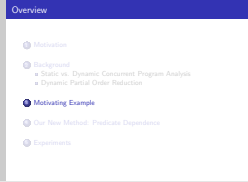
- **View Dependence**: Only reorder transitions if they change the program state

Can we do better?

Background: Where does conflict dependence fail?
int x, y;
void thread1(void) {
x = 10;
// ...
}
void thread2(void) {
x = 10;
// ...
}
View Dependence: Only reorder transitions if they change the program state
Can we do better?

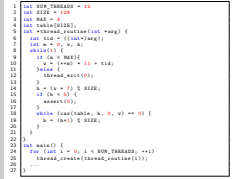
- But, conflict dependence is not perfect.
- Researchers improved on the idea by defining view dependence.
- View dependence considers two statements to be dependent if their order can change program state.
- Consider the following program: both threads set the shared variable x to 10.
- These two statements are conflict dependent since they are from two different threads, accessing the same memory location, and they are both writes.
- However, regardless of their order, the state of the program remains the same.
- As a result, using view dependence results in fewer thread schedules required to be tested.
- This is the starting point for our contribution. We wondered if we could come up with an even more precise definition of dependence.
- A more precise the dependence defintiion results in fewer transitions to test, resulting in faster runtime.

Overview



- Next, I will go over a motivating example for our work

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```

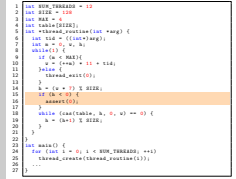


- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```

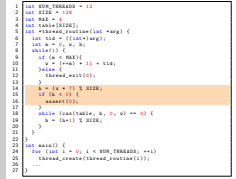

- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



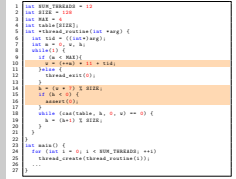
- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



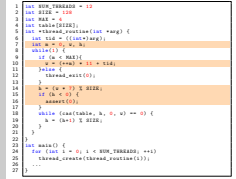
- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



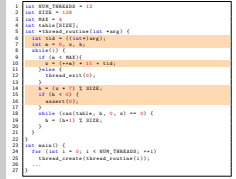
- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



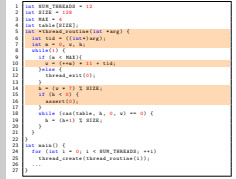
- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



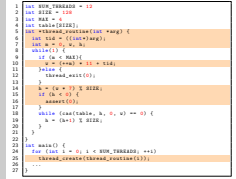
- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



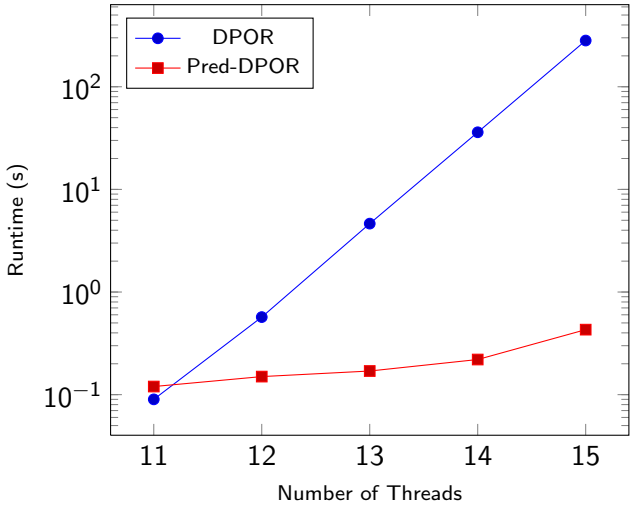
- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

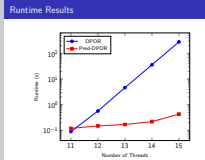
```
1  int NUM_THREADS = 12
2  int SIZE = 128
3  int MAX = 4
4  int table[SIZE];
5  int *thread_routine(int *arg) {
6    int tid = ((int*)arg);
7    int m = 0, w, h;
8    while(1) {
9      if (m < MAX){
10       w = (++m) * 11 + tid;
11     }else {
12       thread_exit(0);
13     }
14     h = (w * 7) % SIZE;
15     if (h < 0) {
16       assert(0);
17     }
18     while (cas(table, h, 0, w) == 0) {
19       h = (h+1) % SIZE;
20     }
21   }
22 }
23 int main() {
24   for (int i = 0; i < NUM_THREADS; ++i)
25     thread_create(thread_routine(i));
26   ...
27 }
```



- To understand the intution behind our method, consider the following program from the International Software Verification Competition.
- Multiple threads are concurrently accessing a shared hash table
- We would like to verify that none of the threads ever access a index of the hash table which is out-of-bounds.
- First, notice that the assertion will fail based off the value of h.
- The value of h depends on the value of w.
- The value of w depends on the value of m and tid
- m is a thread local variable
- tid comes from the arguments passed to the thread
- And the argument is passed to the thread by main.
- Since main sets the arguments before the thread is created, there can be no interference between threads amongst all of these varibles.
- As a result, for the purpose of checking this assertion, we only need to test one thread schedule rather than thousands.

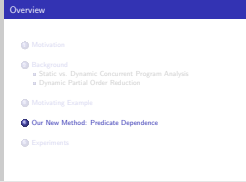
Runtime Results





- The following graph shows the runtime results for our new method compared to traditional dynamic partial order reduction.
- As the number of threads grows, the runtime of DPOR scales exponentially.
- After 15 threads are in the system, the runtime of DPOR exceeds two hours even for this simple program.
- Our new method, in comparison, is several orders of magnitude faster.

Overview

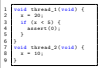


- Next, I will present our new definition of dependence.

Predicate Dependence

```
1  void thread_1(void) {
2    x = 20;
3    if (x < 5) {
4      assert(0);
5    }
6  }
7  void thread_2(void) {
8    x = 10;
9  }
```

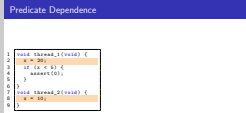

Predicate Dependence



- Consider the following program.
- By all previous definitions of dependence, the following transitions are dependent.
- There are two thread schedules in this program: thread one going first, and thread two going first.
- Notice that, regardless of the order of thread one and thread two, the assertion will never be violated since the value of x is always greater than 5.
- As a result, the order of the two writes to x is actually immaterial to checking the validity of the assertion.
- This is the crux of our contribution: we only reorder transitions which could affect the validity of an assertion.

