CS 489 / 698: Software and Systems Security

Module 6: Common Bugs and Vulnerabilities

other typical bug types

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Outline

Recall the "nice" properties of memory errors

- They have universally accepted definitions
  - Once you find a memory error or data race, you do not need to diligently argue that this is a bug and not a feature
- They often lead to a set of known consequences that are generally considered severe (e.g., data leak or denial-of-service)
  - Once you find a memory error or data race, you do not need to construct a working exploit to justify it
- Finding them typically do not require program-specific domain knowledge
  - If you have a technique that can find memory errors or data races in one codebase, you can scale it up to millions of codebases

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In fact, very few types of vulnerabilities meet these requirements.

$\Longrightarrow$ Most of the bug types covered today do not meet all requirements, but they are representative examples to show easy it is to make a mistake in programming.

Outline

Unsafe integer operations

Mathmetical integers are unbounded

WHILE

Machine integers are bounded by a fixed number of bits.

Unsafe integer operations

```
1  mapping (address => uint256) public balanceOf;
2
3  // INSECURE
4  function transfer(address _to, uint256 _value) {
5      /* Check if sender has balance */
6      require(balanceOf[msg.sender] >= _value);
7
8      /* Add and subtract new balances */
9      balanceOf[msg.sender] -= _value;
10     balanceOf[_to] += _value;
11 }
```

Q: What is the bug here?

Unsafe integer operations

```
1  mapping (address => uint256) public balanceOf;
2
3  // INSECURE
4  function transfer(address _to, uint256 _value) {
5      /* Check if sender has balance */
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7
8      /* Add and subtract new balances */
9      balanceOf[msg.sender] -= _value;
10     balanceOf[_to] += _value;
11 }
```

```
1  // SECURE
2  function transfer(address _to, uint256 _value) {
3      /* Check if sender has balance and for overflows */
4      require(balanceOf[msg.sender] >= _value &&
5              balanceOf[_to] + _value >= balanceOf[_to]);
6
7      /* Add and subtract new balances */
8      balanceOf[msg.sender] -= _value;
9      balanceOf[_to] += _value;
10 }
```

Common cases for integer overflows and underflows

- signed $\leftrightarrow$ unsigned
- size-decreasing cast (a.k.a., truncate)
- +, -, * for both signed and unsigned integers
- / for signed integers
- ++ and -- for both signed and unsigned integers
- +=, -=, *= for both signed and unsigned integers
- /= for signed integers
- Negation - for signed and unsigned integers
- << for both signed and unsigned integers

Unsafe floating-point operations

Mathmetical real numbers are arbitrary precision

WHILE

Machine floating-point numbers are bounded by a limited precision.

The perils of floating point (in Python)

```
>>> .1 + .1 + .1 == .3
```

Q: True or False?

The perils of floating point (in Python)

```
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Q: True or False?

```
>>> round(.1, 1) + round(.1, 1) + round(.1, 1) == round(.3, 1)
```

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Q: True or False?

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>>> round(.1, 1) + round(.1, 1) + round(.1, 1) == round(.3, 1)
```

Q: True or False?

```
>>> round(.1 + .1 + .1, 10) == round(.3, 10)
```

Q: True or False?

The perils of floating point (in Python)

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>>> .1 + .1 + .1 == .3
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Q: True or False?

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>>> round(.1, 1) + round(.1, 1) + round(.1, 1) == round(.3, 1)
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Q: True or False?

```
>>> round(.1 + .1 + .1, 10) == round(.3, 10)
```

Q: True or False?

Further reading: The Perils of Floating Point

Pointer relational comparison

```c
#include <stdio.h>

struct Record {
  int a;
  int b;
};

int main(void) {
  struct Record r = { 0, 0 };
  /* defined behavior */
  if (&r.a < &r.b) {
    printf("Hello\n");
  } else {
    printf("World\n");
  }
  return 0;
}
```

Q: Output?

Pointer relational comparison

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  }
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}
```

Q: Output?

Pointer relational comparison

In C and C++, the relational comparison of pointers to objects (i.e., $<$ or $>$) is only strictly defined if

- the pointers point to members of the same object, or
- the pointers point to elements of the same array.

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Pointer relational comparison

In C and C++, the relational comparison of pointers to objects (i.e., $<$ or $>$) is only strictly defined if

- the pointers point to members of the same object, or
- the pointers point to elements of the same array.

However, most compiler will emit a comparison operation based on the numerical value of the pointers. $\Longrightarrow$ This is not strictly a bug, as undefined behavior means the compiler is free to choose whatever action that might make sense.

Outline

handling untrusted input can be dangerous

SQL injection

```
1  public boolean login(String username, String password) {
2    String sql =
3      "SELECT * FROM Users WHERE " +
4        "username = '" + username + "' AND " +
5        "password = '" + password + "';";
6
7    ResultSet result = db.executeQuery(sql);
8    if (result.next()) {
9      /* login success */
10     return true;
11   } else {
12     /* login failure */
13     return false;
14   }
15 }
```

Mitigating SQL injection with sanitization

