Deadlock Immunity

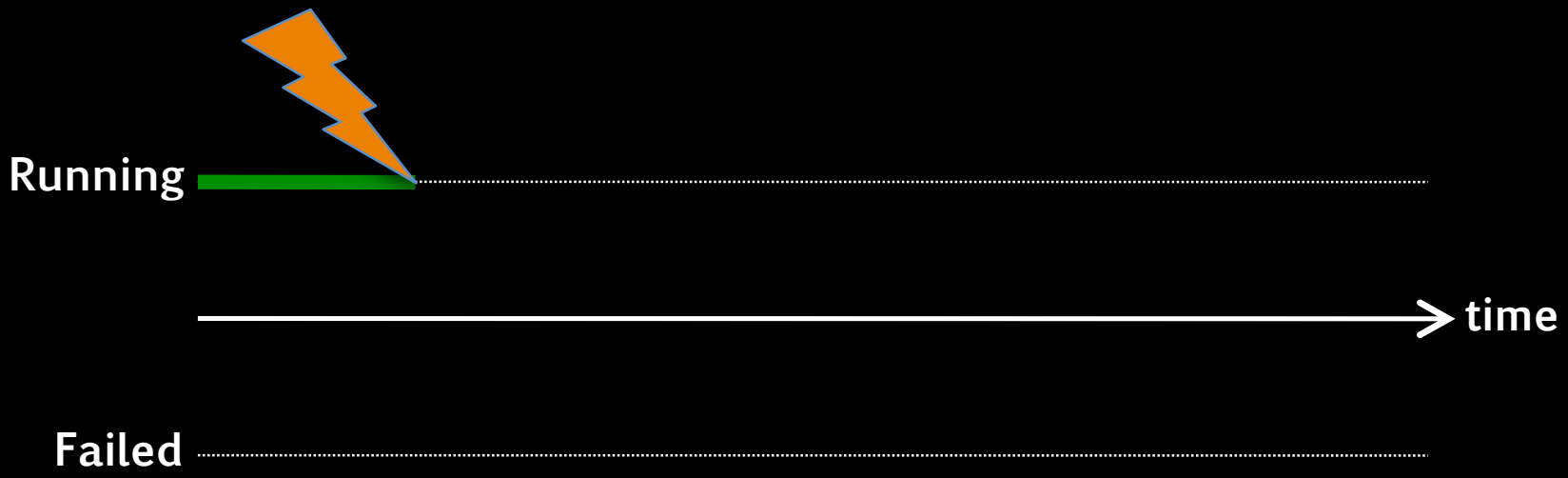
Enabling Systems To Defend Against Deadlocks

Horatiu Jula, Daniel Tralamazza,
Cristian Zamfir, George Candea

Dependable Systems Laboratory

Real Software System

Real Software System



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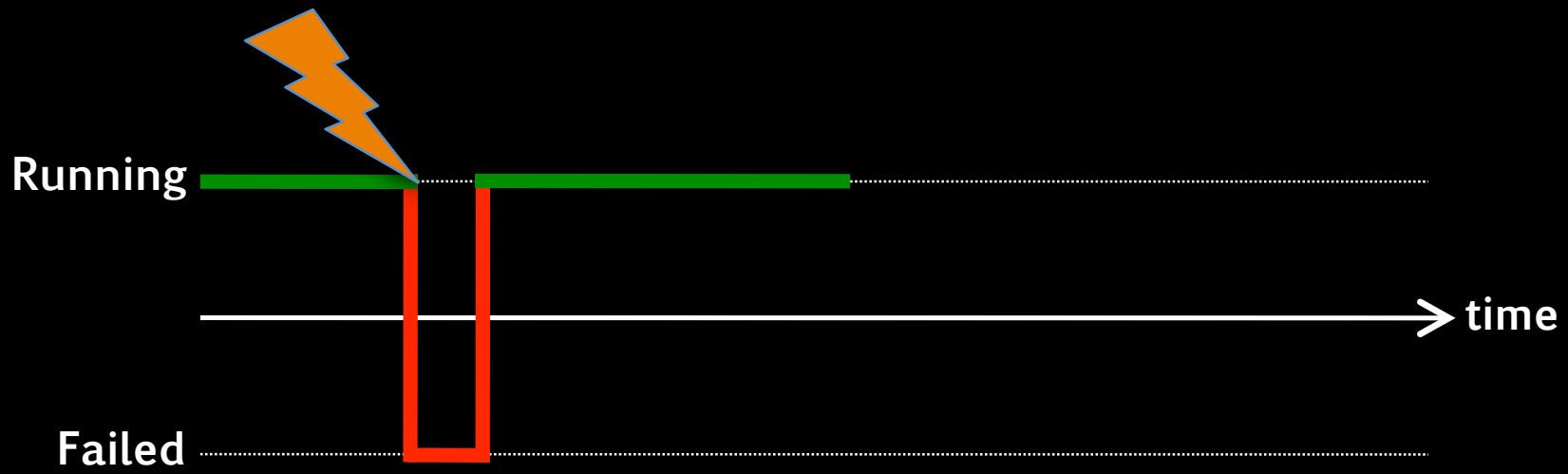

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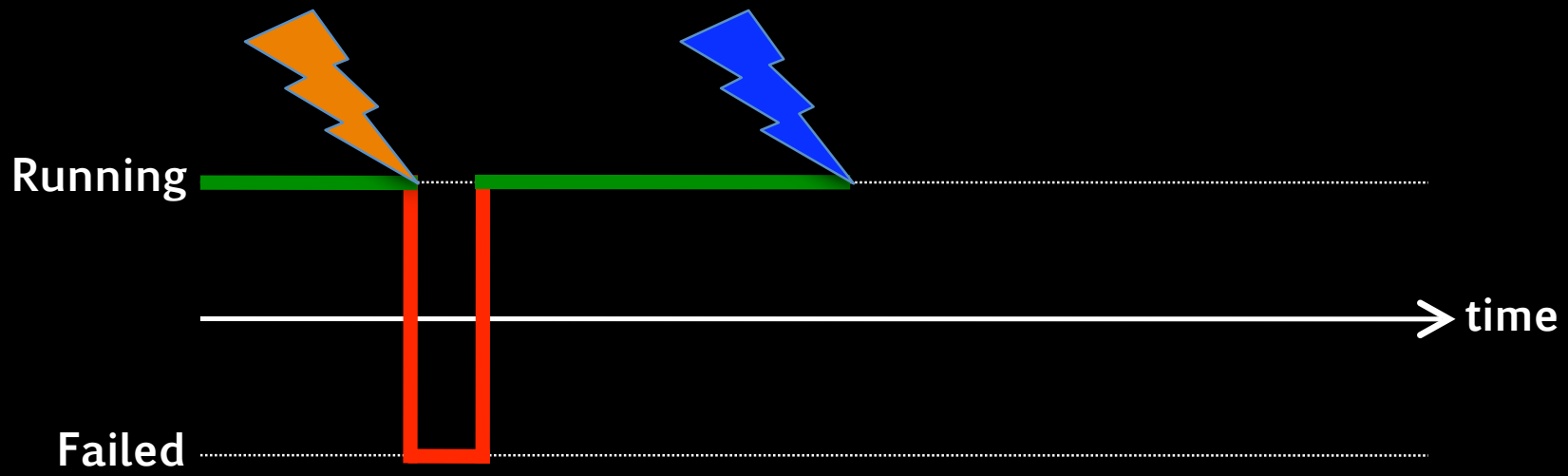

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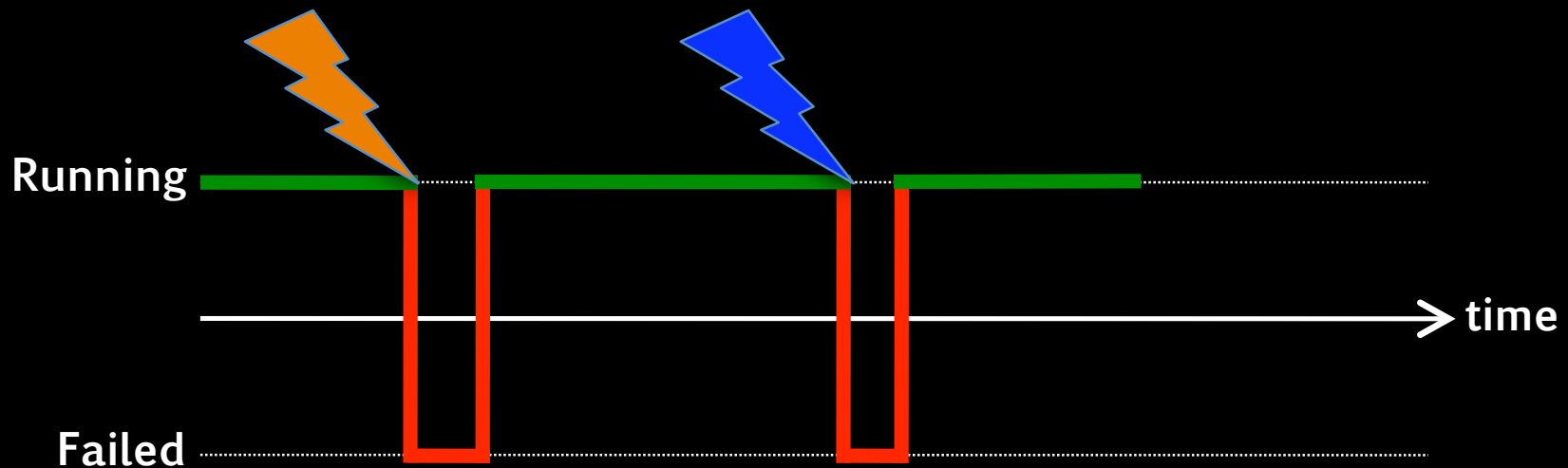

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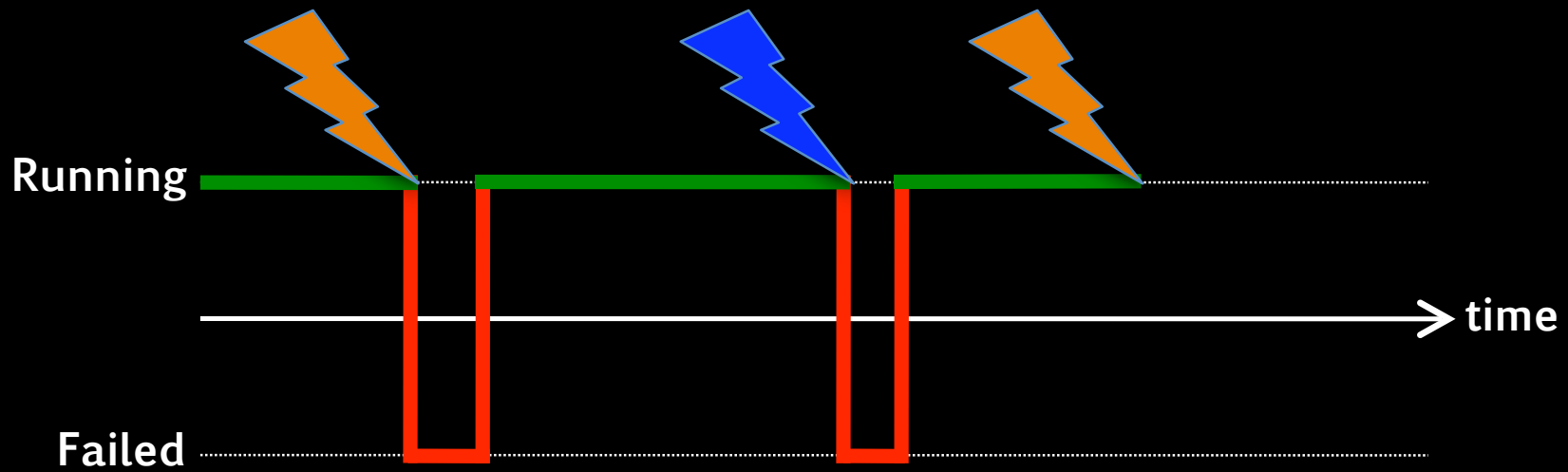

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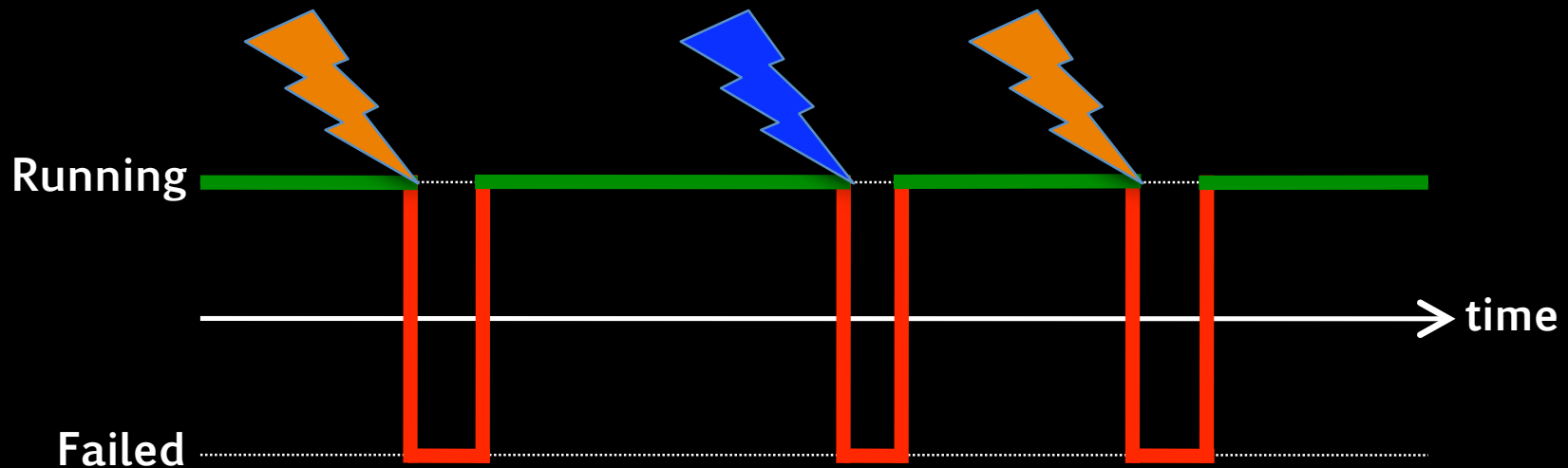