Predicate Dependence

```
1  void thread_1(void) {
2    x = 20;
3    if (x < 5) {
4      assert(0);
5    }
6  }
7  void thread_2(void) {
8    x = 10;
9  }
```

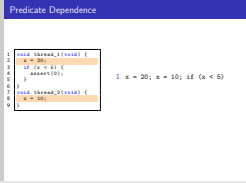



- Consider the following program.
- By all previous definitions of dependence, the following transitions are dependent.
- There are two thread schedules in this program: thread one going first, and thread two going first.
- Notice that, regardless of the order of thread one and thread two, the assertion will never be violated since the value of x is always greater than 5.
- As a result, the order of the two writes to x is actually immaterial to checking the validity of the assertion.
- This is the crux of our contribution: we only reorder transitions which could affect the validity of an assertion.

Predicate Dependence

```
1  void thread_1(void) {
2    x = 20;
3    if (x < 5) {
4      assert(0);
5    }
6  }
7  void thread_2(void) {
8    x = 10;
9  }
```

1. `x = 20; x = 10; if (x < 5)`



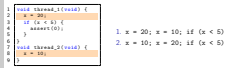
- Consider the following program.
- By all previous definitions of dependence, the following transitions are dependent.
- There are two thread schedules in this program: thread one going first, and thread two going first.
- Notice that, regardless of the order of thread one and thread two, the assertion will never be violated since the value of x is always greater than 5.
- As a result, the order of the two writes to x is actually immaterial to checking the validity of the assertion.
- This is the crux of our contribution: we only reorder transitions which could affect the validity of an assertion.

Predicate Dependence

```
1  void thread_1(void) {
2    x = 20;
3    if (x < 5) {
4      assert(0);
5    }
6  }
7  void thread_2(void) {
8    x = 10;
9  }
```

1. `x = 20; x = 10; if (x < 5)`
2. `x = 10; x = 20; if (x < 5)`

Predicate Dependence



- Consider the following program.
- By all previous definitions of dependence, the following transitions are dependent.
- There are two thread schedules in this program: thread one going first, and thread two going first.
- Notice that, regardless of the order of thread one and thread two, the assertion will never be violated since the value of x is always greater than 5.
- As a result, the order of the two writes to x is actually immaterial to checking the validity of the assertion.
- This is the crux of our contribution: we only reorder transitions which could affect the validity of an assertion.

Predicate Dependence

```
1  void thread_1(void) {
2    x = 20;
3    if (x < 5) {
4      assert(0);
5    }
6  }
7  void thread_2(void) {
8    x = 10;
9  }
```

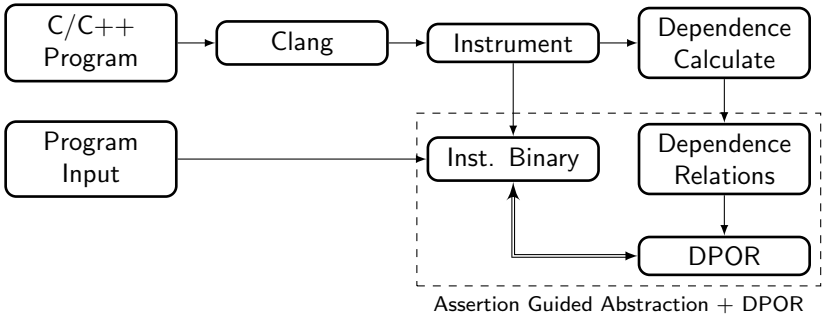
1. `x = 20; x = 10; if (x < 5)`
2. `x = 10; x = 20; if (x < 5)`

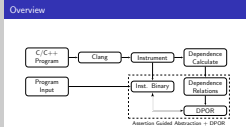
- Only reorder transitions if they could affect the validity of an assertion

Predicate Dependence
1 void thread_1(void) {
2 x = 20;
3 if (x < 5) {
4 assert(0);
5 }
6 }
7 void thread_2(void) {
8 x = 10;
9 }
1. x = 20; x = 10; if (x < 5)
2. x = 10; x = 20; if (x < 5)
Only reorder transitions if they could affect the validity of an assertion

- Consider the following program.
- By all previous definitions of dependence, the following transitions are dependent.
- There are two thread schedules in this program: thread one going first, and thread two going first.
- Notice that, regardless of the order of thread one and thread two, the assertion will never be violated since the value of x is always greater than 5.
- As a result, the order of the two writes to x is actually immaterial to checking the validity of the assertion.
- This is the crux of our contribution: we only reorder transitions which could affect the validity of an assertion.

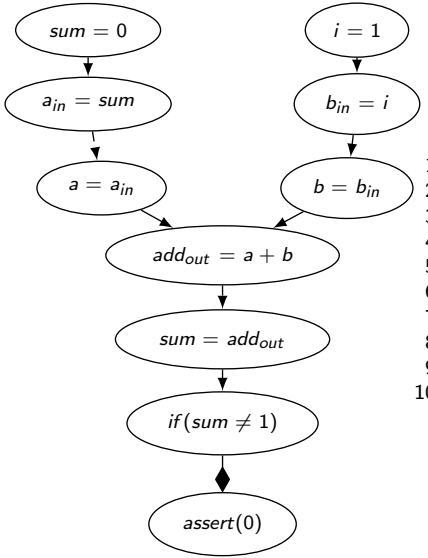
Overview



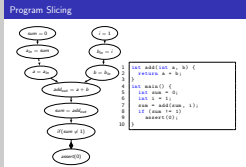


- The following is a high level overview of our method.
- First, we take a multithreaded C/C++ program and compile it using the LLVM frontend clang.
- Next we instrument the code for dynamic analysis.
- After that, we statically analyze the program to calculate the dependencies between statements.
- Finally, we use the dependency information and the program input to dynamically analyze the program.

