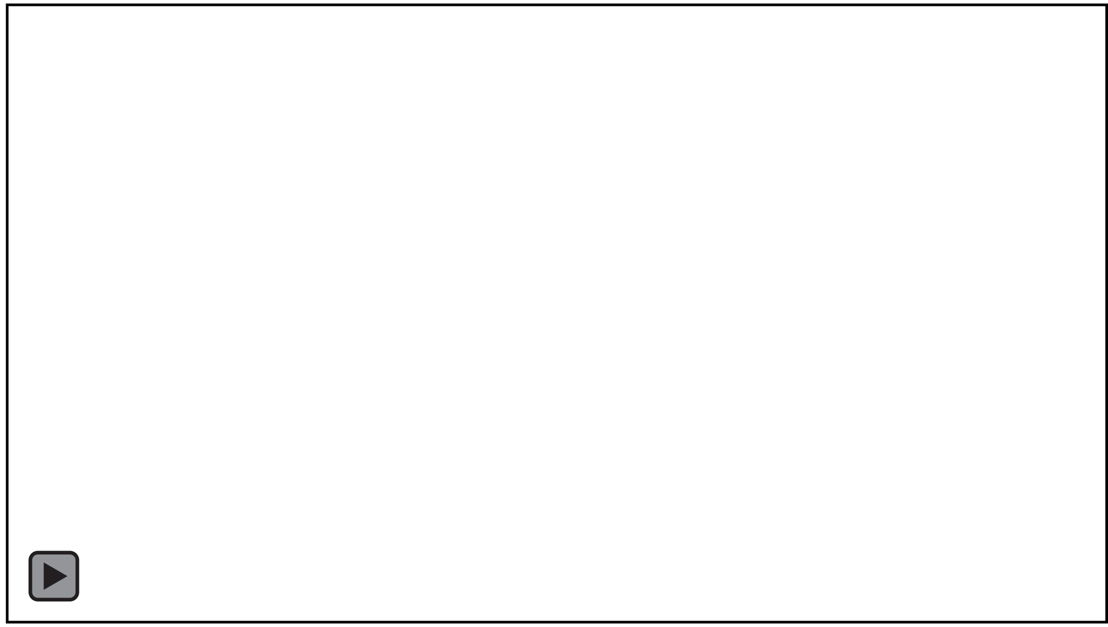
```java
public class Puzzle15 {

    public static void main(String[] args) {
        int[] arr = new int[10000];
        Random rnd = new Random();
        for (int i = 0; i < arr.length; i++) {
            arr[i] = rnd.nextInt(1000);
        }
        long unsortedTime = measureSumTime(arr);
        Arrays.sort(arr);
        long sortedTime = measureSumTime(arr);
        String comparison = ((unsortedTime == sortedTime) ?
                "==" : ((unsortedTime < sortedTime) ? "<" : ">"));
        System.out.println("Unsorted Time " + comparison + " Sorted Time");
    }

    private static long measureSumTime(int[] arr) {
        long start = System.nanoTime();
        int result = 0;
        for (int i = 0; i < arr.length; i++) {
            if (arr[i] < 100) {
                result += arr[i];
            }
        }
        long time = System.nanoTime() - start;
        System.out.println("Sum: " + result + " in " + time + "ns");
        return time;
    }

}
```

Background

- We research tools and techniques that:
  - Produce human-verifiable and comprehensible evidence
  - Are scalable
- Resulted in key concept: Projected Control Graph (PCG)
  - Retains minimal necessary program behaviors
- Verification of lock/unlock pairs in Linux
  - Over 66,000 instances (3 versions of Linux)
  - PCG based tool has resulted in 8 bug reports which have been fixed