Real Software System

Real Software with An Immune System

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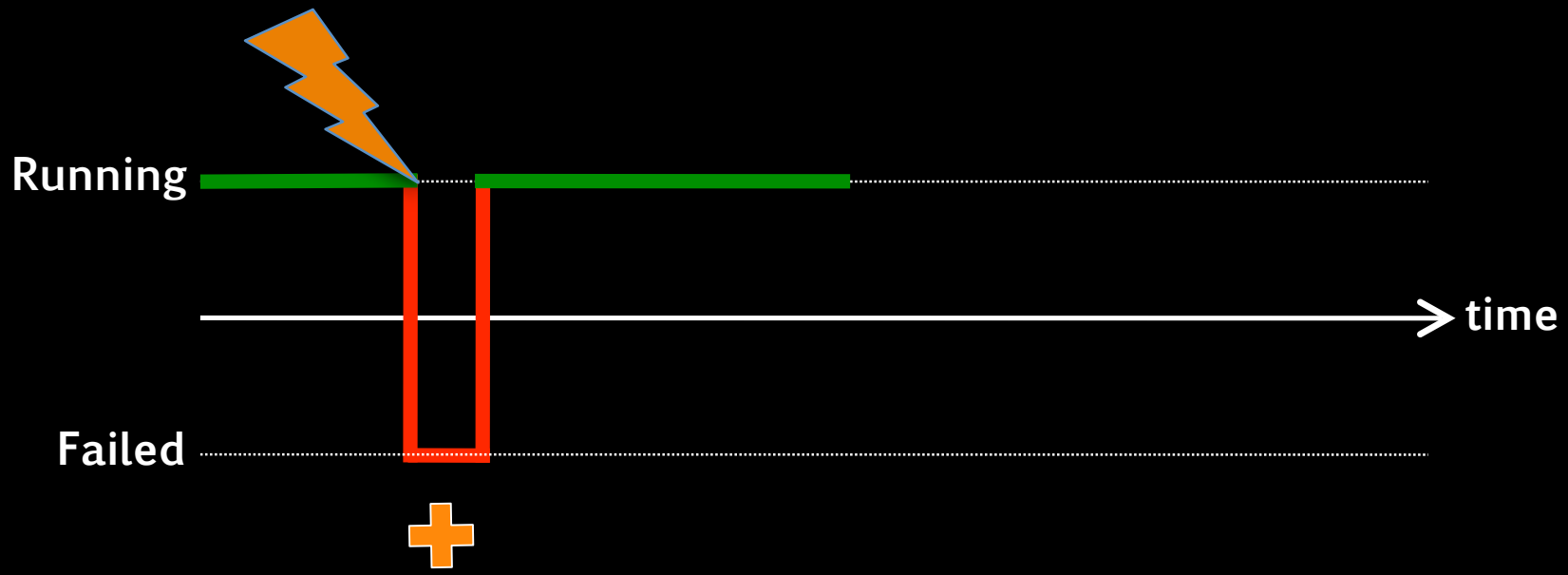

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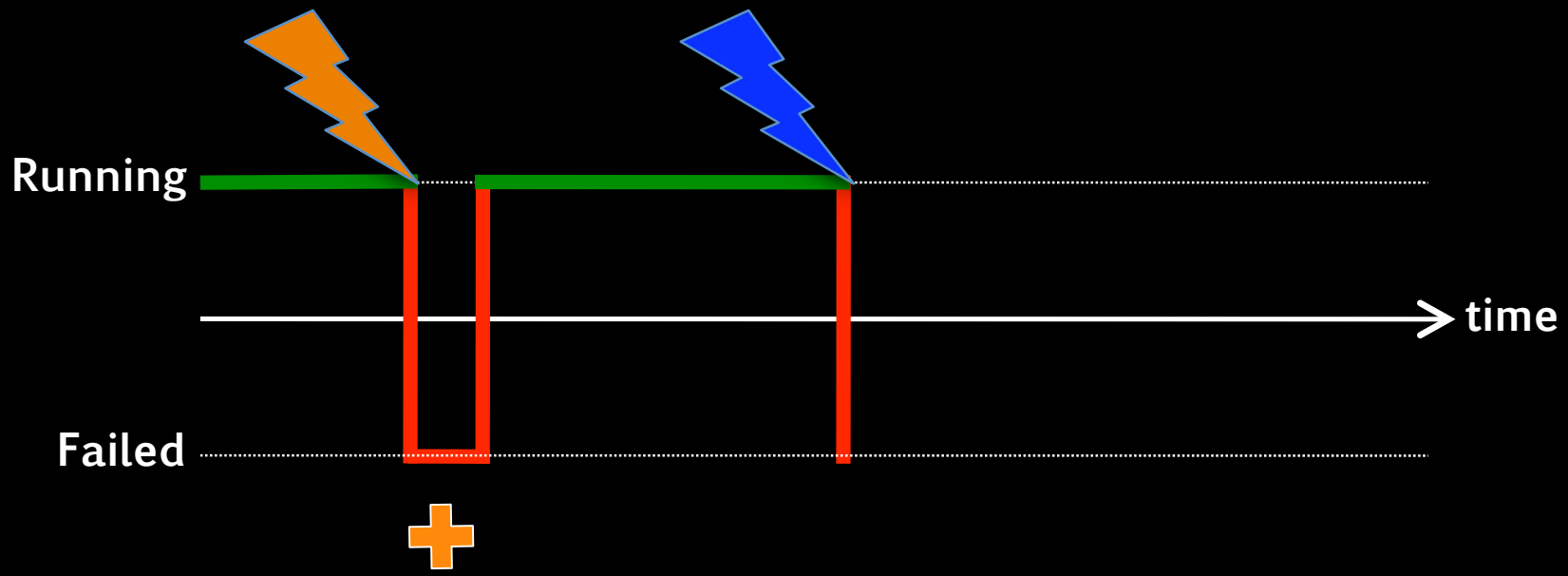

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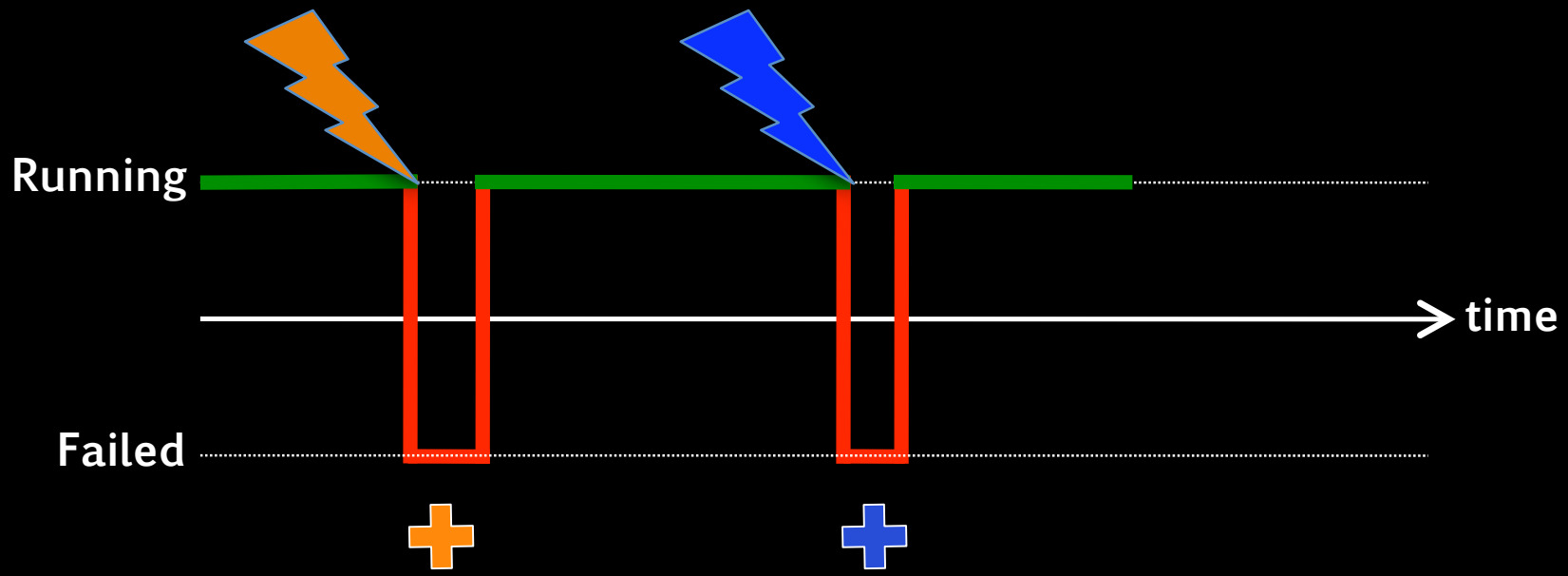

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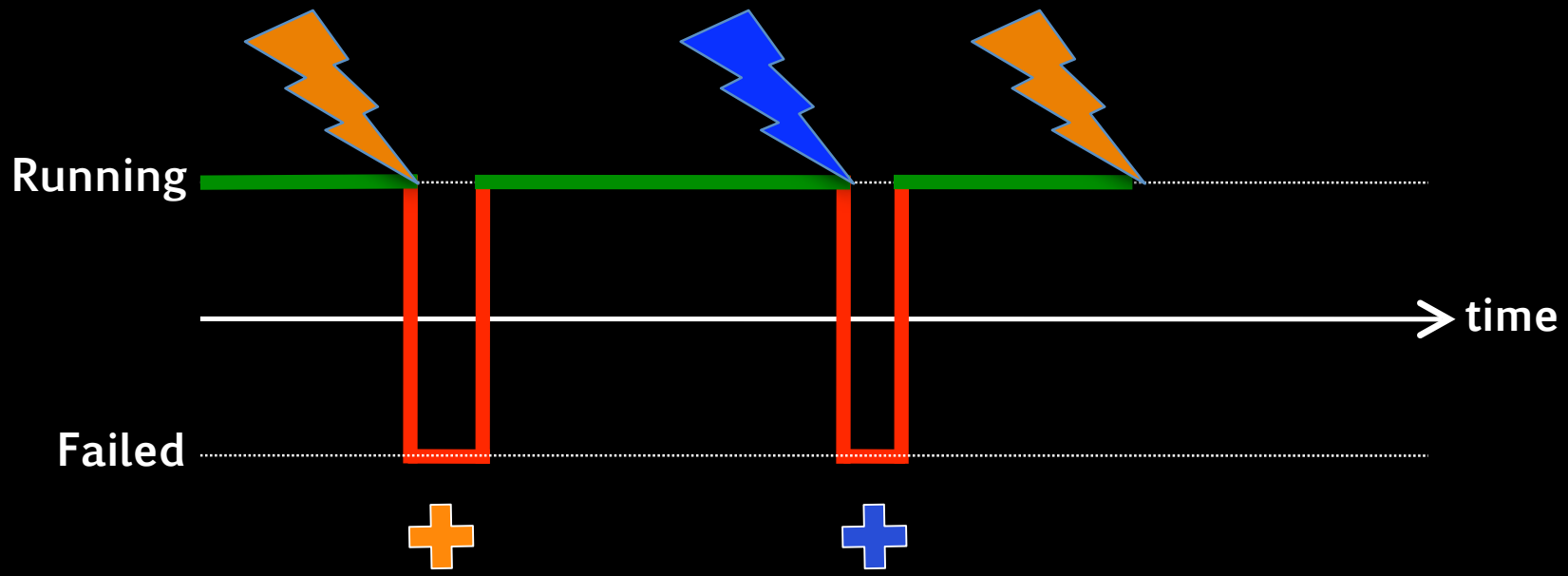