Program Slicing

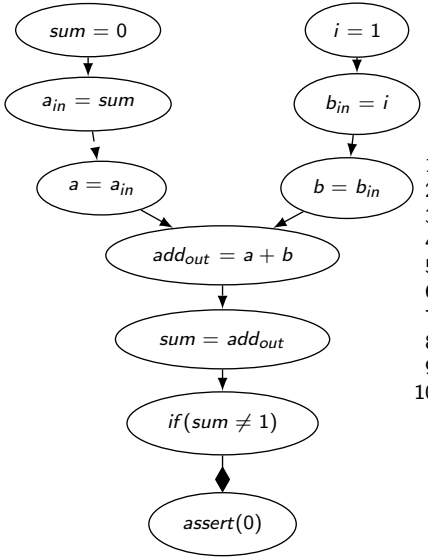



```
1  int add(int a, b) {
2    return a + b;
3  }
4  int main() {
5    int sum = 0;
6    int i = 1;
7    sum = add(sum, i);
8    if (sum != 1)
9      assert(0);
10 }
```

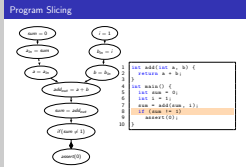



- We use slicing to calculate the dependencies of each assertion in the program.
- Program slicing works by considering both the control and data dependencies of a statement in the program.
- Consider the following example where we slice on the assert statement
- The only control dependency of the assertion is the check if sum is equal to one.
- The first data dependency is on the return of the add function
- The add function depends on its two inputs.
- In this case, both inputs come from the variables sum and i in main.
- Once we have calcuated the control and data dependencies of a statement, as shown in the graph on the left, the slice of a statment is simply a backwards traversal on the statement.
- In this case, the slice contains the entire program

Program Slicing

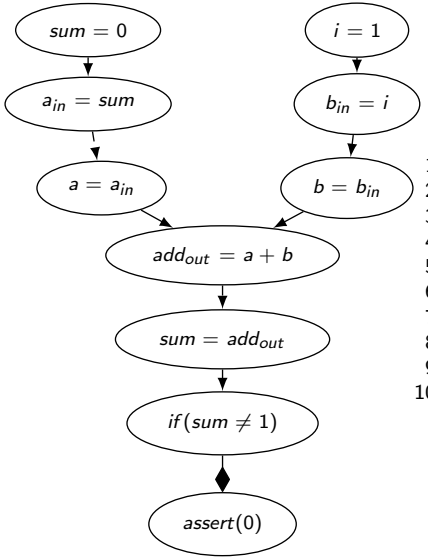



```
1  int add(int a, b) {
2    return a + b;
3  }
4  int main() {
5    int sum = 0;
6    int i = 1;
7    sum = add(sum, i);
8    if (sum != 1)
9      assert(0);
10 }
```

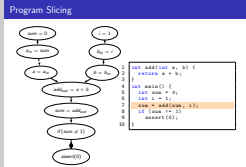



- We use slicing to calculate the dependencies of each assertion in the program.
- Program slicing works by considering both the control and data dependencies of a statement in the program.
- Consider the following example where we slice on the assert statement
- The only control dependency of the assertion is the check if sum is equal to one.
- The first data dependency is on the return of the add function
- The add function depends on its two inputs.
- In this case, both inputs come from the variables sum and i in main.
- Once we have calcuated the control and data dependencies of a statement, as shown in the graph on the left, the slice of a statment is simply a backwards traversal on the statement.
- In this case, the slice contains the entire program

Program Slicing

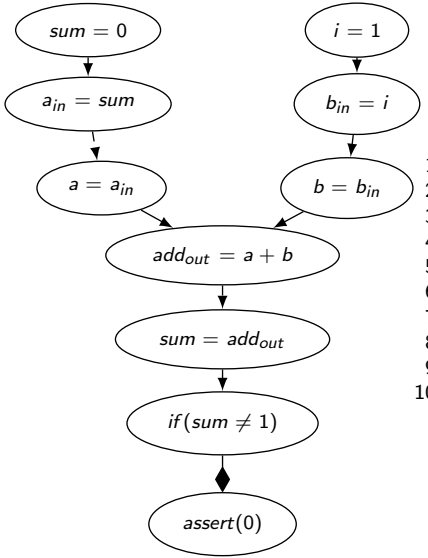



```
1  int add(int a, b) {
2    return a + b;
3  }
4  int main() {
5    int sum = 0;
6    int i = 1;
7    sum = add(sum, i);
8    if (sum != 1)
9      assert(0);
10 }
```

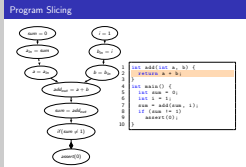



- We use slicing to calculate the dependencies of each assertion in the program.
- Program slicing works by considering both the control and data dependencies of a statement in the program.
- Consider the following example where we slice on the assert statement
- The only control dependency of the assertion is the check if sum is equal to one.
- The first data dependency is on the return of the add function
- The add function depends on its two inputs.
- In this case, both inputs come from the variables sum and i in main.
- Once we have calcuated the control and data dependencies of a statement, as shown in the graph on the left, the slice of a statment is simply a backwards traversal on the statement.
- In this case, the slice contains the entire program

Program Slicing

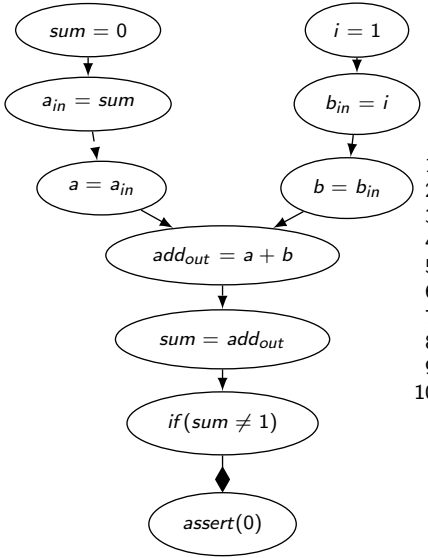



```
1  int add(int a, b) {
2    return a + b;
3  }
4  int main() {
5    int sum = 0;
6    int i = 1;
7    sum = add(sum, i);
8    if (sum != 1)
9      assert(0);
10 }
```

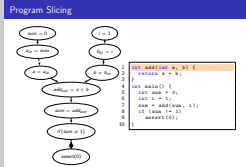



- We use slicing to calculate the dependencies of each assertion in the program.
- Program slicing works by considering both the control and data dependencies of a statement in the program.
- Consider the following example where we slice on the assert statement
- The only control dependency of the assertion is the check if sum is equal to one.
- The first data dependency is on the return of the add function
- The add function depends on its two inputs.
- In this case, both inputs come from the variables sum and i in main.
- Once we have calcuated the control and data dependencies of a statement, as shown in the graph on the left, the slice of a statment is simply a backwards traversal on the statement.
- In this case, the slice contains the entire program

Program Slicing

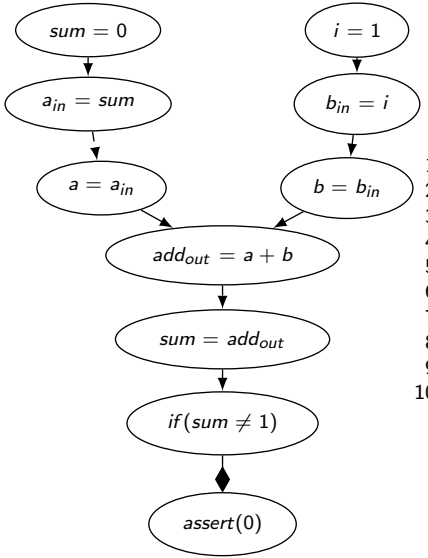



```
1  int add(int a, b) {
2    return a + b;
3  }
4  int main() {
5    int sum = 0;
6    int i = 1;
7    sum = add(sum, i);
8    if (sum != 1)
9      assert(0);
10 }
```