```
1  public boolean login(String username, String password) {
2    PreparedStatement sql = db.prepareStatement(
3      "SELECT * FROM Users WHERE username = ? AND password = ?;")
4    sql.setString(1, username);
5    sql.setString(2, password);
6
7    ResultSet result = db.executeQuery(sql);
8    if (result.next()) {
9      /* login success */
10     return true;
11   } else {
12     /* login failure */
13     return false;
14   }
15 }
```

SQL injection in the wild

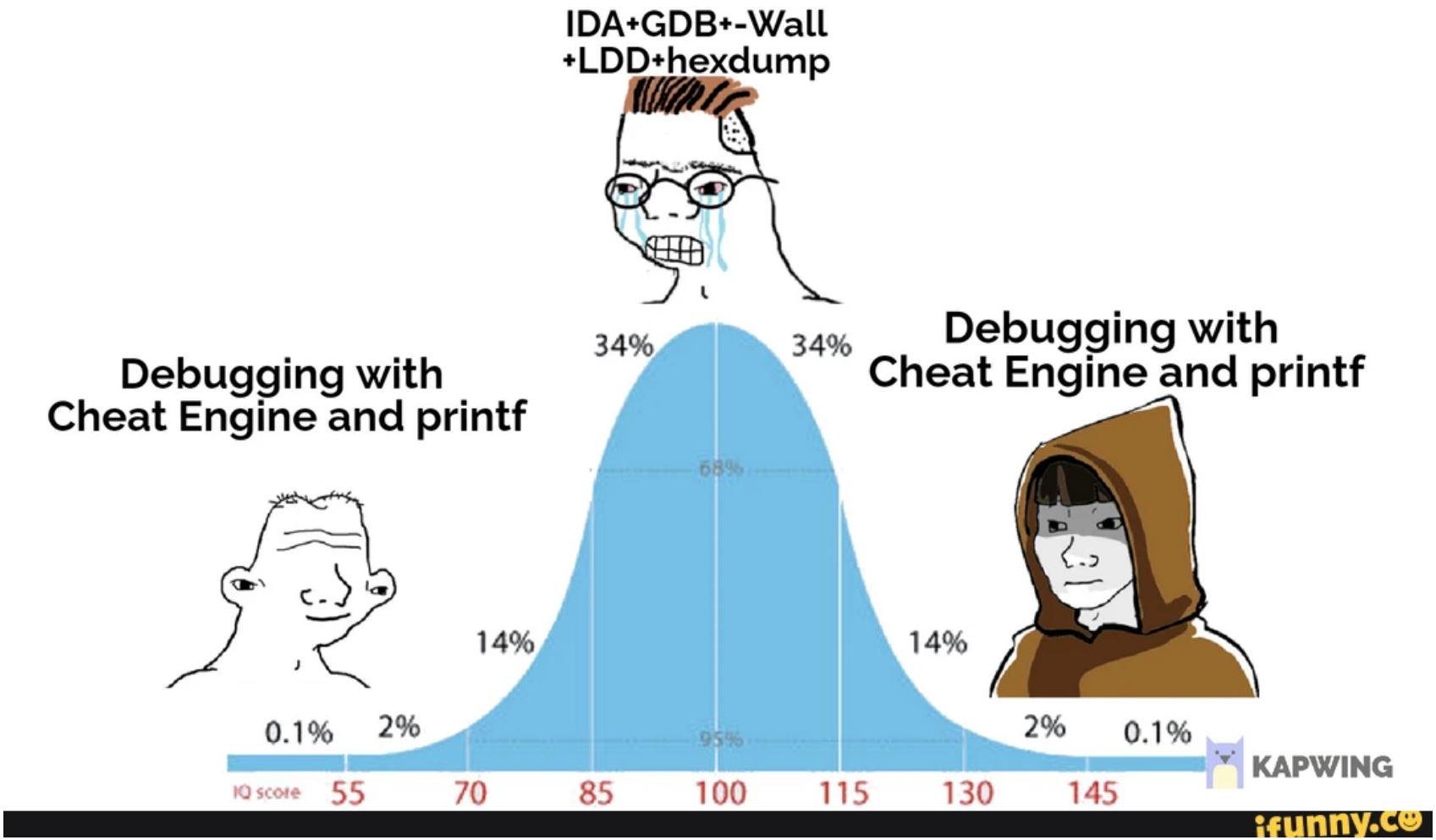
Original source unknown, found on Twitter

`printf` is powerful

A format string vulnerability is a bug where untrusted user input is passed as the format argument to `printf`, `scanf`, or another function in that family.

For details, see the `man page of printf`.

`printf` is powerful



Format string vulnerability demo

```c
#include <stdio.h>
#include <unistd.h>

int main() {
  int secret = 0xdeadbeef;

  char name[64] = {0};
  read(0, name, 64);
  printf("Hello ");
  printf(name);
  printf(", try to get the secret!\n");
  return 0;
}
```

Format string vulnerability demo

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#include <stdio.h>
#include <unistd.h>

int main() {
  int secret = 0xdeadbeef;

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  read(0, name, 64);
  printf("Hello ");
  printf(name);
  printf(", try to get the secret!\n");
  return 0;
}
```

To trigger the vulnerability, try something like `%7$llx`, although %7 can be other values depending on the OS and C compiler version.

Cross-site scripting (XSS)

Cross-site scripting (XSS) enables attackers to inject client-side scripts into web pages viewed by other users.

Same-origin policy

This essentially states that if content from one site (such as https://crysp.uwaterloo.ca) is granted permission to access resources (e.g., cookies etc.) on a web browser, then content from the same origin will share these permissions.