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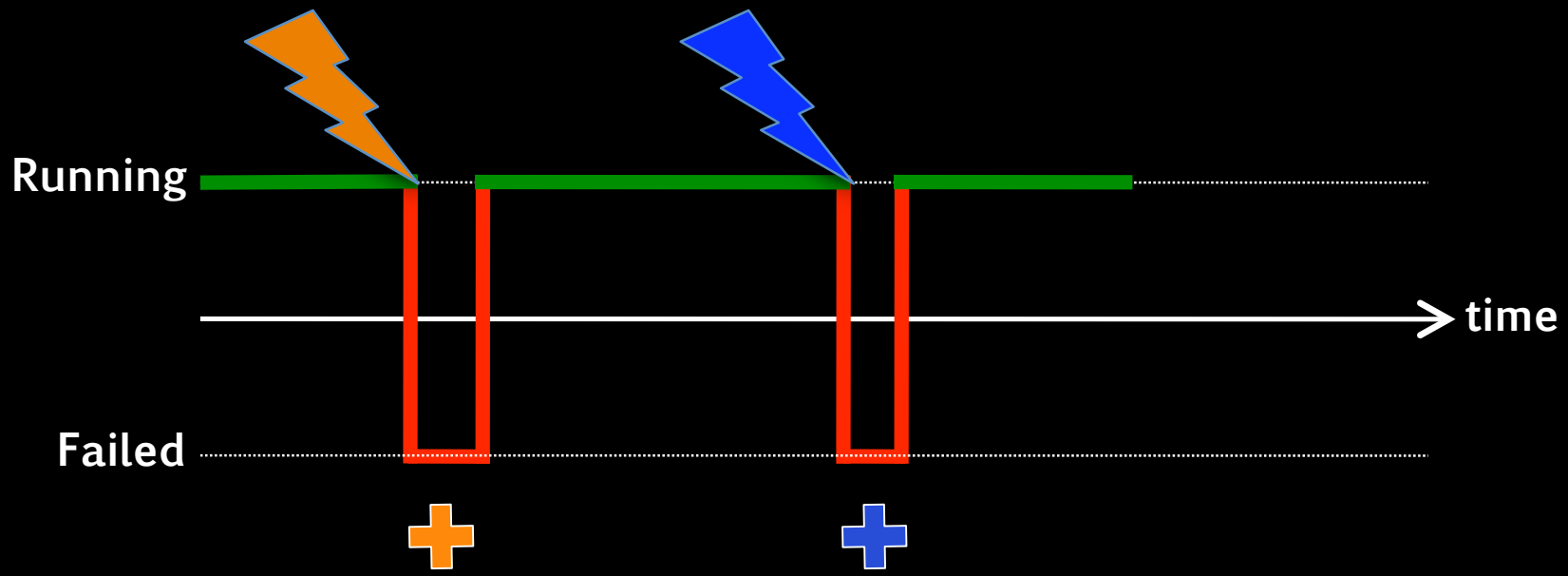

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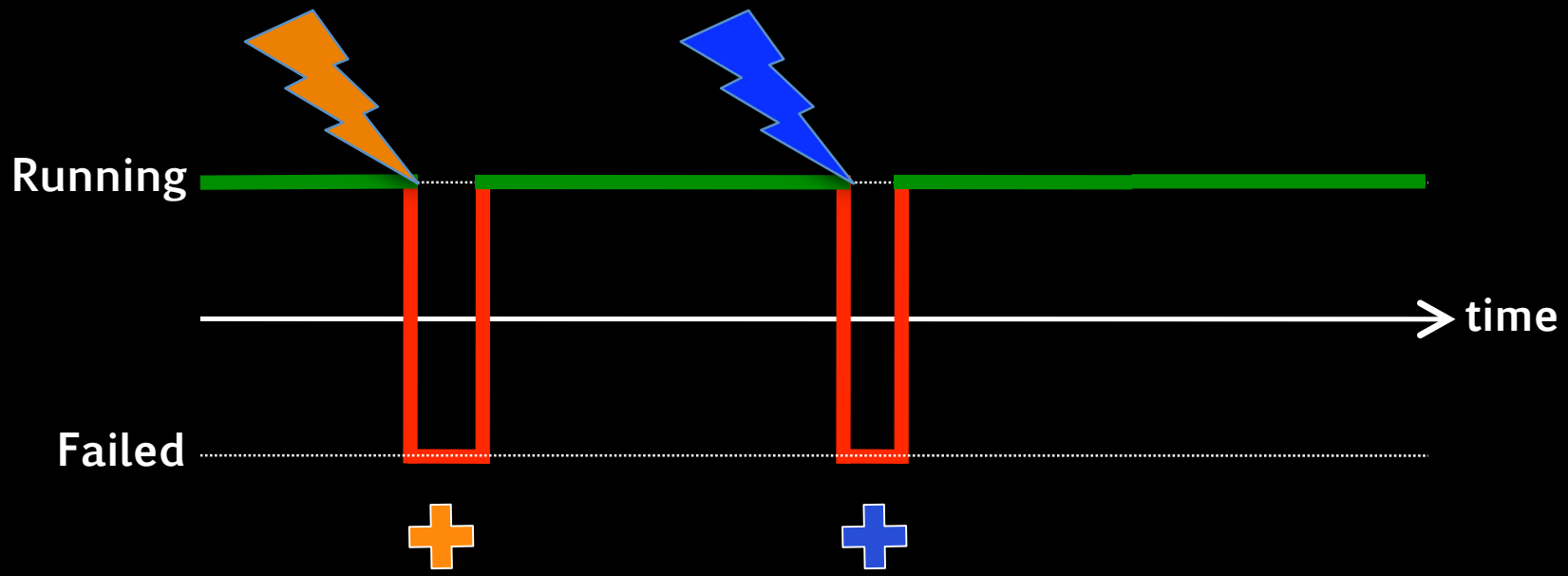

Real Software with An Immune System

Outline

- Immunity Against Deadlocks
- Dimmunix Overview
- Challenges & Solutions
- Discussion & Conclusions

Deadlock Immunity

- Learn executions that lead to deadlock
- Save fingerprints of encountered deadlock patterns into a persistent history
- Avoid executions patterns that have led to deadlock in the past

Example Uses

- **Software vendors**
  - *Example:* **Protect a deadlock-free Web browser**
    - **Users extend browsers with plugins not controlled by the vendor… these can deadlock the browser**
    - **Deadlock occurs → obtain fingerprint → distribute it to all**
- **End users**
  - *Example:* **Deadlock-prone closed-source legacy DB server**
    - **Develop immunity against deadlocks**
    - **No need to upgrade or wait for patches**

```
NLboolean nlClose(NLsocket socket)
{
  if(driver)
  {
    if(nlIsValidSocket(socket) == NL_TRUE)
    {
      nlLockSocket(socket, NL_BOTH);
      driver->Close(socket);
      nlMutexLock(&socklock);
      nlReturnSocket(socket);
      nlMutexUnlock(&socklock);
      nlUnlockSocket(socket, NL_BOTH);
      return NL_TRUE;
    }
    else
    {
      nlSetError(NL_INVALID_SOCKET);
      return NL_TRUE;
    }
  }
  nlSetError(NL_NO_NETWORK);
  return NL_FALSE;
}
```

```
void nlShutdown(void)
{
  if(--nlInitCount > 0)
        return;
  nlMutexLock(&socklock);
  if(nlSockets != NULL)
  {
    NLsocket i;
    for(i=0;i<nlNextsocket;i++)
    {
      if(nlSockets[i] != NULL)
      {
        nlLockSocket(i, NL_BOTH);
        driver->Close(i);
        nlReturnSocket(i);
        nlUnlockSocket(i, NL_BOTH);
        nlFreeSocket(i);
      }
    }
    free(nlSockets);
    nlSockets = NULL;
  }
  nlMutexUnlock(&socklock);
  if(driver != NULL)
  {
    driver->Shutdown();
    driver->initialized = NL_FALSE;
    driver = NULL;
  }
  else
  {
     ....
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```

Thread 1

```
nlLockSocket(socket, NL_BOTH);
nlMutexLock(&socklock);
```

Thread 2

```
nlMutexLock(&socklock);
nlLockSocket(socket, NL_BOTH);
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Thread 1

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nlLockSocket(socket, NL_BOTH);
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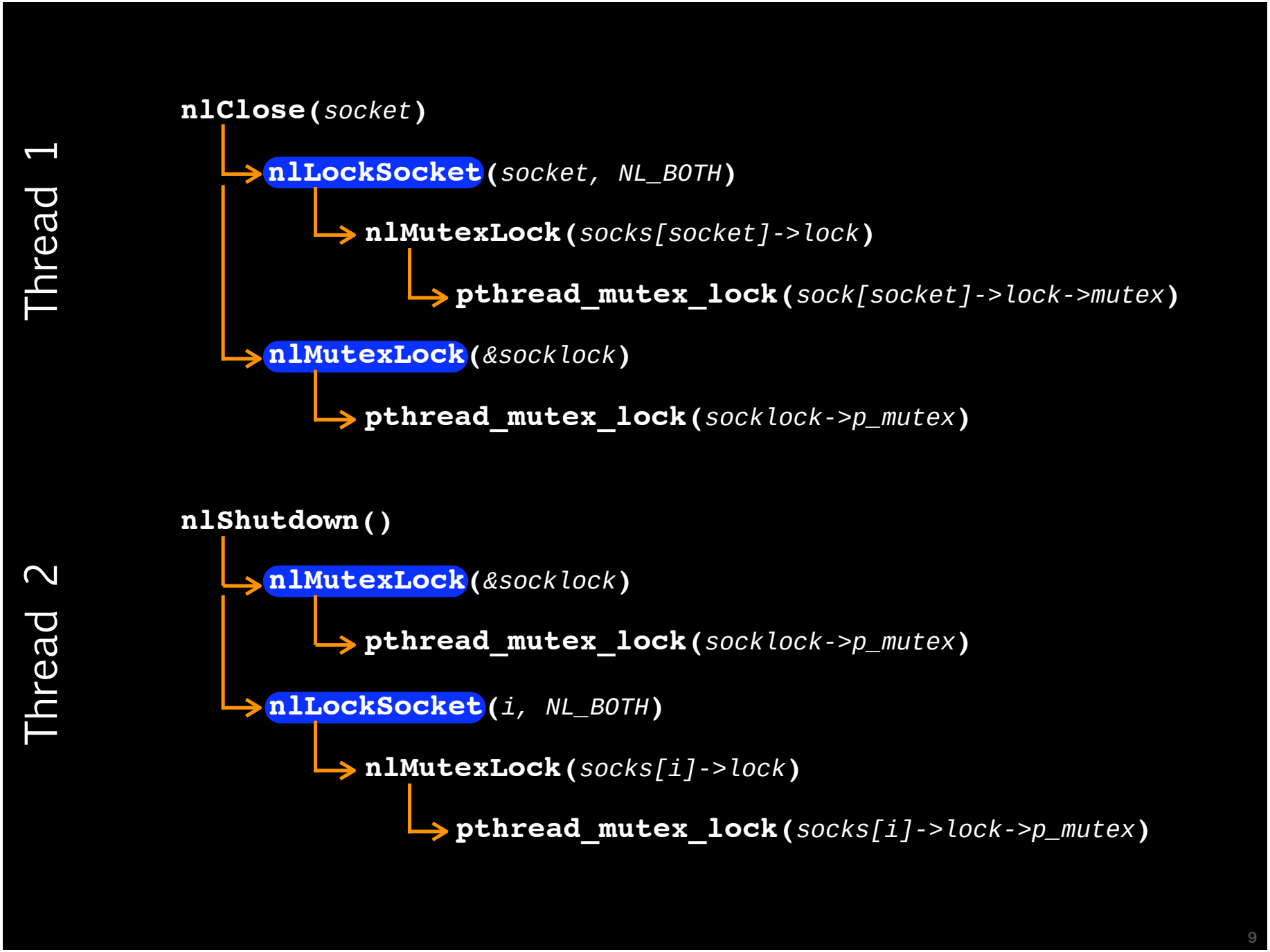
Thread 2

```
nlMutexLock(&socklock);
nlLockSocket(socket, NL_BOTH);
```