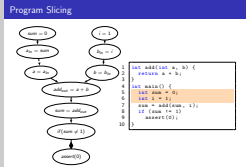



- We use slicing to calculate the dependencies of each assertion in the program.
- Program slicing works by considering both the control and data dependencies of a statement in the program.
- Consider the following example where we slice on the assert statement
- The only control dependency of the assertion is the check if sum is equal to one.
- The first data dependency is on the return of the add function
- The add function depends on its two inputs.
- In this case, both inputs come from the variables sum and i in main.
- Once we have calcuated the control and data dependencies of a statement, as shown in the graph on the left, the slice of a statment is simply a backwards traversal on the statement.
- In this case, the slice contains the entire program

Program Slicing




```
1  int add(int a, b) {
2    return a + b;
3  }
4  int main() {
5    int sum = 0;
6    int i = 1;
7    sum = add(sum, i);
8    if (sum != 1)
9      assert(0);
10 }
```

- We use slicing to calculate the dependencies of each assertion in the program.
- Program slicing works by considering both the control and data dependencies of a statement in the program.
- Consider the following example where we slice on the assert statement
- The only control dependency of the assertion is the check if sum is equal to one.
- The first data dependency is on the return of the add function
- The add function depends on its two inputs.
- In this case, both inputs come from the variables sum and i in main.
- Once we have calcuated the control and data dependencies of a statement, as shown in the graph on the left, the slice of a statment is simply a backwards traversal on the statement.
- In this case, the slice contains the entire program

Aliasing

Aliasing between program statements adds another level of complexity

```
1  int array[12];
2  void thread1() {
3    for (int i = 0; i < 6; ++i) {
4      array[i] = array[i] + 1;
5    }
6  }
7  int main(int argc, char *argv[]) {
8    int idx = atoi(argv[1]) % 12;
9    thread_create(thread1);
10   array[idx] = array[idx] + 1;
11 }
```

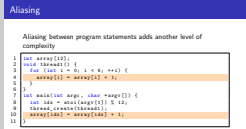

Aliasing
Aliasing between program statements adds another level of complexity

- For simple programs, the previous static slicing method works very well.
- However, for real world programs aliasing between statements creates another complexity.
- Consider the following program where main reads the user's input to determine the index of a shared array.
- Main then creates a thread which accesses the first 6 elements in the array.
- Finally, main modifies the array at the user specified index.
- Depending on the user's input, the statements on lines 4 and 10 may or may not access the same location in memory.
- As a result, a conservative static analysis will have to assume that the statements always access the same location in memory.
- Our new method statically calculates the slice while ignoring aliasing and then at runtime calculates the alias information.

Aliasing

Aliasing between program statements adds another level of complexity

```
1  int array[12];
2  void thread1() {
3    for (int i = 0; i < 6; ++i) {
4      array[i] = array[i] + 1;
5    }
6  }
7  int main(int argc, char *argv[]) {
8    int idx = atoi(argv[1]) % 12;
9    thread_create(thread1);
10   array[idx] = array[idx] + 1;
11 }
```

- For simple programs, the previous static slicing method works very well.
- However, for real world programs aliasing between statements creates another complexity.
- Consider the following program where main reads the user's input to determine the index of a shared array.
- Main then creates a thread which accesses the first 6 elements in the array.
- Finally, main modifies the array at the user specified index.
- Depending on the user's input, the statements on lines 4 and 10 may or may not access the same location in memory.
- As a result, a conservative static analysis will have to assume that the statements always access the same location in memory.
- Our new method statically calculates the slice while ignoring aliasing and then at runtime calculates the alias information.

Aliasing

Aliasing between program statements adds another level of complexity

```
1  int array[12];
2  void thread1() {
3    for (int i = 0; i < 6; ++i) {
4      array[i] = array[i] + 1;
5    }
6  }
7  int main(int argc, char *argv[]) {
8    int idx = atoi(argv[1]) % 12;
9    thread_create(thread1);
10   array[idx] = array[idx] + 1;
11 }
```

- Calculate slice while **ignoring** aliasing
- Calculate aliasing information at **runtime**

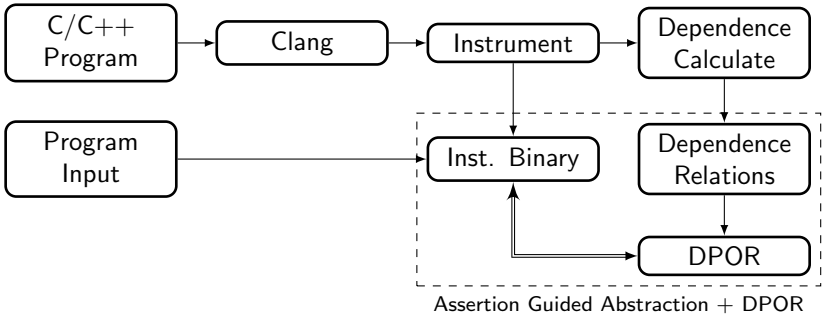
Aliasing

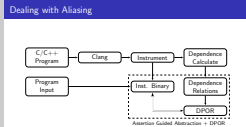
Aliasing between program statements adds another level of complexity

Calculate slice while ignoring aliasing
Calculate aliasing information at runtime

- For simple programs, the previous static slicing method works very well.
- However, for real world programs aliasing between statements creates another complexity.
- Consider the following program where main reads the user's input to determine the index of a shared array.
- Main then creates a thread which accesses the first 6 elements in the array.
- Finally, main modifies the array at the user specified index.
- Depending on the user's input, the statements on lines 4 and 10 may or may not access the same location in memory.
- As a result, a conservative static analysis will have to assume that the statements always access the same location in memory.
- Our new method statically calculates the slice while ignoring aliasing and then at runtime calculates the alias information.