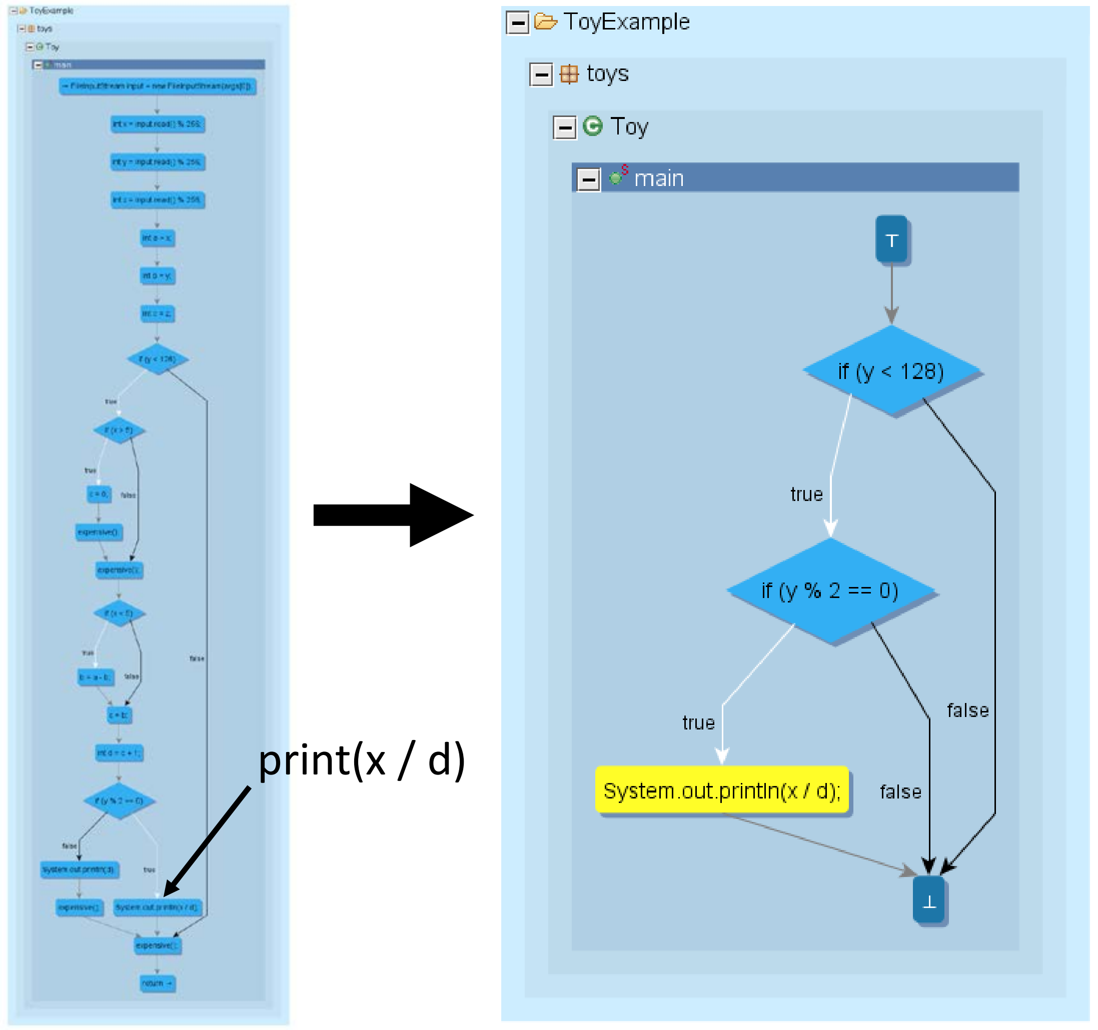
Motivation behind PCGs

- Control Flow Graphs can be HUGE
  - CFG of a single function in Linux
    - lustre_assert_wire_constants function has 2^656 paths!
  - Programmers don’t play dice…
  - Is all of this complexity necessary to solve a given analysis problem?
  - Is there an underlying design pattern that can be leveraged to complete the analysis?



Concept: Projected Control Graph (PCG)

- Proposed by Ahmed Tamrawi in 2016
- Efficiently groups program behaviors into equivalence classes of homomorphic behaviors
  - Parameterized by events of interest
  - Only event statements and necessary conditions are retained
- Result is a compact structure-preserving model of a CFG w.r.t. events of interest