Lock Inversion => Deadlock Bug

```
nlLockSocket(socket, NL_BOTH)
nlMutexLock(&socklock)
```

```
nlMutexLock(&socklock)
nlLockSocket(i, NL_BOTH)
```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nlLockSocket(socket, NL_BOTH)
nlMutexLock(socks[socket]->lock)
pthread_mutex_lock(sock[socket]->lock->mutex)
nlMutexLock(&socklock)
pthread_mutex_lock(socklock->p_mutex)
Thread 2
nlShutdown()
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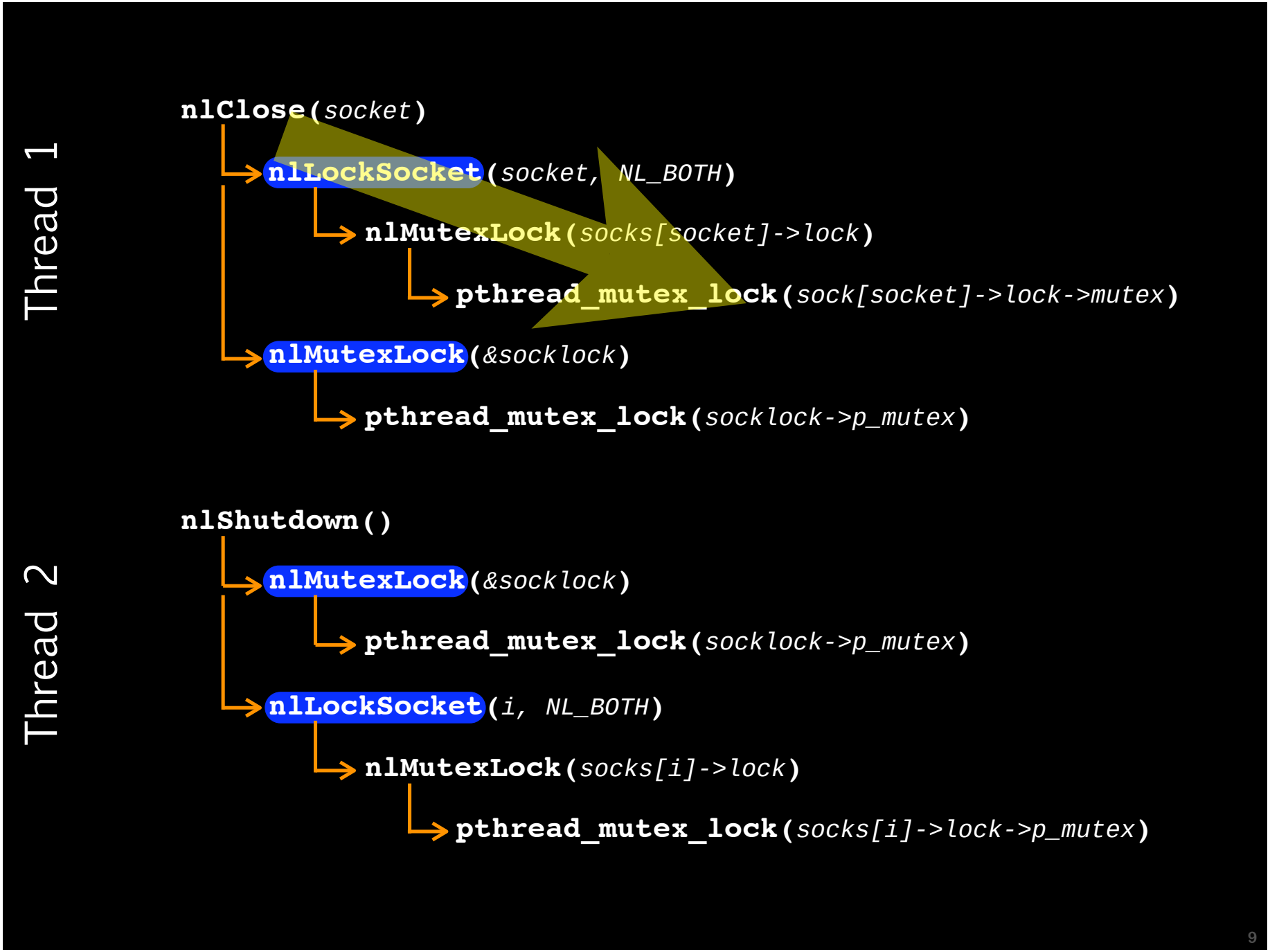
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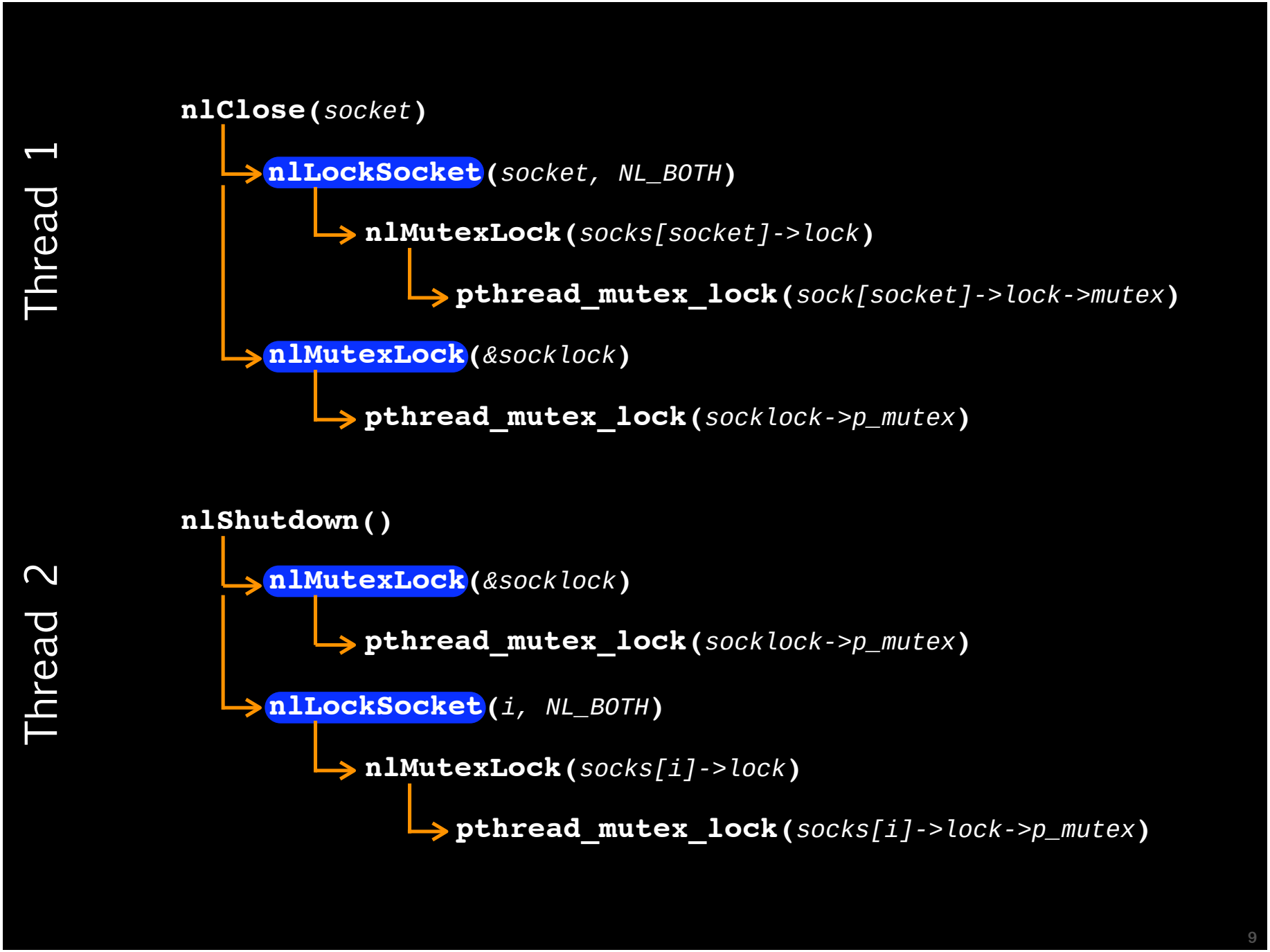
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Thread 1

```
nlClose
    nlLockSocket
        nlMutexLock
            pthread_mutex_lock
    nlMutexLock
        pthread_mutex_lock
```