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The same-origin property is defined as two URLs sharing the same

- URI scheme (e.g. `ftp`, `http`, or `https`)
- hostname (e.g., `crysp.uwaterloo.ca`) and
- port number (e.g., 80)

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- URI scheme (e.g. `ftp`, `http`, or `https`)
- hostname (e.g., `crysp.uwaterloo.ca`) and
- port number (e.g., 80)

For example, these webpages are from the same origin:

- https://crysp.uwaterloo.ca/research/ and
- https://crysp.uwaterloo.ca/courses/

XSS Demo I

```
1  from urllib.parse import unquote as url_unquote
2  from http.server import BaseHTTPRequestHandler, HTTPServer
3
4  HOST = "localhost"
5  PORT = 8080
6
7  PAGE = """<html>
8  <form action='/submit' method='POST'>
9  <input type='text' name='comment' />
10 </form>
11 </html>"""
12
13 class XSSDemoServer(BaseHTTPRequestHandler):
14     def do_GET(self):
15         self.send_response(200)
16         self.send_header("Content-type", "text/html")
17         self.end_headers()
18         self.wfile.write(bytes(PAGE, "utf-8"))
19
20     def do_POST(self):
21         size = int(self.headers.get('Content-Length'))
22         body = url_unquote(self.rfile.read(size).decode('utf-8'))
```

XSS Demo II

```
23          self.send_response(200)
24          self.send_header("Content-type", "text/html")
25          self.end_headers()
26          self.wfile.write(bytes("<html>%s</html>" % body[8:], "utf-8"))
27
28
29  if __name__ == "__main__":
30      server = HTTPServer((HOST, PORT), XSSDemoServer)
31      print("Server started http://%s:%s" % (HOST, PORT))
32
33      try:
34          server.serve_forever()
35      except KeyboardInterrupt:
36          pass
37
38      server.server_close()
39      print("Server stopped.")
```

Q: Try <script>alert("XSS")</script>

Outline

Calling into untrusted code is dangerous

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The DAO attack on Ethereum

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The DAO attack on Ethereum

In 2016, an attacker exploited a vulnerability in The DAO's wallet smart contracts. In a couple of weeks (by Saturday, 18th June), the attacker managed to drain more than 3.6 million ether into an attacker-controlled account. The price of ether dropped from over $20 to under $13.

Calling into untrusted code is dangerous

The DAO attack on Ethereum

> *In 2016, an attacker exploited a vulnerability in The DAO's wallet smart contracts. In a couple of weeks (by Saturday, 18th June), the attacker managed to drain more than 3.6 million ether into an attacker-controlled account. The price of ether dropped from over $20 to under $13.*

The DAO attack was partially recovered by a hard-fork of the Ethereum blockchain that returns all stolen ethers into a special smart contract (which can be subsequently withdrawn). This resulted in two chains: Ethereum classic and Ethereum.

Reentrancy attack (victim contract)

```
1  contract EtherStore {
2      uint256 public withdrawalLimit = 1 ether;
3      mapping(address => uint256) public lastWithdrawTime;
4      mapping(address => uint256) public balances;
5
6      function depositFunds() public payable {
7          balances[msg.sender] += msg.value;
8      }
9
10     function withdrawFunds (uint256 _weiToWithdraw) public {
11         require(balances[msg.sender] >= _weiToWithdraw);
12         require(_weiToWithdraw <= withdrawalLimit);
13         require(now >= lastWithdrawTime[msg.sender] + 1 weeks);
14         require(msg.sender.call.value(_weiToWithdraw)());
15
16         balances[msg.sender] -= _weiToWithdraw;
17         lastWithdrawTime[msg.sender] = now;
18     }
19 }
```

Reentrancy attack (attacker's contract)

```
1  import "EtherStore.sol";
2
3  contract Attack {
4    EtherStore public etherStore;
5
6    constructor(address _etherStoreAddress) {
7        etherStore = EtherStore(_etherStoreAddress);
8    }
9    function pwnEtherStore() public payable {
10       require(msg.value >= 1 ether);
11       etherStore.depositFunds.value(1 ether)();
12       etherStore.withdrawFunds(1 ether);
13   }
14   function collectEther() public {
15       msg.sender.transfer(this.balance);
16   }
17   function () payable {
18       if (etherStore.balance > 1 ether) {
19           etherStore.withdrawFunds(1 ether);
20       }
21   }
22 }
```

Reentrancy attack (attacker's contract)

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1  import "EtherStore.sol";
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3  contract Attack {
4    EtherStore public etherStore;
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6    constructor(address _etherStoreAddress) {
7        etherStore = EtherStore(_etherStoreAddress);
8    }
9    function pwnEtherStore() public payable {
10       require(msg.value >= 1 ether);
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14   function collectEther() public {
15       msg.sender.transfer(this.balance);
16   }
17   function () payable {
18       if (etherStore.balance > 1 ether) {
19           etherStore.withdrawFunds(1 ether);
20       }
21   }
22 }
```

The attacker can drain the balance from the victim contract.

Reentrancy attack (the fix)

```
1  contract EtherStore {
2      bool reentrancyMutex = false;
3      uint256 public withdrawalLimit = 1 ether;
4      mapping(address => uint256) public lastWithdrawTime;
5      mapping(address => uint256) public balances;
6
7      function depositFunds() public payable {
8          balances[msg.sender] += msg.value;
9      }
10
11     function withdrawFunds (uint256 _weiToWithdraw) public {
12         require(balances[msg.sender] >= _weiToWithdraw);
13         require(_weiToWithdraw <= withdrawalLimit);
14         require(now >= lastWithdrawTime[msg.sender] + 1 weeks);
15
16         balances[msg.sender] -= _weiToWithdraw;
17         lastWithdrawTime[msg.sender] = now;
18         reentrancyMutex = true;
19         msg.sender.transfer(_weiToWithdraw);
20         reentrancyMutex = false;
21     }
22 }
```

Outline

What is data race?

What is data race?