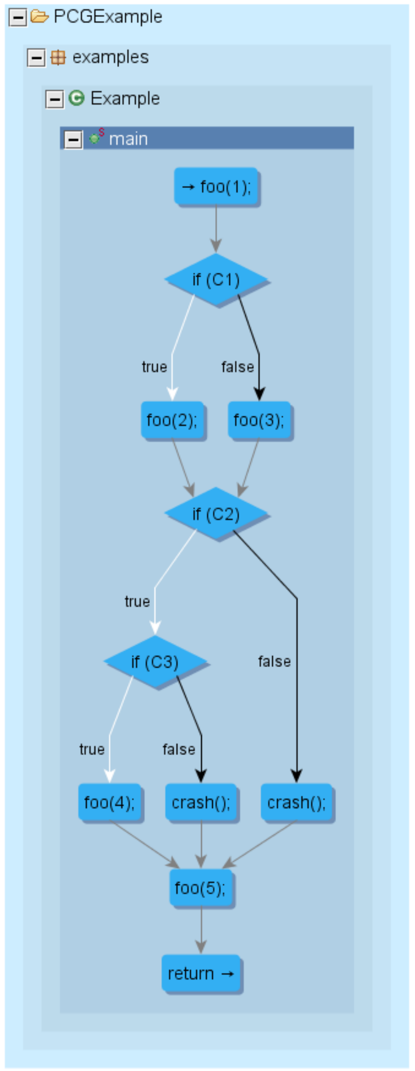


CFG

PCG(E), E=Division Statement

PCG Example

```
public void main() {
    foo(1);
    if (C1) {
        foo(2);
    } else {
        foo(3);
    }
    if (C2) {
        if (C3) {
            foo(4);
        } else {
            crash();
        }
    } else {
        crash();
    }
    foo(5);
    return;
}
```

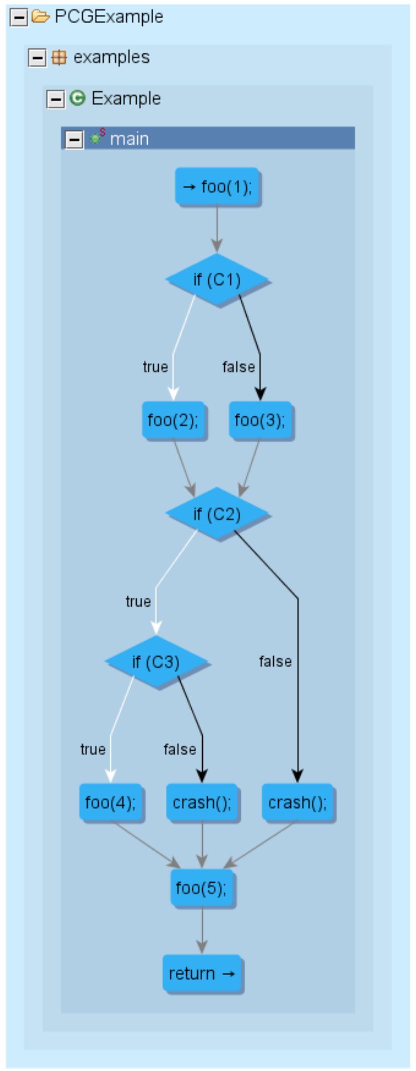


$2^3=8$ possible values for the tuple (C1, C2, C3)

C1	C2	C3	Behavior
False	False	False	
False	False	True	
False	True	False	
False	True	True	
True	False	False	
True	False	True	
True	True	False	
True	True	True	

PCG Example

```
public void main() {
    foo(1);
    if (C1) {
        foo(2);
    } else {
        foo(3);
    }
    if (C2) {
        if (C3) {
            foo(4);
        } else {
            crash();
        }
    } else {
        crash();
    }
    foo(5);
    return;
}
```

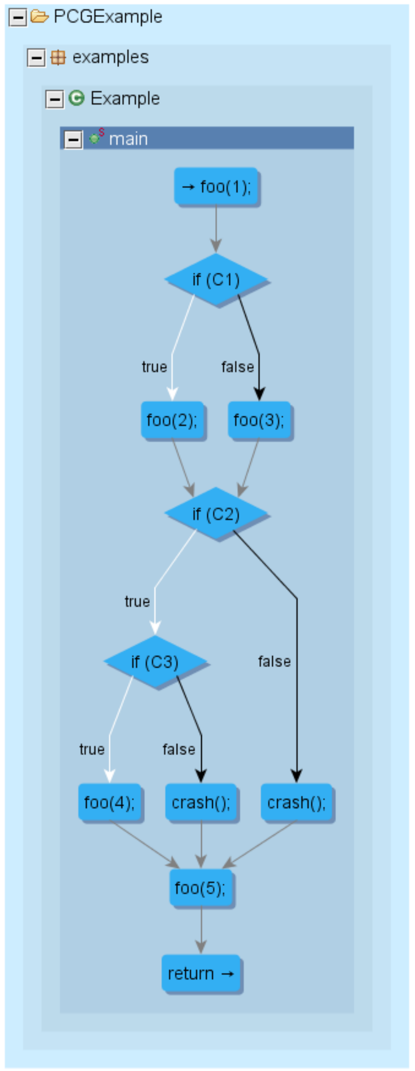


If C2 is false then C3 is not evaluated.