Thread 2

```
nlShutdown
    nlMutexLock
        pthread_mutex_lock
    nlLockSocket
        nlMutexLock
            pthread_mutex_lock
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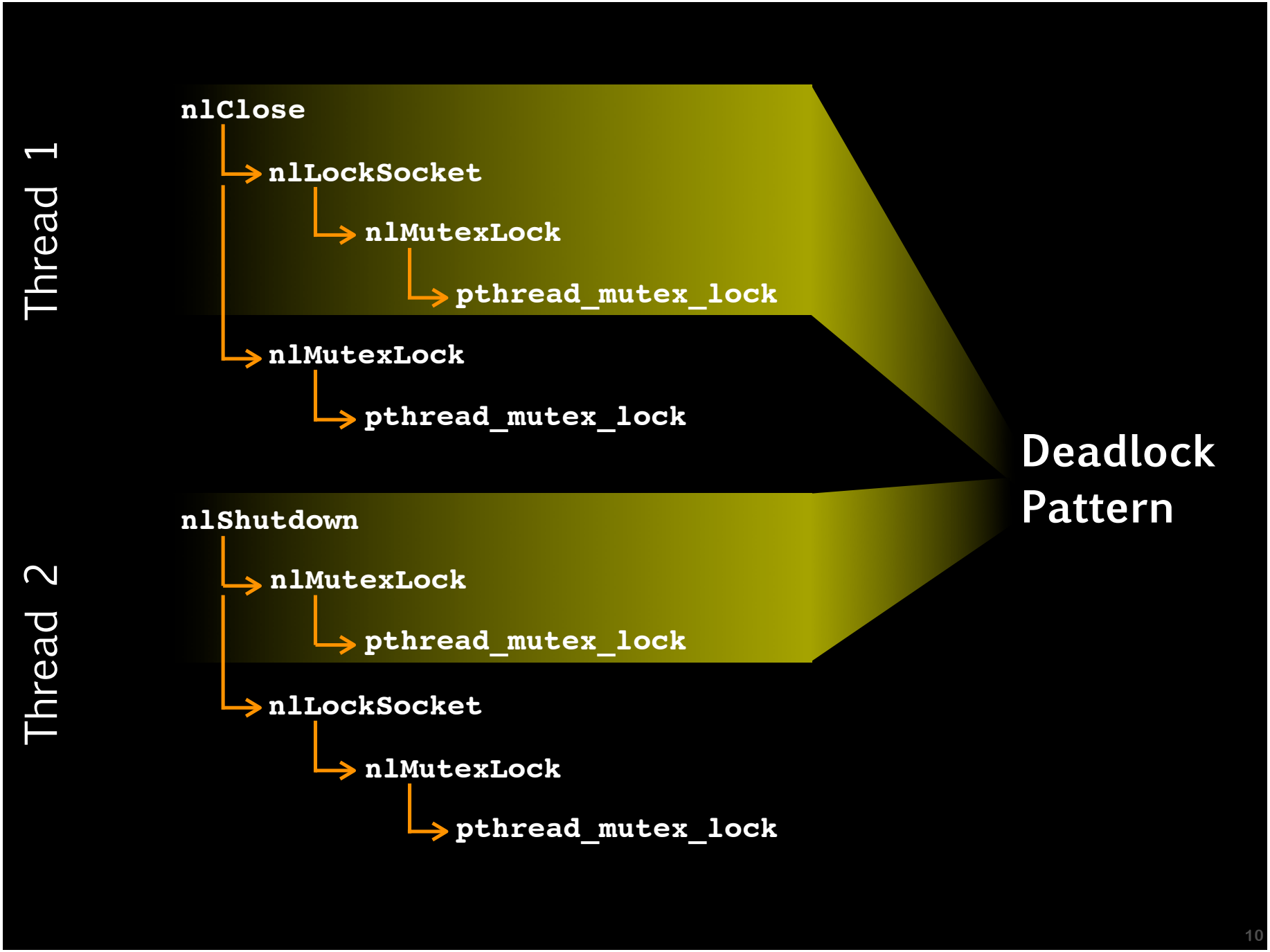
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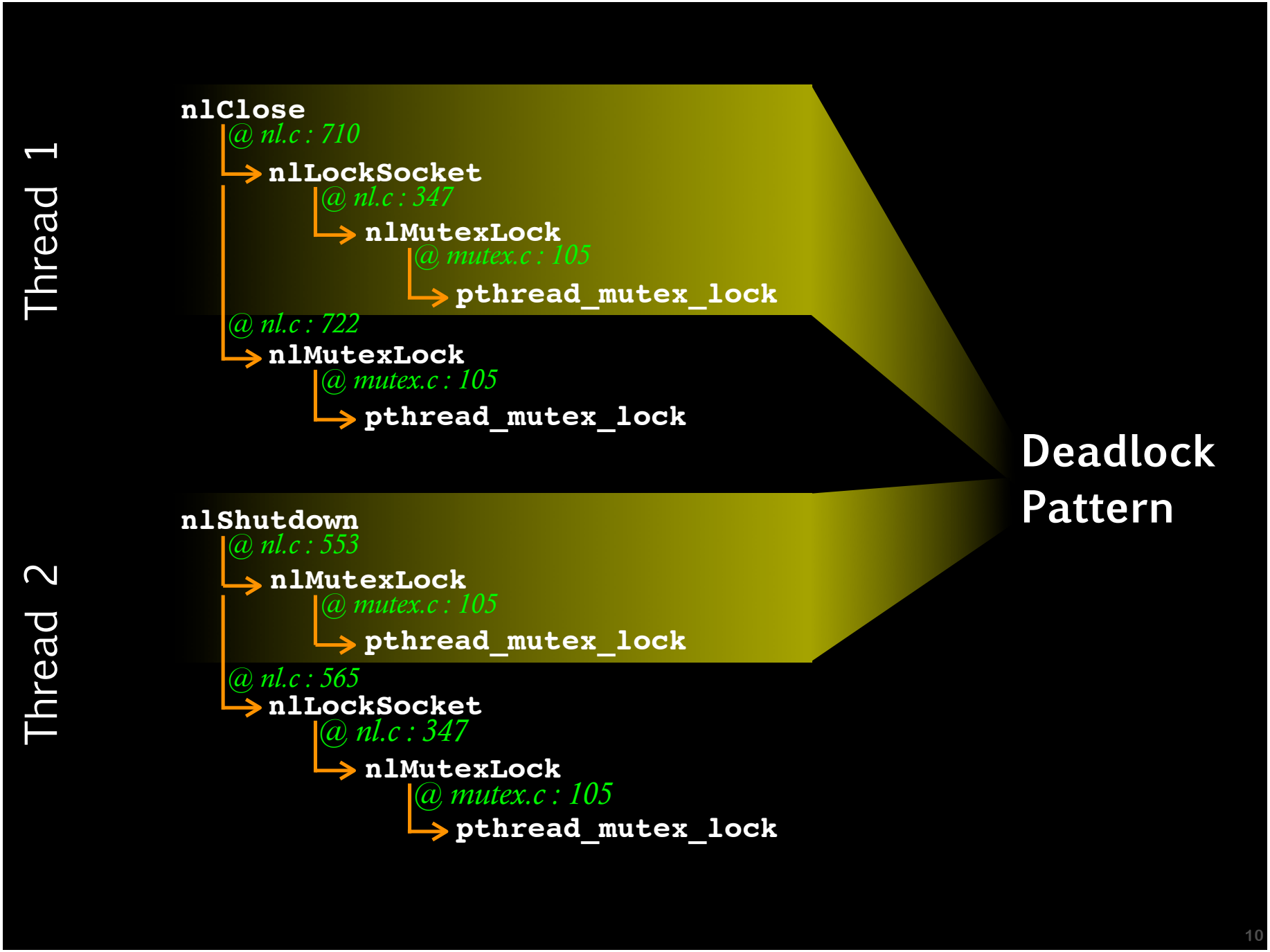
Deadlock Pattern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nlMutexLock
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pthread_mutex_lock
Thread 2
nlShutdown
@ nl.c : 553
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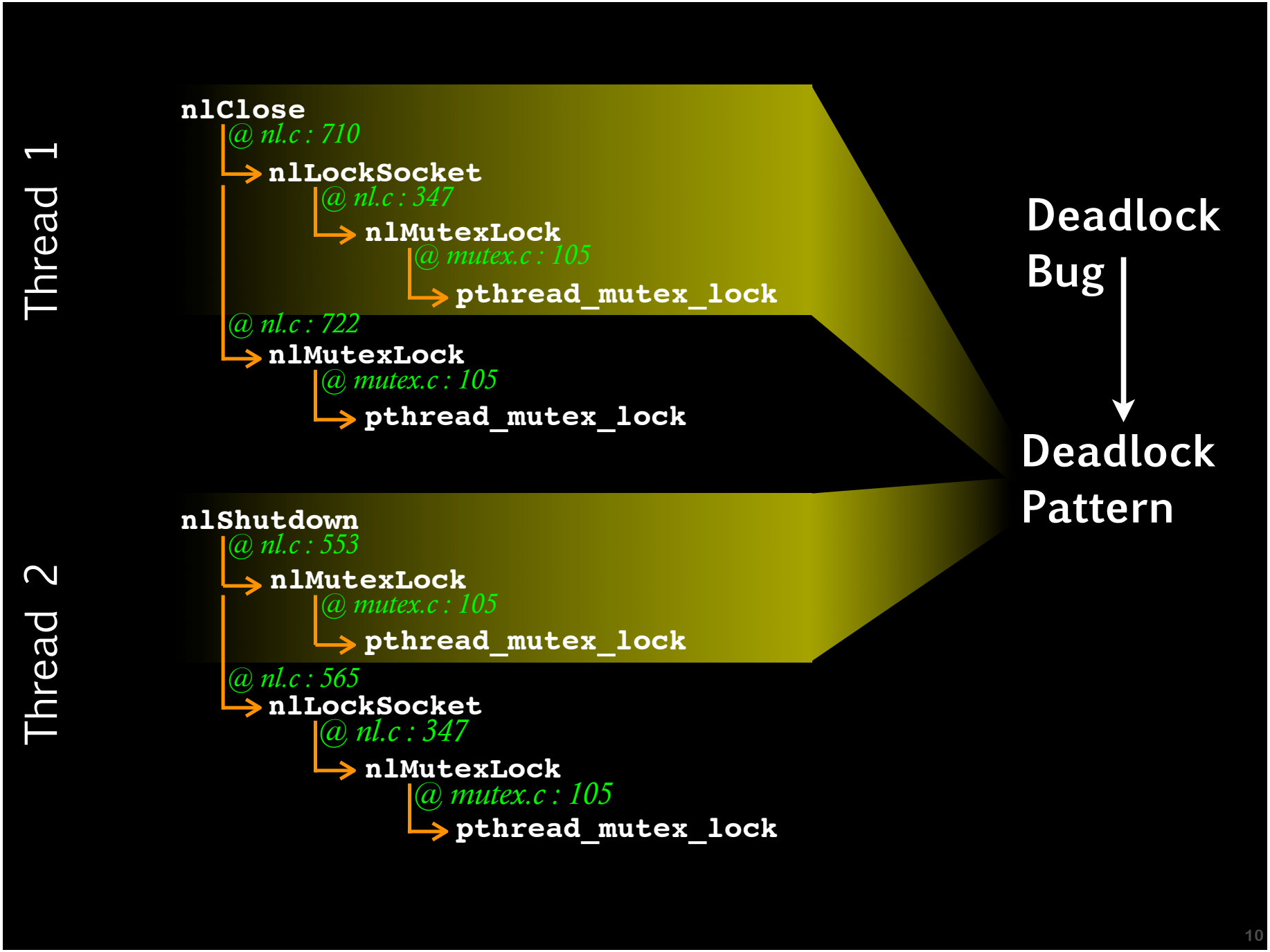