Dealing with Aliasing





- In order to deal with aliasing, we supplement the static analysis at runtime
- Recall that our method first statically analyzes the program before the dynamic analysis begins.
- We start with a slice which was created while ignoring aliasing

Dealing with Aliasing

Given:

1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program

Dealing with Aliasing
Given:
1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program

- Next, we use each sequence of transitions executed by DPOR to expand the slice.
- Specifically, we check each pair of transitions executed at runtime
- If the two transitions are accessing the same memory location and only one of them is on the slice then we add the other transition to the slice.
- The reason this works is that if the two transitions are accessing the same memory location they are aliasing.
- As a result, we avoid the issue of over-approximating the alias analysis statically.

Dealing with Aliasing

Given:

1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program

Algorithm:

- For each pair of runtime events (t_i, t_j)

Dealing with Aliasing
Given:
1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program
Algorithm:
- For each pair of runtime events (t_i, t_j)

- Next, we use each sequence of transitions executed by DPOR to expand the slice.
- Specifically, we check each pair of transitions executed at runtime
- If the two transitions are accessing the same memory location and only one of them is on the slice then we add the other transition to the slice.
- The reason this works is that if the two transitions are accessing the same memory location they are aliasing.
- As a result, we avoid the issue of over-approximating the alias analysis statically.

Dealing with Aliasing

Given:

1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program

Algorithm:

- For each pair of runtime events (t_i, t_j)
- If t_i and t_j are accessing the same memory location, and
- t_i is on the slice but t_j is not,

Dealing with Aliasing
Given:
1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program
Algorithm:
- For each pair of runtime events (t_i, t_j)
- If t_i and t_j are accessing the same memory location, and
- t_i is on the slice but t_j is not,

- Next, we use each sequence of transitions executed by DPOR to expand the slice.
- Specifically, we check each pair of transitions executed at runtime
- If the two transitions are accessing the same memory location and only one of them is on the slice then we add the other transition to the slice.
- The reason this works is that if the two transitions are accessing the same memory location they are aliasing.
- As a result, we avoid the issue of over-approximating the alias analysis statically.

Dealing with Aliasing

Given:

1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program

Algorithm:

- For each pair of runtime events (t_i, t_j)
- If t_i and t_j are accessing the same memory location, and
- t_i is on the slice but t_j is not,
- then, add t_j to the slice

Dealing with Aliasing
Given:
1. A slice created ignoring aliasing
2. A sequence of transitions executed by the program
Algorithm:
- For each pair of runtime events (t_i, t_j)
- If t_i and t_j are accessing the same memory location, and
- t_i is on the slice but t_j is not,
- then, add t_j to the slice

- Next, we use each sequence of transitions executed by DPOR to expand the slice.
- Specifically, we check each pair of transitions executed at runtime
- If the two transitions are accessing the same memory location and only one of them is on the slice then we add the other transition to the slice.
- The reason this works is that if the two transitions are accessing the same memory location they are aliasing.
- As a result, we avoid the issue of over-approximating the alias analysis statically.

Example

```
int a;
void thread1(void) {
  a = 0;        // 3
}
void thread2(void) {
  a = 1;        // 6
  if (a != 1)   // 7
    assert(0); // 8
}
```


Example

- As an example of the algorithm, consider the following program:
- Two threads are modifying the shared variable a.
- One of them checks that the value of the variable is equal to 1.
- First, we generate the slice of the assertion while ignoring aliasing and get the following.
- Notice that the crucial write to a by thread 1 is missing from the slice.
- Then, at runtime we expand the slice by examining each sequence of transitions
- For example, consider that the first sequence run is the following.
- Our algorithm examines each pair from the sequence.
- Consider the first pair selected to be (3,6). Notice that both statement 3 and statement 6 are accessing the same location in memory.
- Additinoally, 6 is on the slice and 3 is not on the slice.
- So we ad 3 to the slice
- After this, our algorithm continues to examine the remaining pairs, but the slice is complete.

Example

```
int a;
void thread1(void) {
  a = 0;        // 3
}
void thread2(void) {
  a = 1;        // 6
  if (a != 1)   // 7
    assert(0); // 8
}
```

- Slice: $\{ 8, 7, 6 \}$

Example
int a;
void thread1(void) {
a = 0; // 3
}
void thread2(void) {
a = 1; // 6
if (a != 1) // 7
assert(0); // 8
}
Slice: { 8, 7, 6 }

- As an example of the algorithm, consider the following program:
- Two threads are modifying the shared variable a.
- One of them checks that the value of the variable is equal to 1.
- First, we generate the slice of the assertion while ignoring aliasing and get the following.
- Notice that the crucial write to a by thread 1 is missing from the slice.
- Then, at runtime we expand the slice by examining each sequence of transitions
- For example, consider that the first sequence run is the following.
- Our algorithm examines each pair from the sequence.
- Consider the first pair selected to be (3,6). Notice that both statement 3 and statement 6 are accessing the same location in memory.
- Additinoally, 6 is on the slice and 3 is not on the slice.
- So we ad 3 to the slice
- After this, our algorithm continues to examine the remaining pairs, but the slice is complete.

Example

```
int a;
void thread1(void) {
  a = 0;        // 3
}
void thread2(void) {
  a = 1;        // 6
  if (a != 1)   // 7
    assert(0); // 8
}
```

- Slice: $\{ 8, 7, 6 \}$
- Sequence: $S_1 = 3, 6, 7$

Example

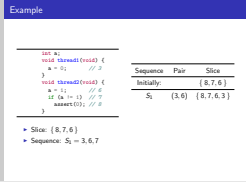
- As an example of the algorithm, consider the following program:
- Two threads are modifying the shared variable a.
- One of them checks that the value of the variable is equal to 1.
- First, we generate the slice of the assertion while ignoring aliasing and get the following.
- Notice that the crucial write to a by thread 1 is missing from the slice.
- Then, at runtime we expand the slice by examining each sequence of transitions
- For example, consider that the first sequence run is the following.
- Our algorithm examines each pair from the sequence.
- Consider the first pair selected to be (3,6). Notice that both statement 3 and statement 6 are accessing the same location in memory.
- Additinoally, 6 is on the slice and 3 is not on the slice.
- So we ad 3 to the slice
- After this, our algorithm continues to examine the remaining pairs, but the slice is complete.

Example

```
int a;
void thread1(void) {
  a = 0;        // 3
}
void thread2(void) {
  a = 1;        // 6
  if (a != 1)   // 7
    assert(0); // 8
}
```

Sequence	Pair	Slice
Initially:		$\{ 8, 7, 6 \}$
S_1	$(3, 6)$	$\{ 8, 7, 6, 3 \}$

- Slice: $\{ 8, 7, 6 \}$
- Sequence: $S_1 = 3, 6, 7$



- As an example of the algorithm, consider the following program:
- Two threads are modifying the shared variable a.
- One of them checks that the value of the variable is equal to 1.
- First, we generate the slice of the assertion while ignoring aliasing and get the following.
- Notice that the crucial write to a by thread 1 is missing from the slice.
- Then, at runtime we expand the slice by examining each sequence of transitions
- For example, consider that the first sequence run is the following.
- Our algorithm examines each pair from the sequence.
- Consider the first pair selected to be (3,6). Notice that both statement 3 and statement 6 are accessing the same location in memory.
- Additinoally, 6 is on the slice and 3 is not on the slice.
- So we ad 3 to the slice
- After this, our algorithm continues to examine the remaining pairs, but the slice is complete.