C1	C2	C3	Behavior
False	False	N/A	
False	False	N/A	
False	True	False	
False	True	True	
True	False	N/A	
True	False	N/A	
True	True	False	
True	True	True	

PCG Example

```
public void main() {
    foo(1);
    if (C1) {
        foo(2);
    } else {
        foo(3);
    }
    if (C2) {
        if (C3) {
            foo(4);
        } else {
            crash();
        }
    } else {
        crash();
    }
    foo(5);
    return;
}
```

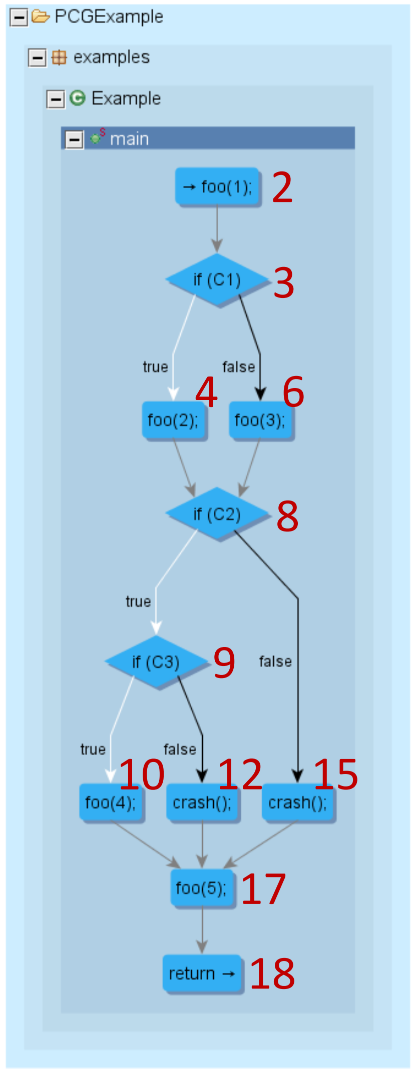


CFG has 6 paths.

C1	C2	C3	Behavior
False	False	N/A	
False	True	False	
False	True	True	
True	False	N/A	
True	True	False	
True	True	True	

PCG Example

```
 1  public void main() {
 2      foo(1);
 3      if (C1) {
 4          foo(2);
 5      } else {
 6          foo(3);
 7      }
 8      if (C2) {
 9          if (C3) {
10              foo(4);
11          } else {
12              crash();
13          }
14      } else {
15          crash();
16      }
17      foo(5);
18      return;
19  }
```

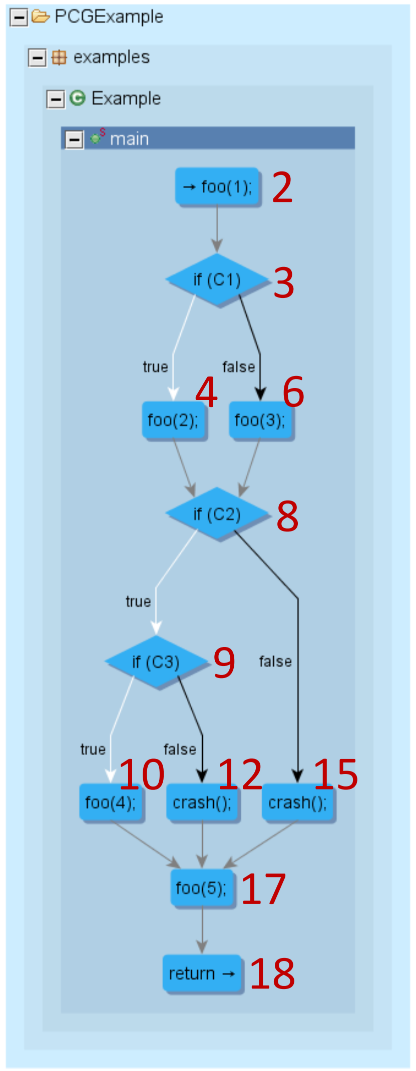


Which paths include a “crash” event?