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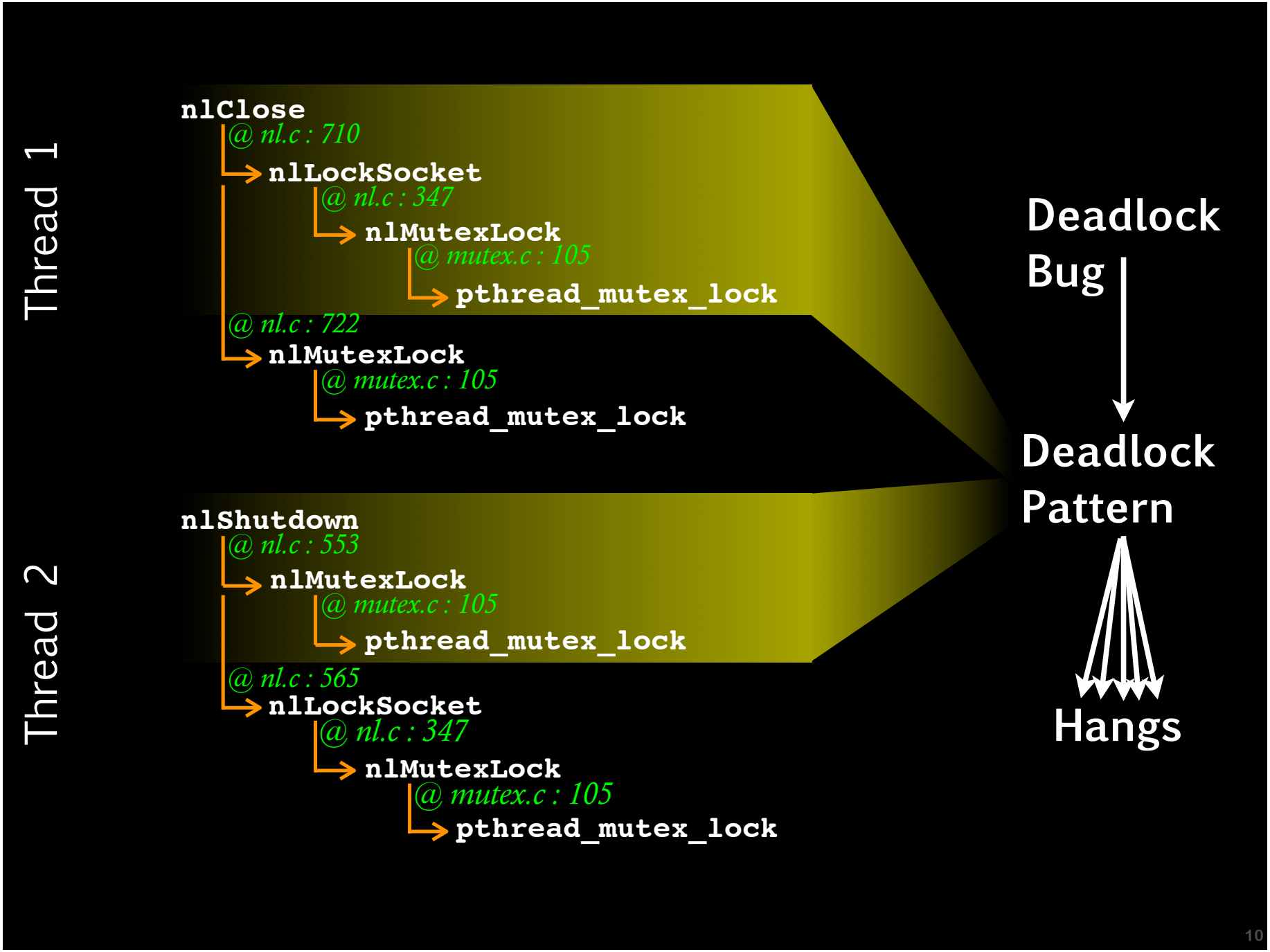
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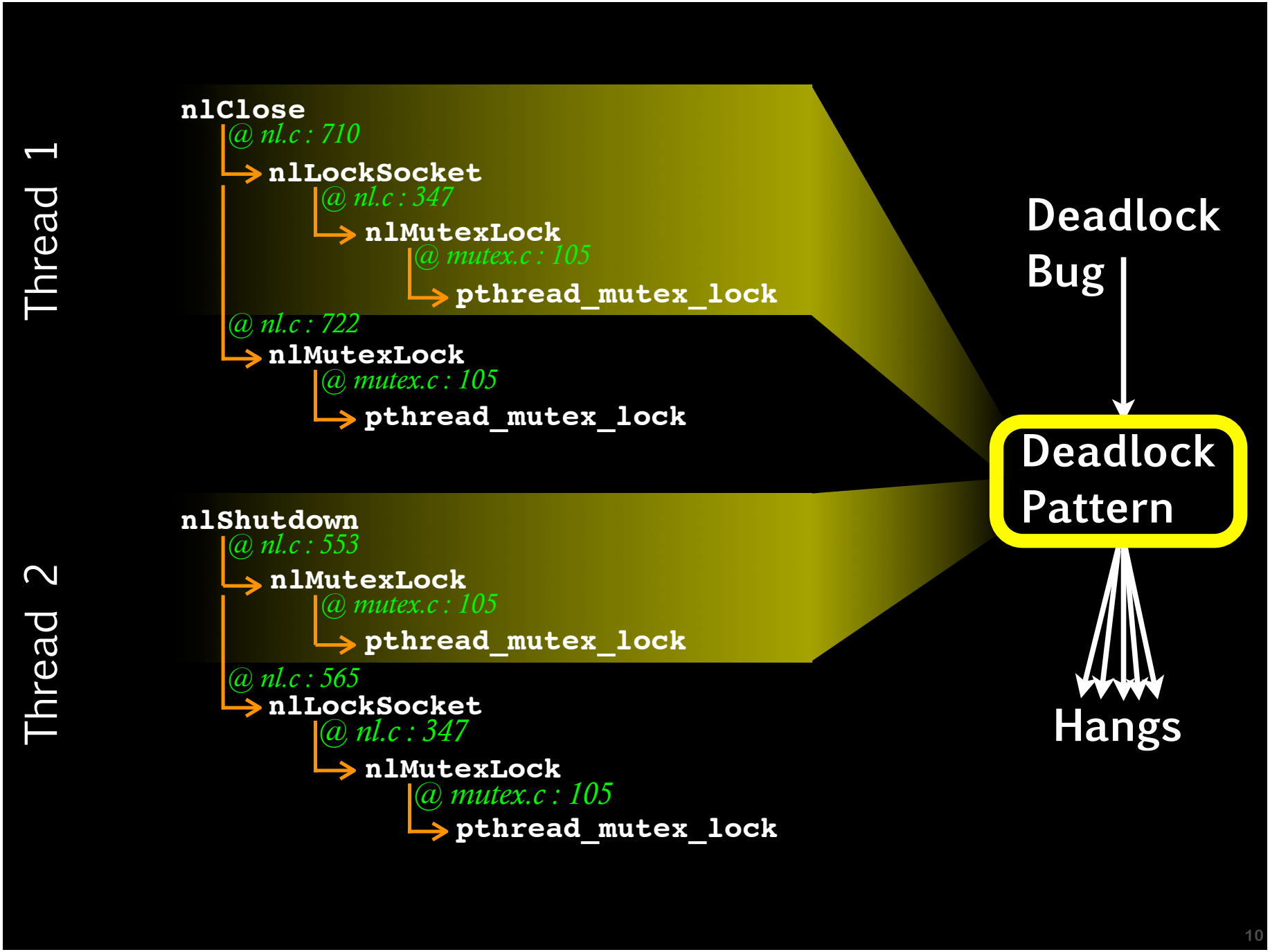
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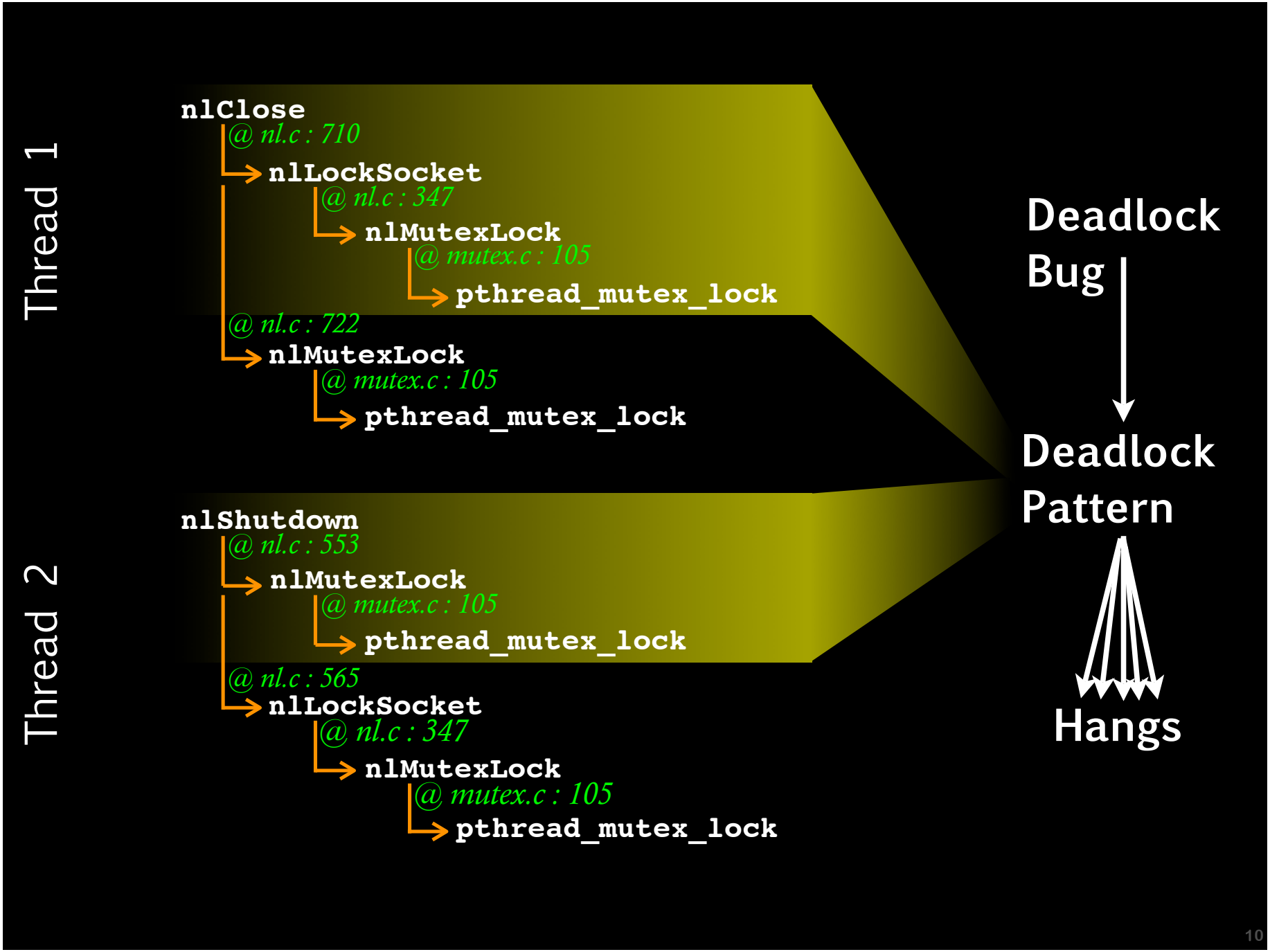
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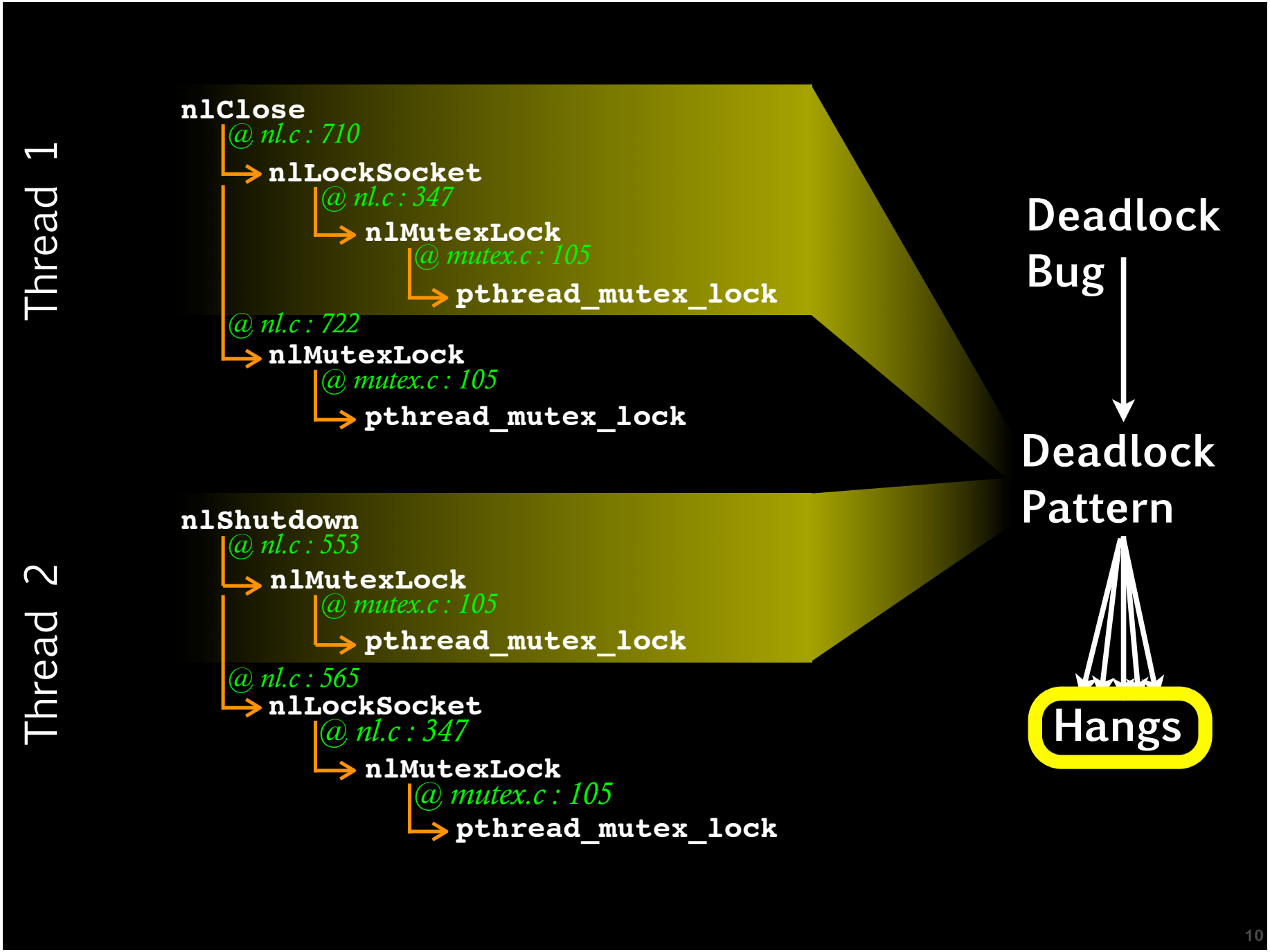
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- Saves the observed deadlock pattern
- Avoids executions that match saved patterns

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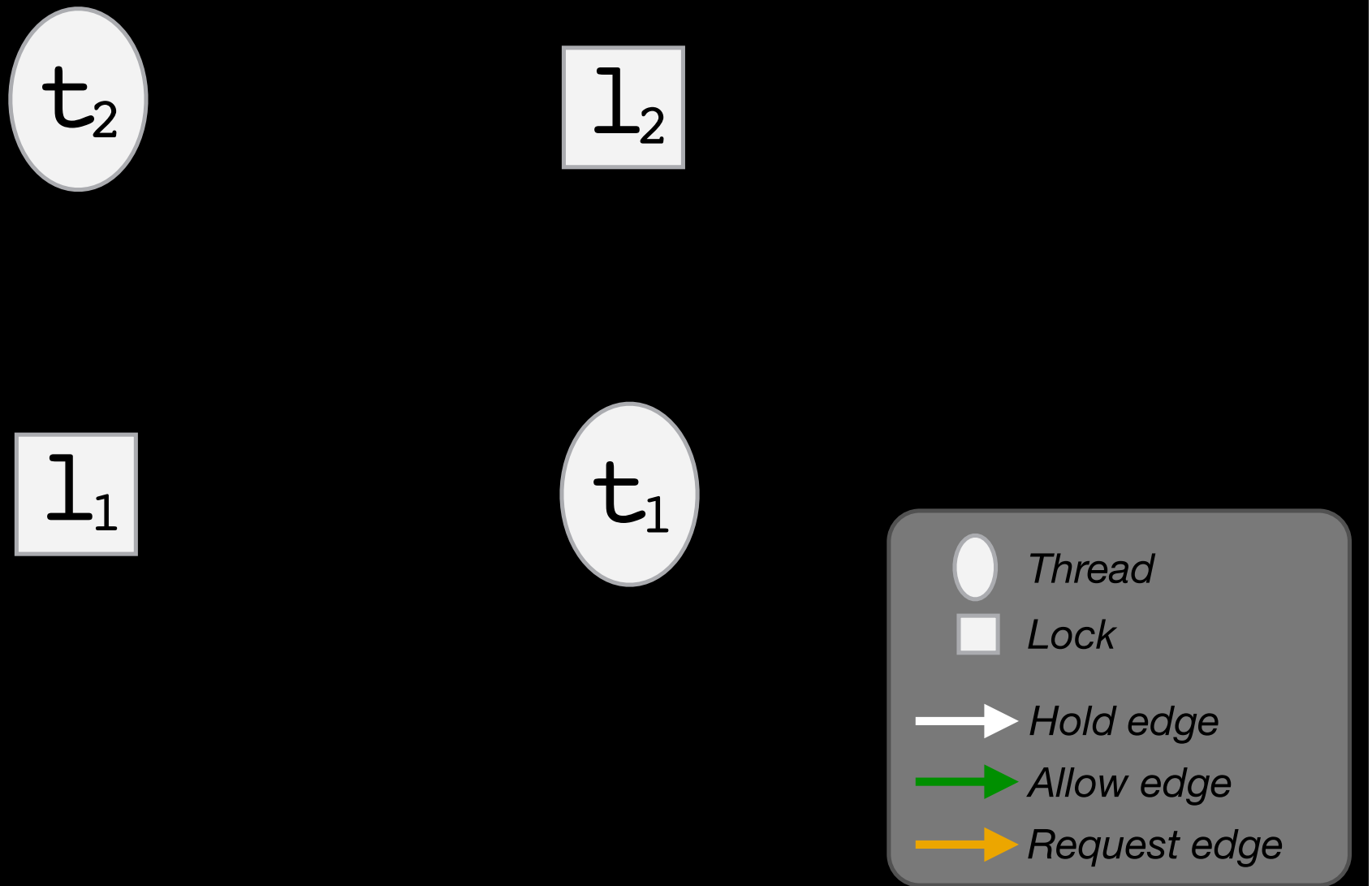
History of patterns = immune system

Interception

- Two versions