Example

```
int a;
void thread1(void) {
  a = 0;        // 3
}
void thread2(void) {
  a = 1;        // 6
  if (a != 1)   // 7
    assert(0); // 8
}
```

Sequence	Pair	Slice
Initially:		$\{ 8, 7, 6 \}$
S_1	$(3, 6)$	$\{ 8, 7, 6, 3 \}$
S_1	$(3, 7)$	$\{ 8, 7, 6, 3 \}$
S_1	$(6, 7)$	$\{ 8, 7, 6, 3 \}$

- Slice: $\{ 8, 7, 6 \}$
- Sequence: $S_1 = 3, 6, 7$

Example
int a;
void thread1(void) {
a = 0; // 3
}
void thread2(void) {
a = 1; // 6
if (a != 1) // 7
assert(0); // 8
}
Sequence Pair Slice
Initially: {8,7,6}
S_1 (3,6) {8,7,6,3}
S_1 (3,7) {8,7,6,3}
S_1 (6,7) {8,7,6,3}
Slice: {8,7,6}
Sequence: $S_1 = 3, 6, 7$

- As an example of the algorithm, consider the following program:
- Two threads are modifying the shared variable a.
- One of them checks that the value of the variable is equal to 1.
- First, we generate the slice of the assertion while ignoring aliasing and get the following.
- Notice that the crucial write to a by thread 1 is missing from the slice.
- Then, at runtime we expand the slice by examining each sequence of transitions
- For example, consider that the first sequence run is the following.
- Our algorithm examines each pair from the sequence.
- Consider the first pair selected to be (3,6). Notice that both statement 3 and statement 6 are accessing the same location in memory.
- Additinoally, 6 is on the slice and 3 is not on the slice.
- So we ad 3 to the slice
- After this, our algorithm continues to examine the remaining pairs, but the slice is complete.

Optimizations

1. Critical section peeking
2. Write–Write pruning

Applicable to DPOR, not just our method

Optimizations
1. Critical section peeking
2. Write–Write pruning
Applicable to DPOR, not just our method

- We also present two optimizations which are applicable not just for our method but DPOR in general.
- One we call critical section peeking and the other write–write pruning

Optimizations: Critical Section Peeking

- Reordering mutex lock calls reorders all internal statements
- If the statements aren't dependent, why bother?

```
1  mutex array_lock;
2  int array[16];
3  void thread_1() {
4    for (int i = 0; i < 8; ++i) {
5      lock(array_lock);
6      array[i] = array[i] + 1;
7      unlock(array_lock);
8    }
9  }
10 void thread_2() {
11   for (int i = 8; i < 16; ++i) {
12     lock(array_lock);
13     array[i] = array[i] + 1;
14     unlock(array_lock);
15   }
16 }
```

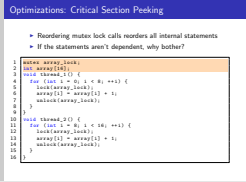

Optimizations: Critical Section Peeking
- Reordering mutex lock calls reorders all internal statements
- If the statements aren't dependent, why bother?

- Previous DPOR implementation consider lock calls to the same mutex to always be dependent.
- At a highlevel, reordering two lock calls reoders all internal statements.
- The intuition of our method is that we do not need to reorder the locks calls if all the internal statements are independent.
- For example, in this program a single mutex protects an entire array
- Thread one is accessing array items 0 through 7 while thread 2 is accessing items 8 through 15.
- Since within each lock-unlock call the threads never access the same memory location we do not need to consider the two locks dependent.
- Using this optimization for this example, we can reduce the number of runs from 12 thousand to one.

Optimizations: Critical Section Peeking

- Reordering mutex lock calls reorders all internal statements
- If the statements aren't dependent, why bother?

```
1  mutex array_lock;
2  int array[16];
3  void thread_1() {
4    for (int i = 0; i < 8; ++i) {
5      lock(array_lock);
6      array[i] = array[i] + 1;
7      unlock(array_lock);
8    }
9  }
10 void thread_2() {
11   for (int i = 8; i < 16; ++i) {
12     lock(array_lock);
13     array[i] = array[i] + 1;
14     unlock(array_lock);
15   }
16 }
```

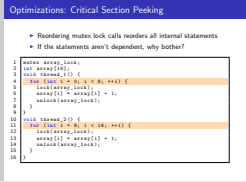



- Previous DPOR implementation consider lock calls to the same mutex to always be dependent.
- At a highlevel, reordering two lock calls reoders all internal statements.
- The intuition of our method is that we do not need to reorder the locks calls if all the internal statements are independent.
- For example, in this program a single mutex protects an entire array
- Thread one is accessing array items 0 through 7 while thread 2 is accessing items 8 through 15.
- Since within each lock-unlock call the threads never access the same memory location we do not need to consider the two locks dependent.
- Using this optimization for this example, we can reduce the number of runs from 12 thousand to one.

Optimizations: Critical Section Peeking

- Reordering mutex lock calls reorders all internal statements
- If the statements aren't dependent, why bother?

```
1  mutex array_lock;
2  int array[16];
3  void thread_1() {
4    for (int i = 0; i < 8; ++i) {
5      lock(array_lock);
6      array[i] = array[i] + 1;
7      unlock(array_lock);
8    }
9  }
10 void thread_2() {
11   for (int i = 8; i < 16; ++i) {
12     lock(array_lock);
13     array[i] = array[i] + 1;
14     unlock(array_lock);
15   }
16 }
```

- Previous DPOR implementation consider lock calls to the same mutex to always be dependent.
- At a highlevel, reordering two lock calls reoders all internal statements.
- The intuition of our method is that we do not need to reorder the locks calls if all the internal statements are independent.
- For example, in this program a single mutex protects an entire array
- Thread one is accessing array items 0 through 7 while thread 2 is accessing items 8 through 15.
- Since within each lock-unlock call the threads never access the same memory location we do not need to consider the two locks dependent.
- Using this optimization for this example, we can reduce the number of runs from 12 thousand to one.