```
global var count = 0
```

Thread 1	Thread 2
`for(i = 0; i < x; i++) {`	`for(i = 0; i < y; i++) {`
`  /* do sth critical */`	`  /* do sth critical */`
`  ......`	`  ......`
`  count++;`	`  count++;`
`}`	`}`

Q: What is the value of `count` when both threads terminate?

What is data race?

```
global var count = 0
global var mutex = ⊥
```

```
for(i = 0; i < x; i++) {
  /* do sth critical */
  ......
  lock(mutex);
  count++;
  unlock(mutex);
}
```

Thread 1

```
for(i = 0; i < y; i++) {
  /* do sth critical */
  ......
  lock(mutex);
  count++;
  unlock(mutex);
}
```

Thread 2

Q: What is the value of count when both threads terminate?

Data race in other settings

Data races are not tied to a specific programming language, instead, they are tied to data sharing in concurrent execution.

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Data races are not tied to a specific programming language, instead, they are tied to data sharing in concurrent execution.

For example, in the database context:

Q: If two database clients send the following requests concurrently, what will be the result (both try to withdraw $100 from Alice)?

Client 1

```
SELECT @balance = Balance
  FROM Ledger WHERE Name = "Alice";

UPDATE Ledger SET Balance =
  @balance - 100 WHERE Name = "Alice";
```

Client 2

```
SELECT @balance = Balance
  FROM Ledger WHERE Name = "Alice";

UPDATE Ledger SET Balance =
  @balance - 100 WHERE Name = "Alice";
```

Data race in a database setting

One possible interleaving (that messes up the states)

```
SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
```

Data race in a database setting

One possible interleaving (that messes up the states)

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SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
```

Q: How to prevent the data race in this case?

Data race in a database setting

One possible interleaving (that messes up the states)

```
SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
```

Q: How to prevent the data race in this case?

Interleavings with transactions

```
BEGIN TRANSACTION;
  SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
  UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
COMMIT TRANSACTION;
BEGIN TRANSACTION;
  SELECT @balance = Balance FROM Ledger WHERE Name = "Alice";
  UPDATE Ledger SET Balance = @balance - 100 WHERE Name = "Alice";
COMMIT TRANSACTION;
```

Data race may lead to memory errors

p is a global pointer initialized to NULL

Thread 1	Thread 2

`if (!p) {`
`  p = malloc(128);`
`}`
	`if (!p) {`
	`  p = malloc(256);`
	`}`

Q: What are the possible outcomes of this execution?

Data race may lead to memory errors

p is a global pointer initialized to NULL

Thread 1	Thread 2

`if (!p) {`
`  p = malloc(128);`
`}`
	`if (!p) {`
	`  p = malloc(256);`
	`}`

Q: What are the possible outcomes of this execution?

Data race may lead to memory errors

p is a global pointer initialized to NULL

Thread 1

```
if (!p) {
  p = malloc(128);
}

if (p) {
  free(p);
  p = NULL;
}
```

Thread 2

```
if (!p) {
  p = malloc(256);
}

if (p) {
  free(p);
  p = NULL;
}
```

Q: What are the possible outcomes of this execution?

Data race as heisenbug

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Programs which contain data races usually demonstrate unexpected and even non-deterministic behavior.

Data race as heisenbug

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- The outcome might depend on a specific execution order (a.k.a. thread interleaving).
- Re-running the program may not always produce the same results.

Data race as heisenbug

Programs which contain data races usually demonstrate unexpected and even non-deterministic behavior.

- The outcome might depend on a specific execution order (a.k.a. thread interleaving).
- Re-running the program may not always produce the same results.

Concurrent programs are hard to debug and even harder to ensure correctness.

Data race definition in C++ standard

When

- *an evaluation of an expression writes to a memory location* **and**
- *another evaluation reads or modifies the same memory location,*

the expressions are said to conflict.

A program that has two conflicting evaluations has a data race unless:

- *both evaluations execute on the same thread,* **or**
- *both conflicting evaluations are atomic operations,* **or**
- *one of the conflicting evaluations happens-before another.*

Adapted from a community-backed C++ reference site. For the full version, please refer to the related sections in C++ working draft.