C1	C2	C3	Behavior
False	False	N/A	2,3,6,8,15,17,18
False	True	False	2,3,6,8,9,12,17,18
False	True	True	2,3,6,8,9,10,17,18
True	False	N/A	2,3,4,8,15,17,18
True	True	False	2,3,4,8,9,12,17,18
True	True	True	2,3,4,8,9,10,17,18

PCG Example

```
1   public void main() {
2       foo(1);
3       if (C1) {
4           foo(2);
5       } else {
6           foo(3);
7       }
8       if (C2) {
9           if (C3) {
10              foo(4);
11          } else {
12              crash();
13          }
14      } else {
15          crash();
16      }
17      foo(5);
18      return;
19  }
```

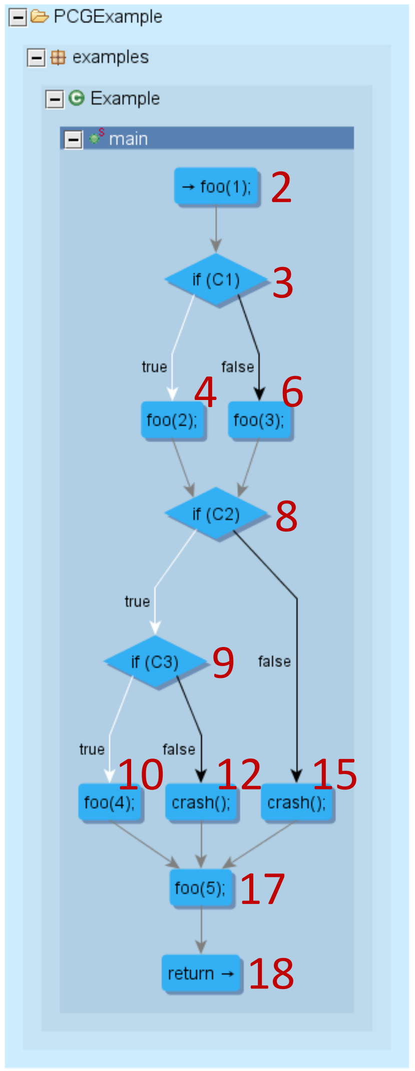


4 of 6 behaviors have "crash" events.
2 of 6 behaviors do not have "crash" events.

C1	C2	C3	Behavior
False	False	N/A	2,3,6,8,15,17,18
False	True	False	2,3,6,8,9,12,17,18
~~False~~	~~True~~	~~True~~	~~2,3,6,8,9,10,17,18~~
True	False	N/A	2,3,4,8,15,17,18
True	True	False	2,3,4,8,9,12,17,18
~~True~~	~~True~~	~~True~~	~~2,3,4,8,9,10,17,18~~

PCG Example

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```



Consider necessary conditions for “crash” events.

C1	C2	C3	Behavior
False	False	N/A	2,3,6,8,15,17,18
False	True	False	2,3,6,8,9,12,17,18
~~False~~	~~True~~	~~True~~	~~2,3,6,8,9,10,17,18~~
True	False	N/A	2,3,4,8,15,17,18
True	True	False	2,3,4,8,9,12,17,18
~~True~~	~~True~~	~~True~~	~~2,3,4,8,9,10,17,18~~