Optimizations: Write–Write Pruning

- A blocked thread can only read the *last* value written to a shared variable
- From `main`'s perspective, a can only be 1 or 6

```
1  int a = 0;
2  void t1_main(){
3    a = 7;
4    a = 6;
5  }
6  void t2_main() {
7    a = 0;
8    a = 1;
9  }
10 int main(int argc, char *argv[]) {
11   thread_create(t1_main);
12   thread_create(t2_main);
13   thread_join(t1_main);
14   thread_join(t2_main);
15   assert(a != 7);
16   return 0;
17 }
```


Optimizations: Write–Write Pruning
- A blocked thread can only read the last value written to a shared variable
- From main's perspective, a can only be 1 or 6

- Our other optimization, Write–Write pruning, is based on the following intuition.
- If a thread is blocked, for example while joining another thread, it is only able to read the last value written to a shared variable.
- Here, main spawns two threads which are both modifying a shared variable.
- Main then joins both threads.
- A tranditional DPOR implementation would reorder all possible combinations of the writes between both threads.
- However, from the perspective of main at the time of the assertion call, since each thread has already run to completion, the value of a can only be 6 or 1.
- As a result, we only need to reorder the last write from each thread.

Optimizations: Write–Write Pruning

- A blocked thread can only read the *last* value written to a shared variable
- From `main`'s perspective, a can only be 1 or 6

```
1  int a = 0;
2  void t1_main(){
3    a = 7;
4    a = 6;
5  }
6  void t2_main() {
7    a = 0;
8    a = 1;
9  }
10 int main(int argc, char *argv[]) {
11   thread_create(t1_main);
12   thread_create(t2_main);
13   thread_join(t1_main);
14   thread_join(t2_main);
15   assert(a != 7);
16   return 0;
17 }
```


Optimizations: Write–Write Pruning
- A blocked thread can only read the last value written to a shared variable
- From main's perspective, a can only be 1 or 6

- Our other optimization, Write–Write pruning, is based on the following intuition.
- If a thread is blocked, for example while joining another thread, it is only able to read the last value written to a shared variable.
- Here, main spawns two threads which are both modifying a shared variable.
- Main then joins both threads.
- A tranditional DPOR implementation would reorder all possible combinations of the writes between both threads.
- However, from the perspective of main at the time of the assertion call, since each thread has already run to completion, the value of a can only be 6 or 1.
- As a result, we only need to reorder the last write from each thread.

Optimizations: Write–Write Pruning

- A blocked thread can only read the *last* value written to a shared variable
- From `main`'s perspective, a can only be 1 or 6

```
1  int a = 0;
2  void t1_main(){
3    a = 7;
4    a = 6;
5  }
6  void t2_main() {
7    a = 0;
8    a = 1;
9  }
10 int main(int argc, char *argv[]) {
11   thread_create(t1_main);
12   thread_create(t2_main);
13   thread_join(t1_main);
14   thread_join(t2_main);
15   assert(a != 7);
16   return 0;
17 }
```


Optimizations: Write–Write Pruning
- A blocked thread can only read the last value written to a shared variable
- From main's perspective, a can only be 1 or 6

- Our other optimization, Write–Write pruning, is based on the following intuition.
- If a thread is blocked, for example while joining another thread, it is only able to read the last value written to a shared variable.
- Here, main spawns two threads which are both modifying a shared variable.
- Main then joins both threads.
- A tranditional DPOR implementation would reorder all possible combinations of the writes between both threads.
- However, from the perspective of main at the time of the assertion call, since each thread has already run to completion, the value of a can only be 6 or 1.
- As a result, we only need to reorder the last write from each thread.

Optimizations: Write–Write Pruning

- A blocked thread can only read the *last* value written to a shared variable
- From `main`'s perspective, a can only be 1 or 6

```
1  int a = 0;
2  void t1_main(){
3    a = 7;
4    a = 6;
5  }
6  void t2_main() {
7    a = 0;
8    a = 1;
9  }
10 int main(int argc, char *argv[]) {
11   thread_create(t1_main);
12   thread_create(t2_main);
13   thread_join(t1_main);
14   thread_join(t2_main);
15   assert(a != 7);
16   return 0;
17 }
```


Optimizations: Write–Write Pruning
- A blocked thread can only read the last value written to a shared variable
- From main's perspective, a can only be 1 or 6

- Our other optimization, Write–Write pruning, is based on the following intuition.
- If a thread is blocked, for example while joining another thread, it is only able to read the last value written to a shared variable.
- Here, main spawns two threads which are both modifying a shared variable.
- Main then joins both threads.
- A tranditional DPOR implementation would reorder all possible combinations of the writes between both threads.
- However, from the perspective of main at the time of the assertion call, since each thread has already run to completion, the value of a can only be 6 or 1.
- As a result, we only need to reorder the last write from each thread.

Overview

Overview
Motivation
Background
Static vs. Dynamic Concurrent Program Analysis
Dynamic Partial Order Reduction
Motivating Example
Our New Method: Predicate Dependence
Experiments

- Next I'll provide a summary of our experimental results

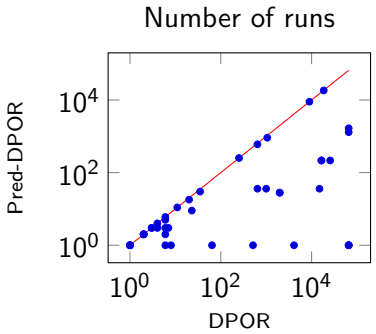
Experiments

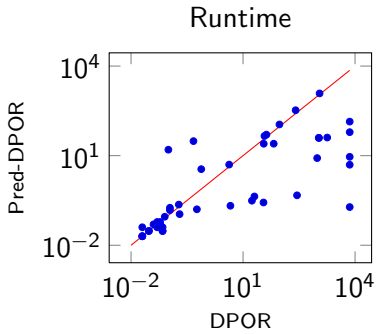
- Tests run on a consumer laptop (Intel i5-3230M)
- C/C++ programs compiled with Clang
- Static analysis done using LLVM
- Limited testing time to two hours
- Tests prorams taken from SVCOMP and real world open source programs

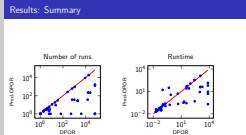
Experiments
- Tests run on a consumer laptop (Intel i5-3230M)
- C/C++ programs compiled with Clang
- Static analysis done using LLVM
- Limited testing time to two hours
- Tests prorams taken from SVCOMP and real world open source programs