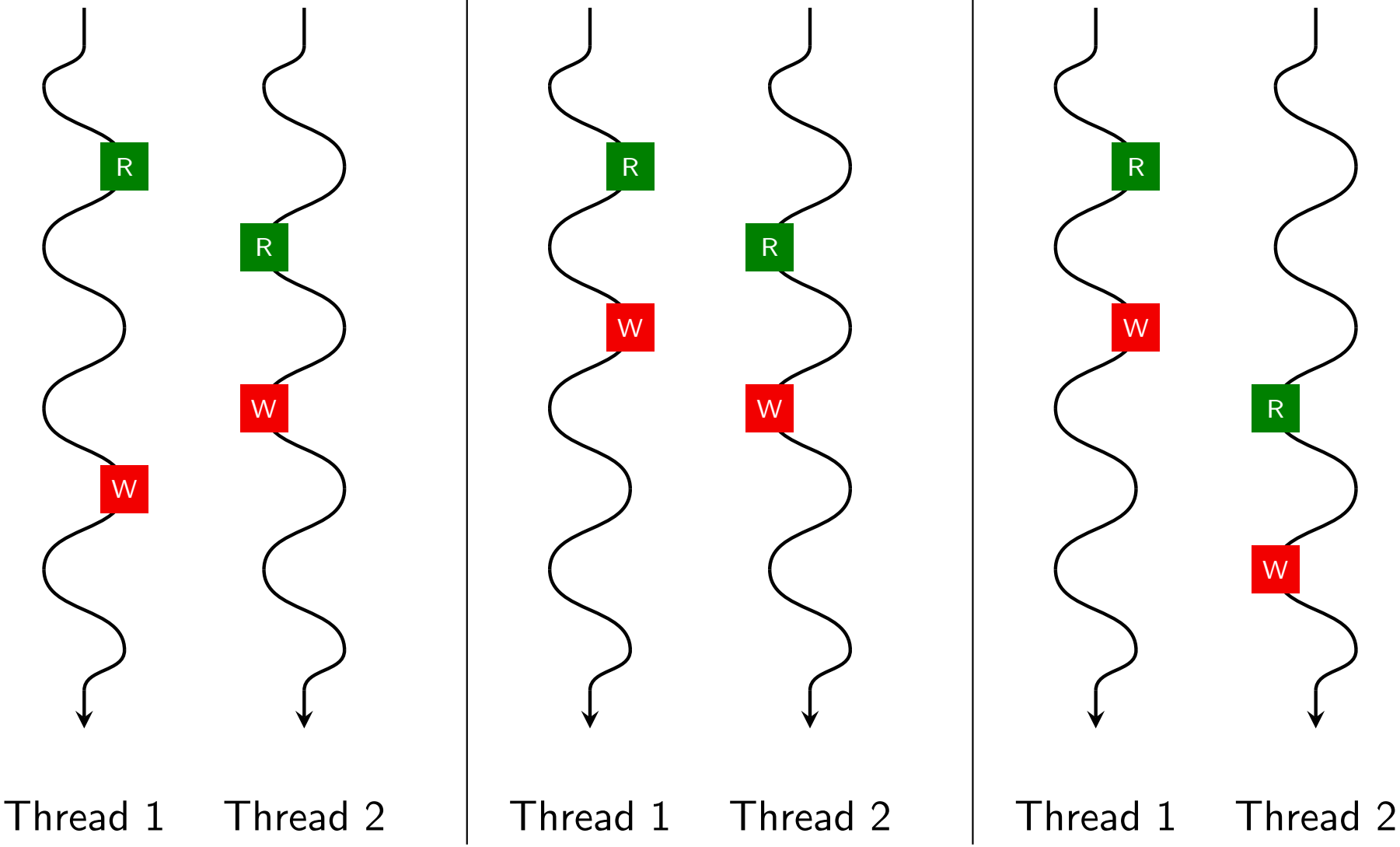
Revisit the example

```
global var count = 0
```

Thread 1	Thread 2

`for(i = 0; i < x; i++) {`
`  count++;`
`}`
	`for(i = 0; i < y; i++) {`
	`  count++;`
	`}`

Free interleavings without locking



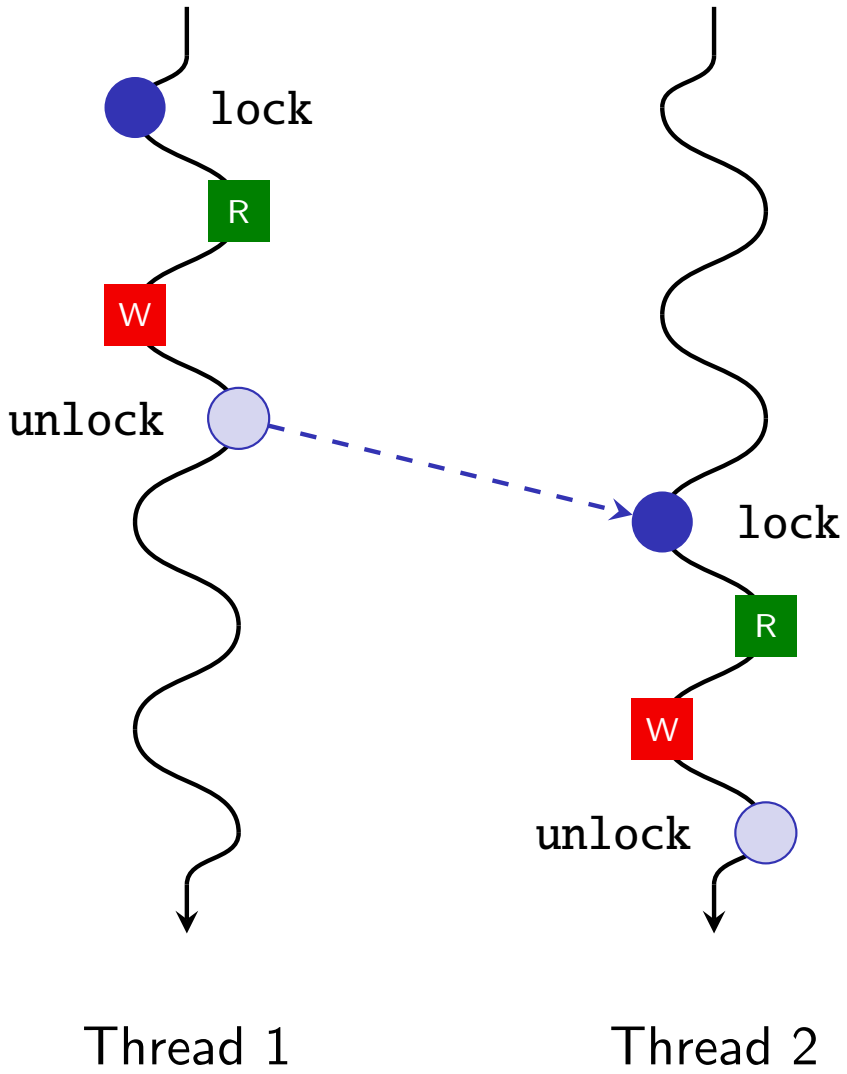
Revisit the example

```
global var count = 0
```