  - Java: Direct instrumentation
  - POSIX Threads: Modified pthreads shared library
- Benefits
  - Zero assistance from programmers
  - Zero assistance from users
  - Zero need for source code

Deadlock Detection



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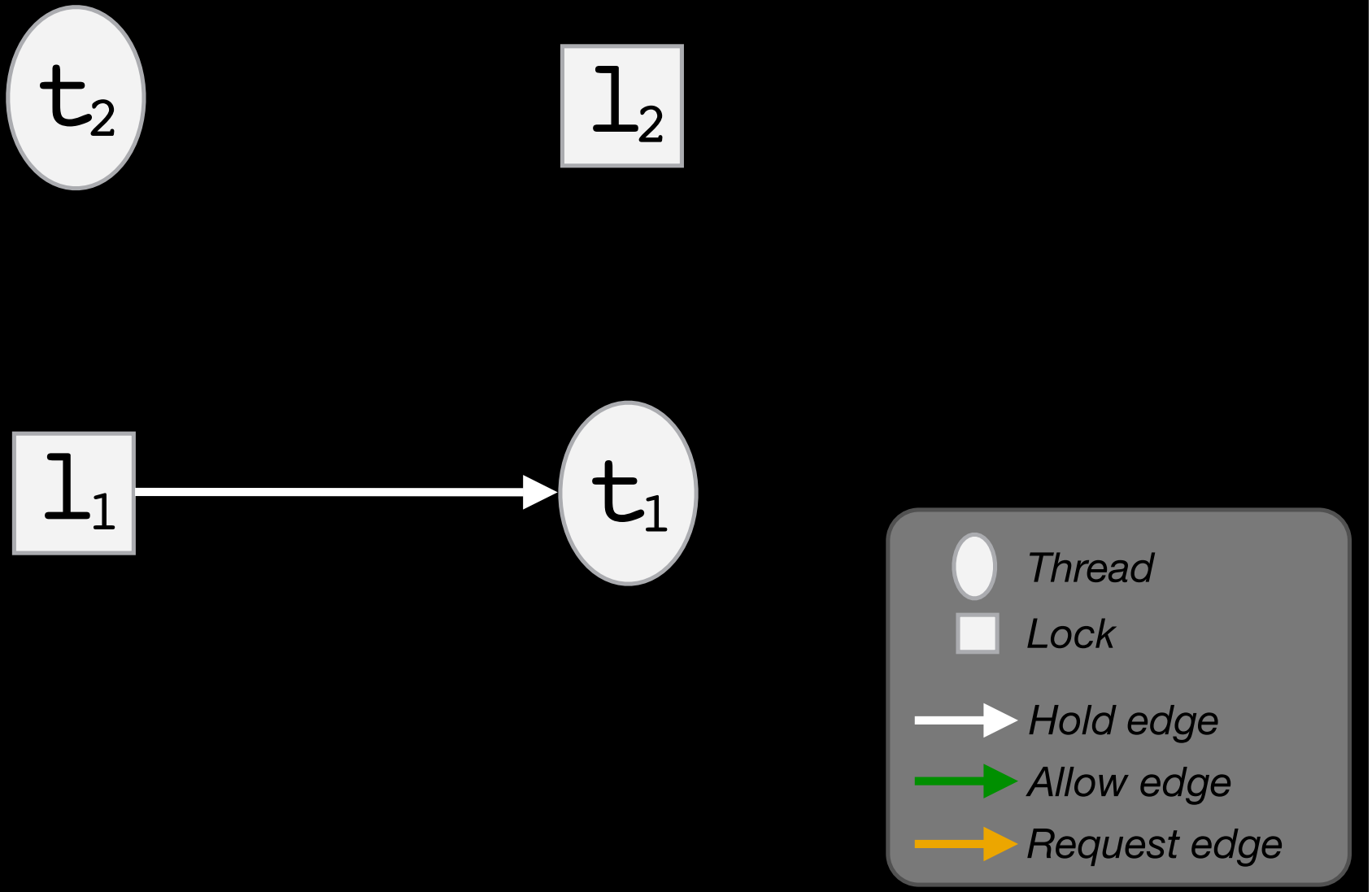

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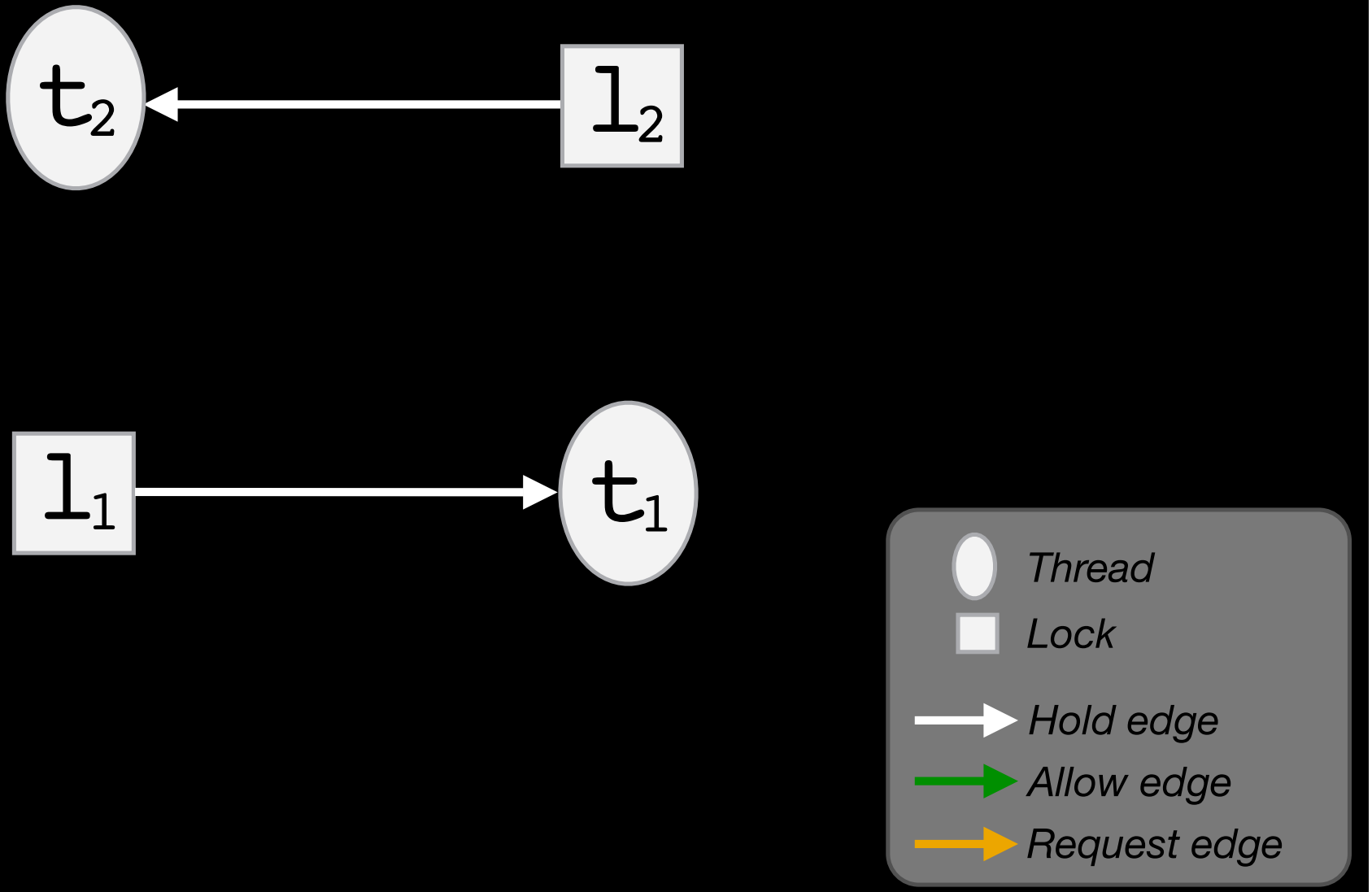

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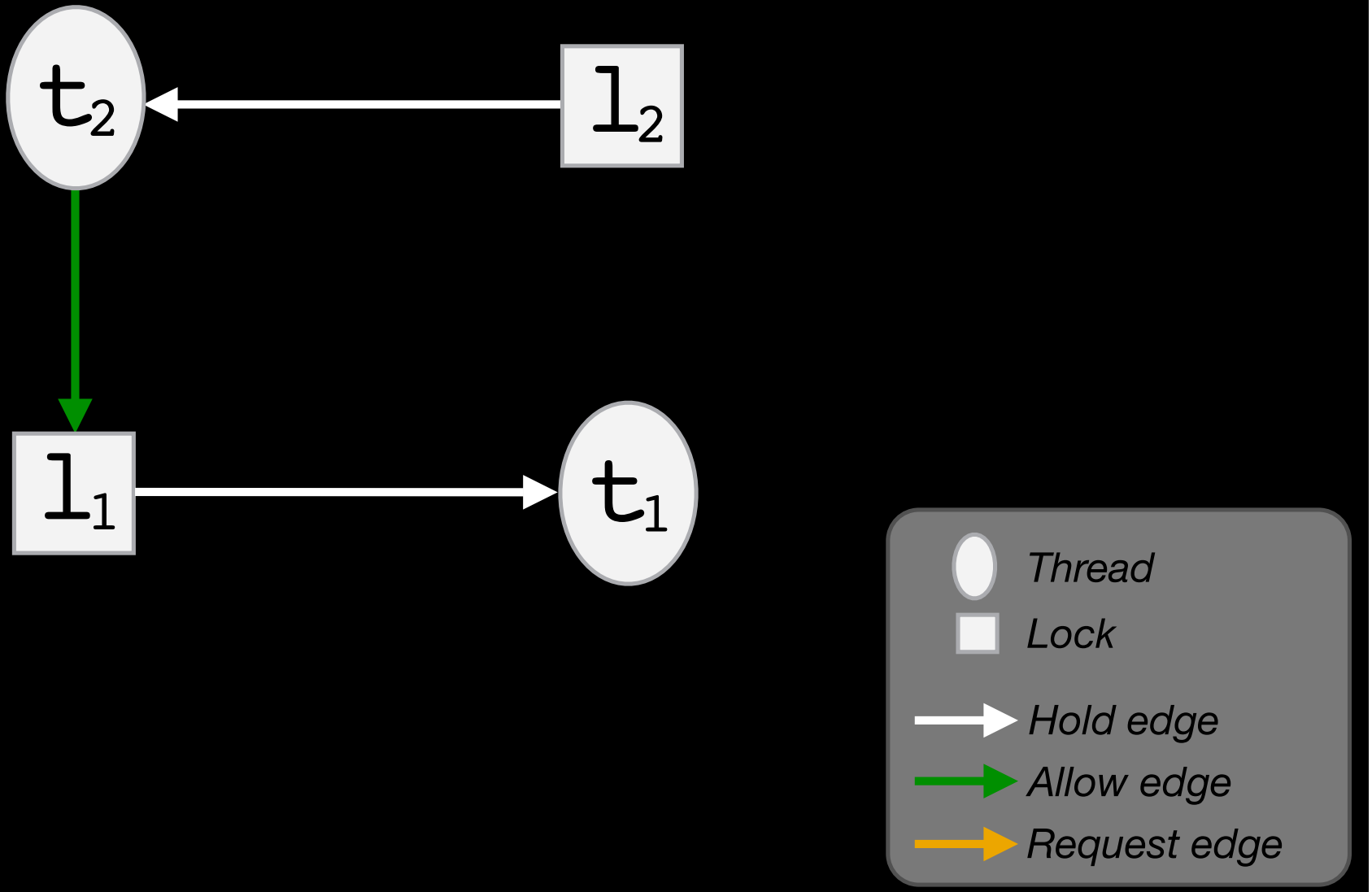

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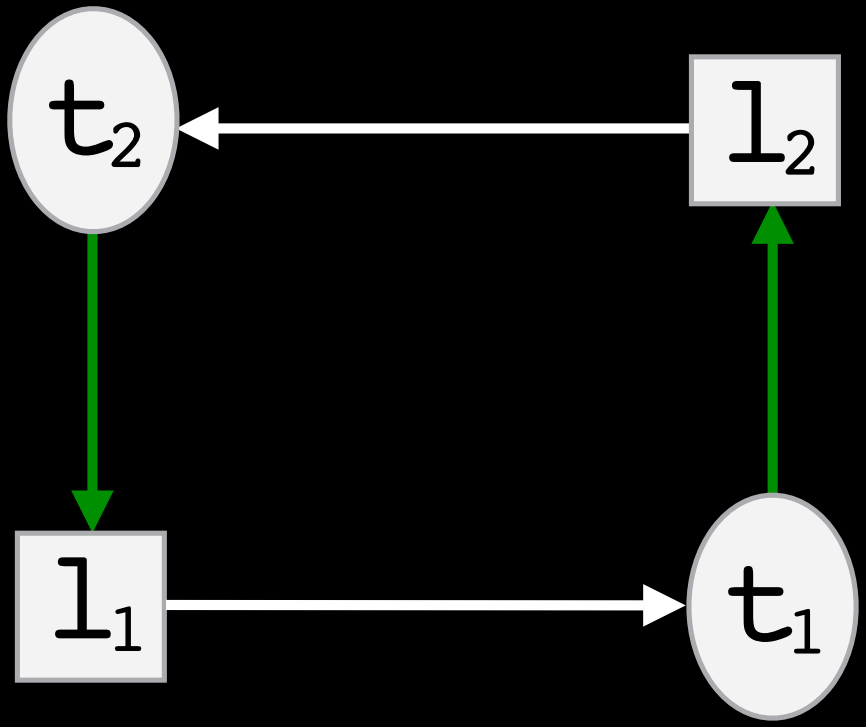

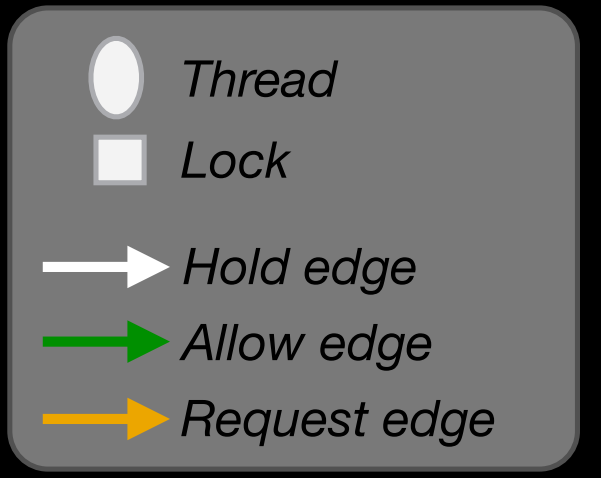