PCG Example

```
1  public void main() {
2      foo(1);
3      if (C1) {
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6          foo(3);
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8      if (C2) {
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10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```
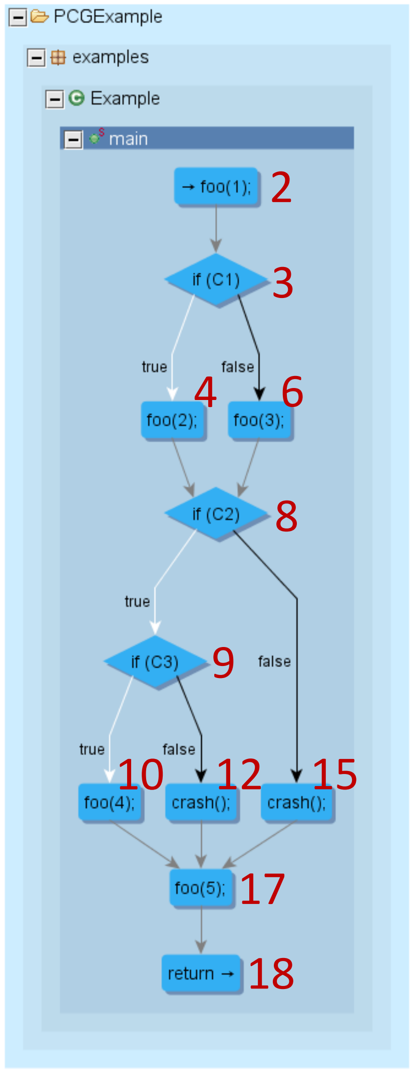
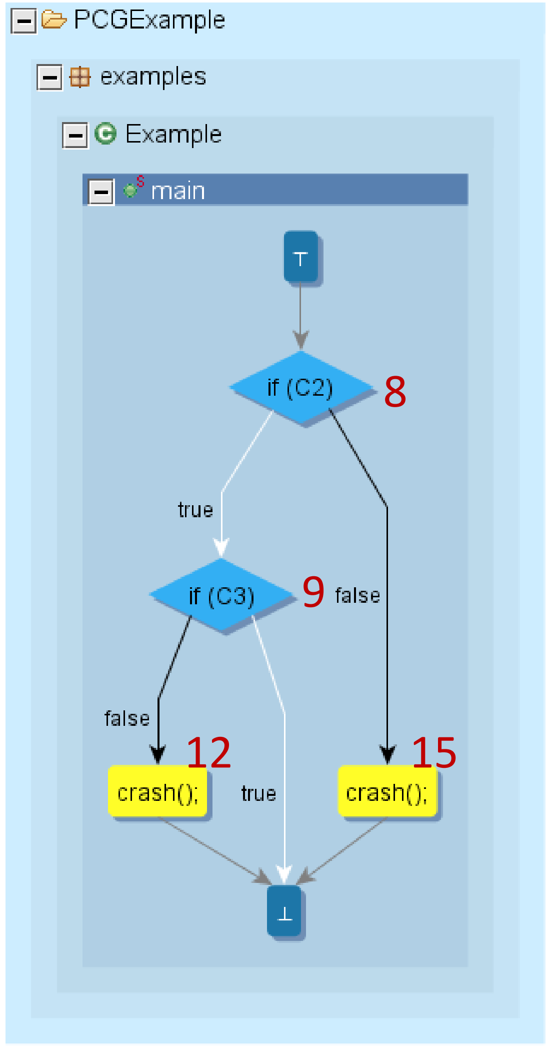



There are 3 unique behaviors w.r.t. "crash" events.

C1	C2	C3	Homomorphic Behavior	
False	False	N/A	8,15	B1
False	True	False	8,9,12	B2
~~False~~	~~True~~	~~True~~	~~8,9~~	B3
True	False	N/A	8,15	
True	True	False	8,9,12	
~~True~~	~~True~~	~~True~~	~~8,9~~	

PCG Example

```
 1  public void main() {
 2      foo(1);
 3      if (C1) {
 4          foo(2);
 5      } else {
 6          foo(3);
 7      }
 8      if (C2) {
 9          if (C3) {
10              foo(4);
11          } else {
12              crash();
13          }
14      } else {
15          crash();
16      }
17      foo(5);
18      return;
19  }
```



2 of 3 homomorphic behaviors (B1, B2) have “crash” events.
1 of 3 homomorphic behaviors (B3) are void w.r.t. “crash” events.

C1	C2	C3	Homomorphic Behavior	
False	False	N/A	8,15	B1
False	True	False	8,9,12	B2
~~False~~	~~True~~	~~True~~	~~8,9~~	B3
True	False	N/A	8,15	
True	True	False	8,9,12	
~~True~~	~~True~~	~~True~~	~~8,9~~	

Demo

- Interactive Smart Views
- Automatic Pairing Analysis of Lock/Unlock events