Thread 1	Thread 2

`for(i = 0; i < x; i++) {`
`  lock(mutex);`
`  count++;`
`  unlock(mutex);`
`}`
	`for(i = 0; i < y; i++) {`
	`  lock(mutex);`
	`  count++;`
	`  unlock(mutex);`
	`}`

Limited interleavings with locking



Common synchronization primitives

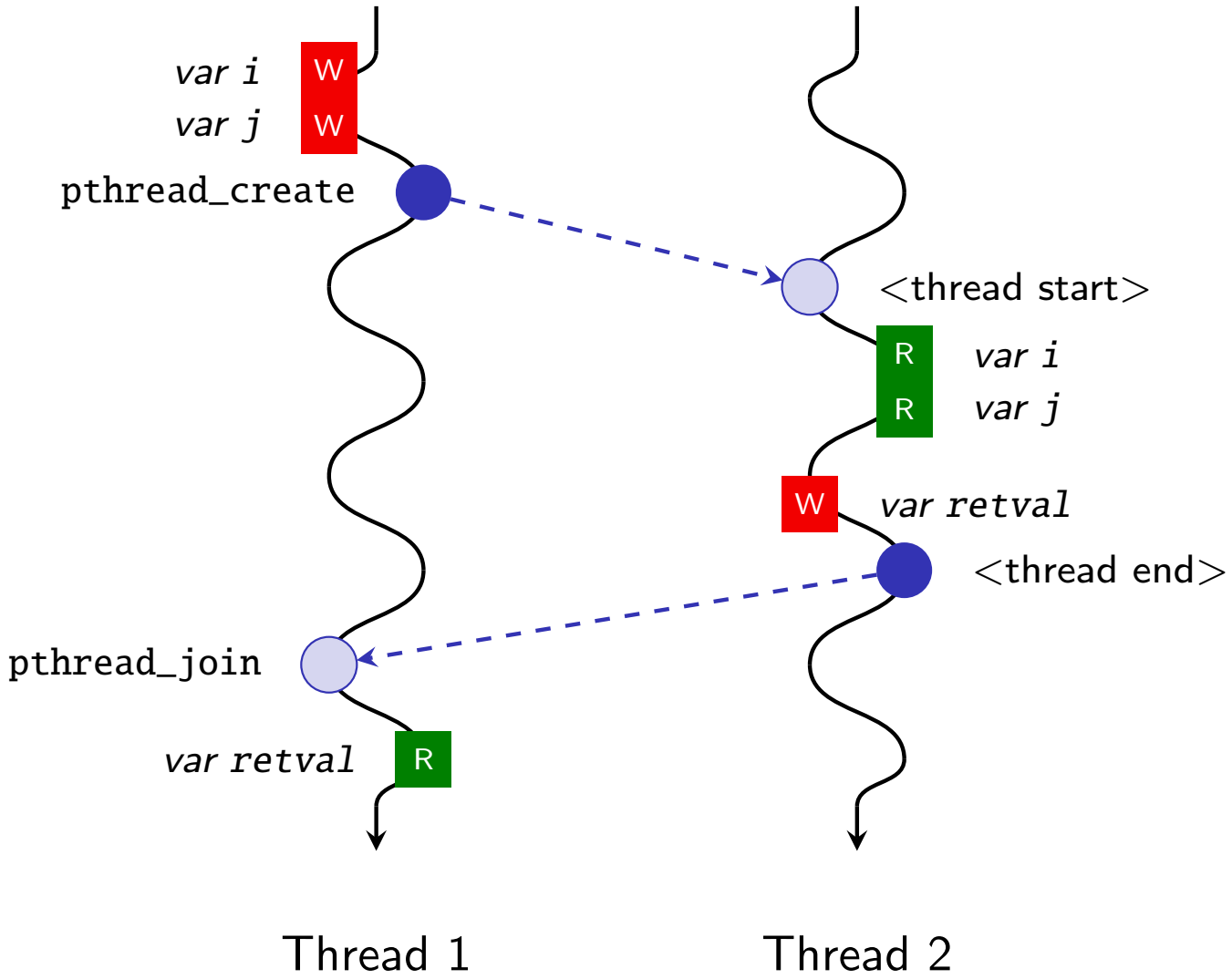
Common synchronization primitives

- Lock / Mutex / Critical section
- Read-write lock
- Barrier
- Semaphore

Causality relations: an example

```
1  #include <stdio.h>
2  #include <pthread.h>
3
4  int i;
5  int retval;
6
7  void* foo(void* p){
8      printf("Value of i: %d\n", i);
9      printf("Value of j: %d\n", *(int *)p);
10     pthread_exit(&retval);
11 }
12
13 int main(void){
14     int i = 1;
15     int j = 2;
16
17     pthread_t id;
18     pthread_create(&id, NULL, foo, &j);
19     pthread_join(id, NULL);
20
21     printf("Return value from thread: %d\n", retval);
22 }
```