- Our experiments were performed on a consumer laptop with a mobile i5 processor
- We ran our code on C/C++ programs
- We used the Clang frontend to LLVM to perform static analysis.
- For each test, we allotted two hours runtime
- We performed our tests on benchmarks from the International Software Verification Competition and from real world open source programs

Results: Summary

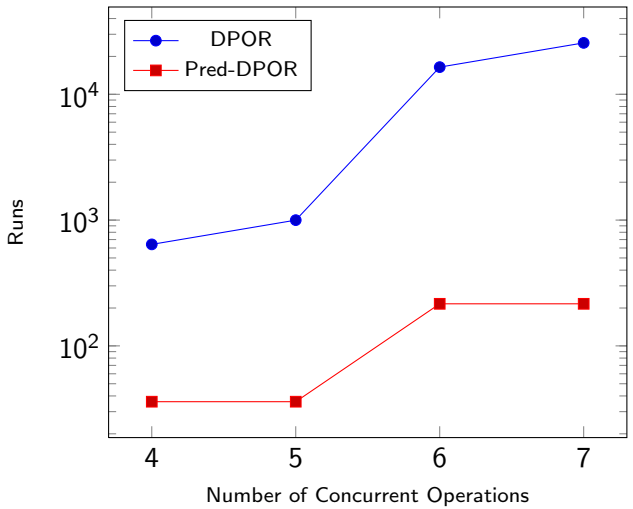




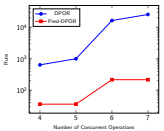


- We ran our method on 46 programs to compare it to DPOR.
- For some programs, we did not have any reduction in the number of runs.
- For these cases, our new method does not incur too high of a runtime overhead.
- However, for those programs where we could find a reduction, we often were able to significantly reduce the runtime.

Results: nbds-hashtable



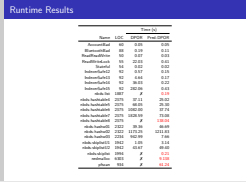
Results: nbds-hashtable



- For example, the following are the results for our method running on a nonblocking hashtable.
- The results show that our new method can reduce the number of runs required significantly.
- After only 7 concurrent operations by each thread, DPOR exceeds the two hour time limit while our method can finish within a reasonable amount of time.

Runtime Results

		Time (s)	
Name	LOC	DPOR	Pred-DPOR
AccountBad	60	0.05	0.05
BluetoothBad	88	0.19	0.11
ReadReadWrite	50	0.07	0.03
ReadWriteLock	55	22.03	0.41
Stateful	54	0.02	0.02
IndexerSafe12	92	0.57	0.15
IndexerSafe13	92	4.64	0.17
IndexerSafe14	92	36.03	0.22
IndexerSafe15	92	282.06	0.43
nbds-list	1887	✗	0.19
nbds-hashtable4	2375	37.11	25.02
nbds-hashtable5	2375	68.05	25.30
nbds-hashtable6	2375	1082.00	37.74
nbds-hashtable7	2375	1828.59	73.08
nbds-hashtable8	2375	✗	138.04
nbds-hashw01	2322	39.36	46.69
nbds-hashw02	2322	1173.25	1211.83
nbds-hashw03	2234	942.99	7.66
nbds-skiplistU1	1942	1.05	3.14
nbds-skiplistU2	1942	43.67	49.40
nbds-skiplist	1994	✗	0.21
nedmalloc	6303	✗	9.138
pfscan	934	✗	61.24



- For all the tests were we could find a reduction, the following table summarizes the runtime results.
- Especially for larger programs, we were able to achieve a significant reduction in runtime.
- For example, many of the programs where DPOR timed out, marked with an X in this table, we were able to finish in under a minute.

Conclusions

- Static–dynamic concurrent program analysis
- Sound verification of assertion violations
- Experimentally, our new method out performs DPOR
- Verifies previously intractable programs

Conclusions
- Static-dynamic concurrent program analysis
- Sound verification of assertion violations
- Experimentally, our new method out performs DPOR
- Verifies previously intractable programs

- In conclusion, we present a sound optimization for verifying mutlithreaded programs.
- In comparison to DPOR, our method can offer a significant reduction in runtime
- As a result, we were able to verify some programs which were previously intractable

Questions? I

- Parosh Abdulla, Stavros Aronis, Bengt Jonsson, and Konstantinos Sagonas.
  Optimal dynamic partial order reduction.
  SIGPLAN Not., 49(1):373–384, January 2014.
- Edmund M. Clarke and E. Allen Emerson.
  Design and synthesis of synchronization skeletons using branching-time temporal logic.
  In *Logic of Programs, Workshop*, pages 52–71, London, UK, UK, 1982. Springer-Verlag.
- Edmund M. Clarke, Jr., Orna Grumberg, and Doron A. Peled.
  Model Checking.
  MIT Press, Cambridge, MA, USA, 1999.

Questions? I

Parosh Abdulla, Stavros Aronis, Bengt Jonsson, and Konstantinos Sagonas.
Optimal dynamic partial order reduction.
SIGPLAN Not., 49(1):373-384, January 2014.

Edmund M. Clarke and E. Allen Emerson.
Design and synthesis of synchronization skeletons using branching-time temporal logic.
In *Logic of Programs, Workshop*, pages 52–71, London, UK, UK, 1982. Springer-Verlag.

Edmund M. Clarke, Jr., Orna Grumberg, and Doron A. Peled.
Model Checking.
MIT Press, Cambridge, MA, USA, 1999.

Questions? II

Cormac Flanagan and Patrice Godefroid.
Dynamic partial-order reduction for model checking software.
In *Proceedings of the 32Nd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL '05, pages 110–121, New York, NY, USA, 2005. ACM.

Azadeh Farzan and Zachary Kincaid.
Verification of parameterized concurrent programs by modular reasoning about data and control.
SIGPLAN Not., 47(1):297–308, January 2012.

Patrice Godefroid.
Partial-Order Methods for the Verification of Concurrent Systems: An Approach to the State-Explosion Problem.
Springer-Verlag New York, Inc., Secaucus, NJ, USA, 1996.

Questions? II

Cormac Flanagan and Patrice Godefroid.
Dynamic partial-order reduction for model checking software.
In *Proceedings of the 32Nd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, POPL '05, pages 110–121, New York, NY, USA, 2005. ACM.

Azadeh Farzan and Zachary Kincaid.
Verification of parameterized concurrent programs by modular reasoning about data and control.
SIGPLAN Not., 47(1):297–308, January 2012.

Patrice Godefroid.
Partial-Order Methods for the Verification of Concurrent Systems: An Approach to the State-Explosion Problem.
Springer-Verlag New York, Inc., Secaucus, NJ, USA, 1996.