Causality relations



Outline

Is this a data race?

```
1 int x = 0;
2 bool flag = false;
3 lock mutex = unlocked;
```

```
1 x++;
2 lock(mutex);
3 flag = true;
4 unlock(mutex);
```

Thread 1

```
1 while(true) {
2     lock(mutex);
3     if (flag) {
4         unlock(mutex);
5         break;
6     }
7     unlock(mutex);
8 }
9 x--;
```

Thread 2

Is this a data race?

```
1 int x = 0;
2 bool flag = false;
```

Thread 1	Thread 2
`1 x++;` `2 flag = true;`	`1 while (!flag) {};` `2 x--;`

Revisit the example

```
global var count = 0
```

Thread 1

```
for(i = 0; i < x; i++) {
  lock(mutex);
  t = count;
  unlock(mutex);

  t++;

  lock(mutex);
  count = t;
  unlock(mutex);
}
```

Thread 2

```
for(i = 0; i < y; i++) {
  lock(mutex);
  t = count;
  unlock(mutex);

  t++;

  lock(mutex);
  count = t;
  unlock(mutex);
}
```

Revisit the example

Q: In this modified example, is there a data race?

Revisit the example

Q: In this modified example, is there a data race?

A: No

Revisit the example

Q: In this modified example, is there a data race?

A: No

Q: But the results are the same with all locks removed?

```
global var count = 0
```

```
for(i = 0; i < x; i++) {
   t = count;
   t++;
   count = t;
}
```

```
for(i = 0; i < y; i++) {
   t = count;
   t++;
   count = t;
}
```

Revisit the example

Q: In this modified example, is there a data race?

A: No

Q: But the results are the same with all locks removed?

```
global var count = 0
```

```
for(i = 0; i < x; i++) {
  t = count;
  t++;
  count = t;
}
```

```
for(i = 0; i < y; i++) {
  t = count;
  t++;
  count = t;
}
```

A: No, depending on how hardware works (e.g., per-bit conflict)

Extract the commonalities of the two variants

Q: What is common in developers' expectations in the two variants?

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A: States do not change for a critical section during execution.

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A: States do not change for a critical section during execution.

A: **Generalization**: states remain integral for a critical section during execution. No change of states is just one way of remaining integral (assuming state is integral before the critical section).

State integrity example

```
1 struct R { x: int, y: int } g;
2 [invariant] g.x + g.y == 100;
```

Thread 1

```
1 int add_x(v: int) {
2   g.x += v;
3   g.y -= v;
4 }
```

Thread 2

```
1 int add_y(v: int) {
2   g.y += v;
3   g.x -= v;
4 }
```

State integrity example

```
1 struct R { x: int, y: int } g;
2 [invariant] g.x + g.y == 100;
3 lock mutex = unlocked;
```

```
1 int add_x(v: int) {
2   lock(mutex);
3   g.x += v;
4   unlock(mutex);
5   lock(mutex);
6   g.y -= v;
7   unlock(mutex);
8 }
```

Thread 1

```
1 int add_y(v: int) {
2   lock(mutex);
3   g.y += v;
4   unlock(mutex);
5   lock(mutex);
6   g.x -= v;
7   unlock(mutex);
8 }
```

Thread 2

Q: Is this the right way of adding locks?

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7   unlock(mutex);
8 }
```

Thread 2

Q: Is this the right way of adding locks?

A: No, as the invariant is not guaranteed

State integrity example

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Q: Is this the right way of adding locks?

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```

Thread 2

Q: Is this the right way of adding locks?

A: Yes, the invariant is guaranteed at each entry and exit of the critical section in both threads

State integrity is hard to capture

However, in practice, the invariant often exists in

- some architectural design documents (which no one reads)
- code comments in a different file (which no one notices)
- forklore knowledge among the dev team
- the mind of the developer who has resigned a few years ago...

Outline

Conclusion

All these bugs are violations of developers' expectations.

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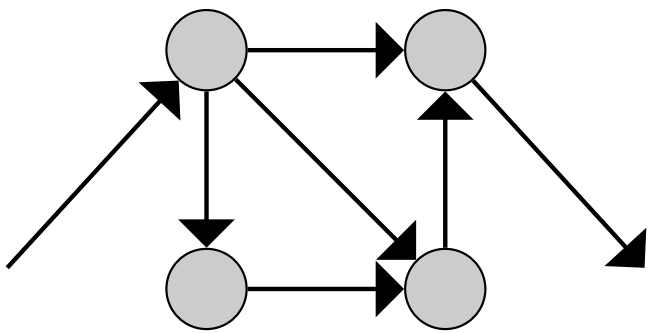

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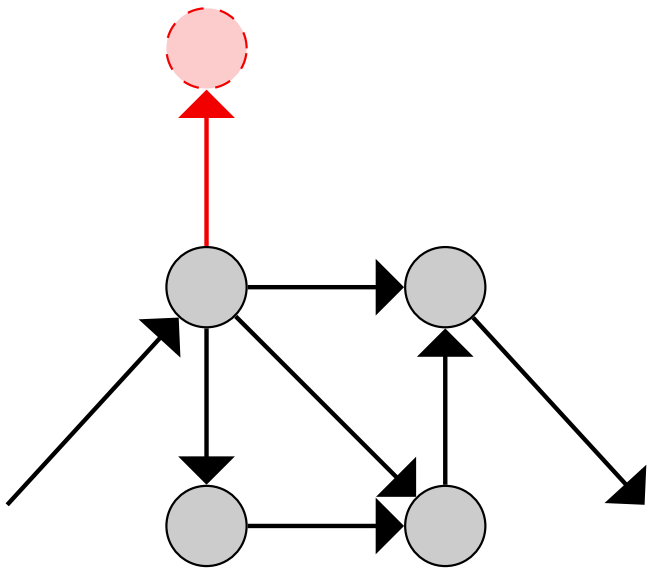

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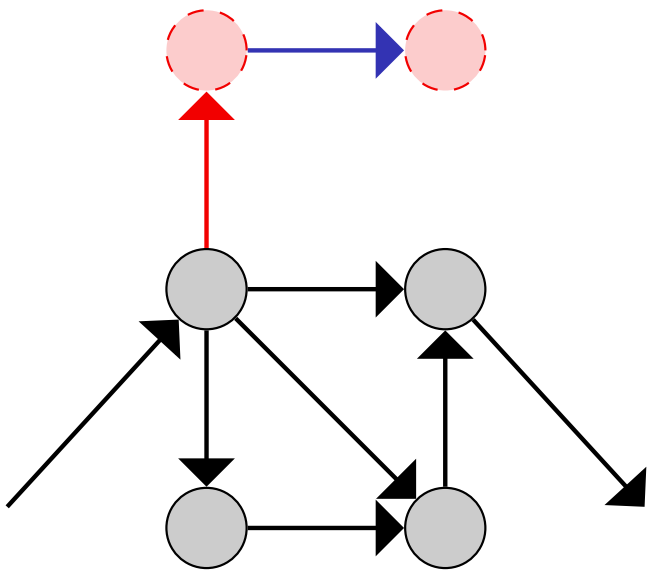

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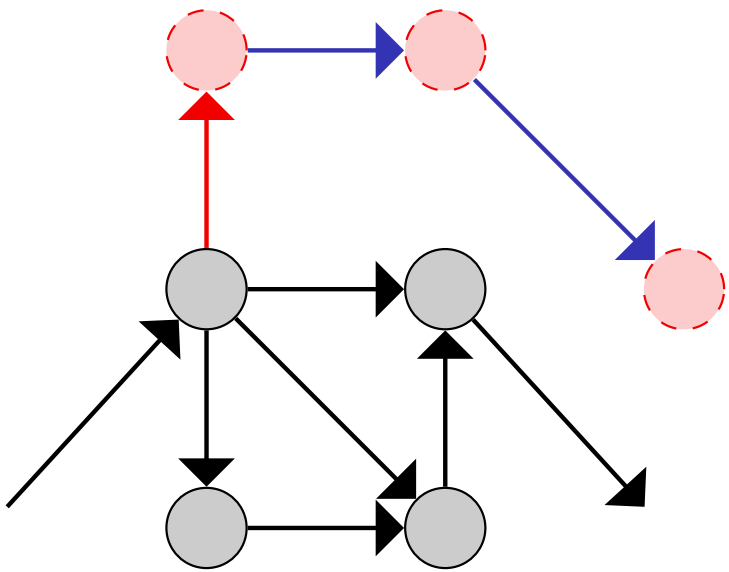

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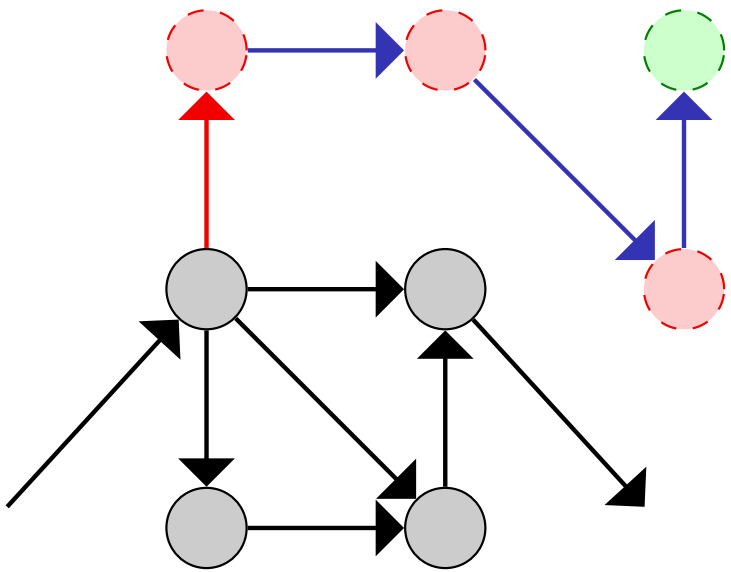

⟨ End ⟩