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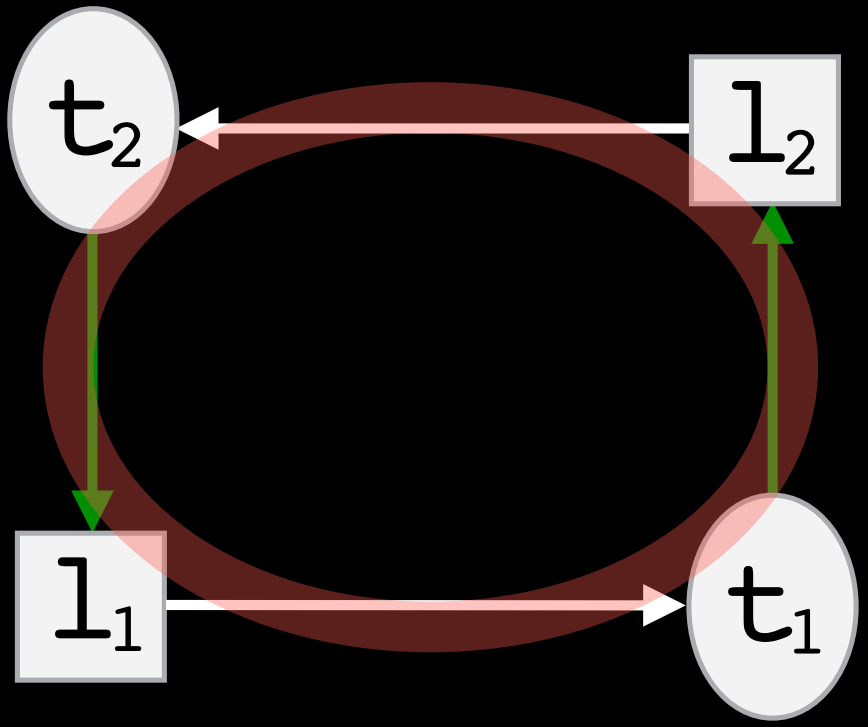
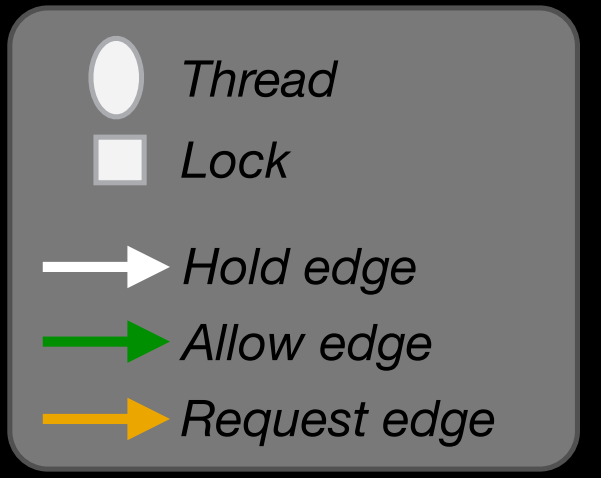
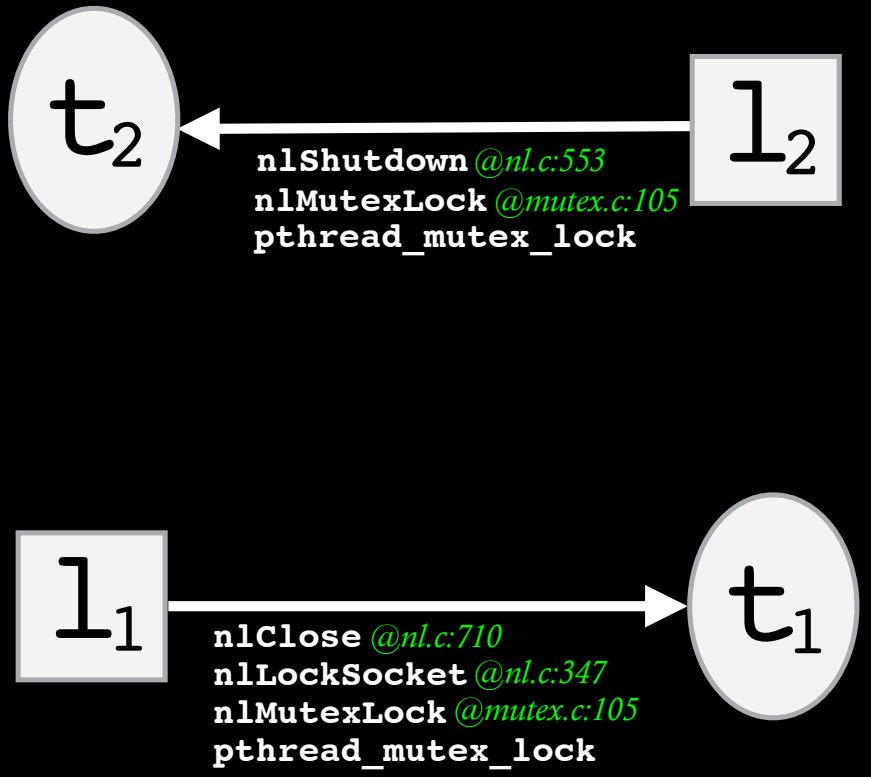




Fingerprinting Deadlocks



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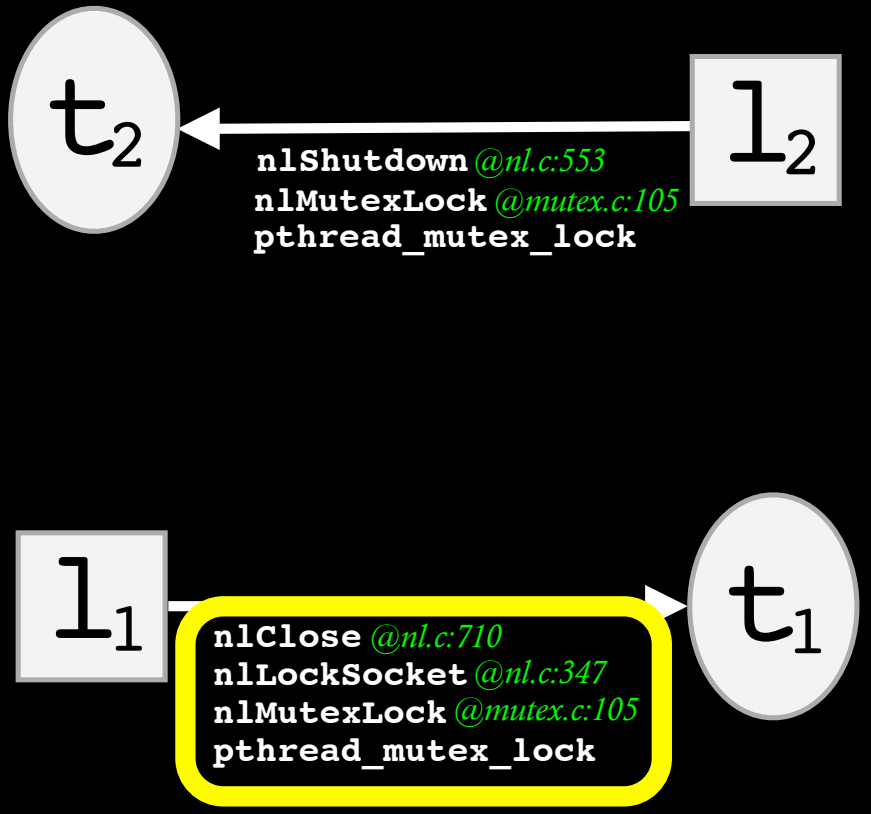

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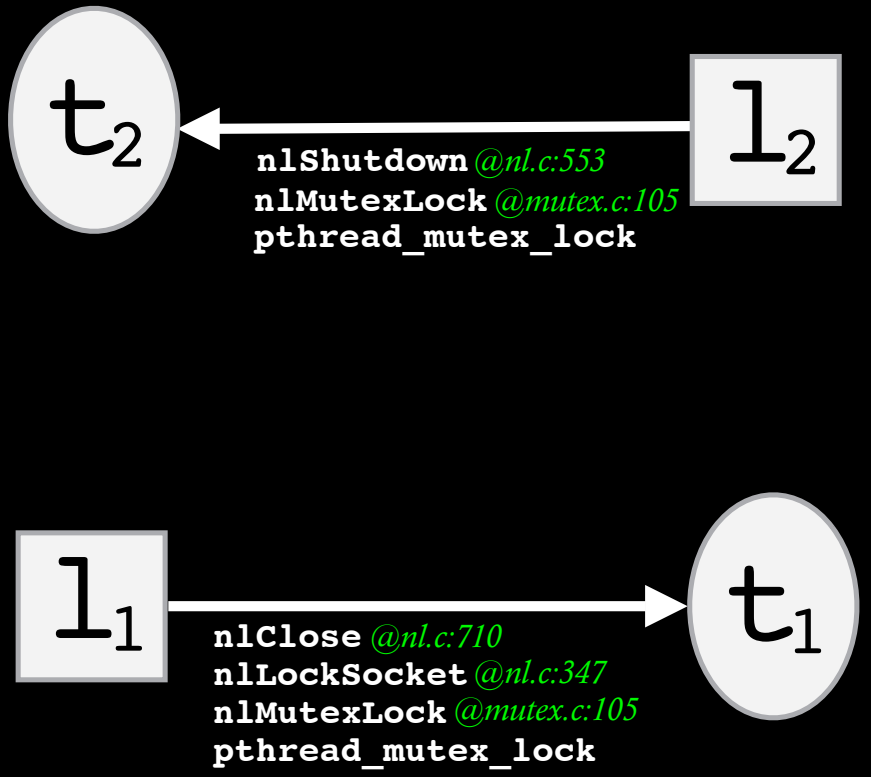

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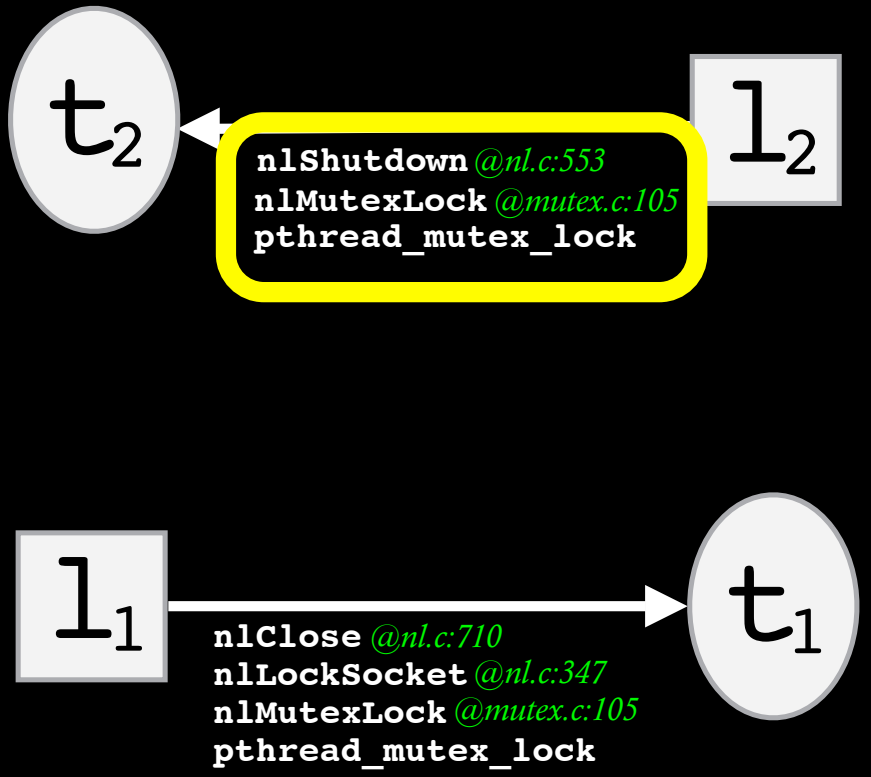

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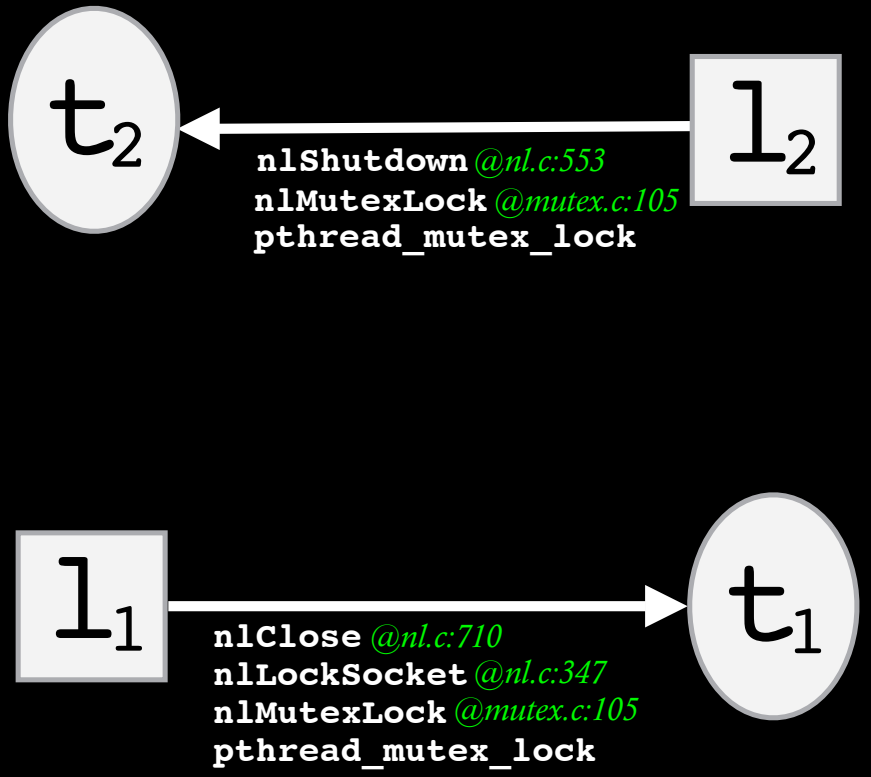

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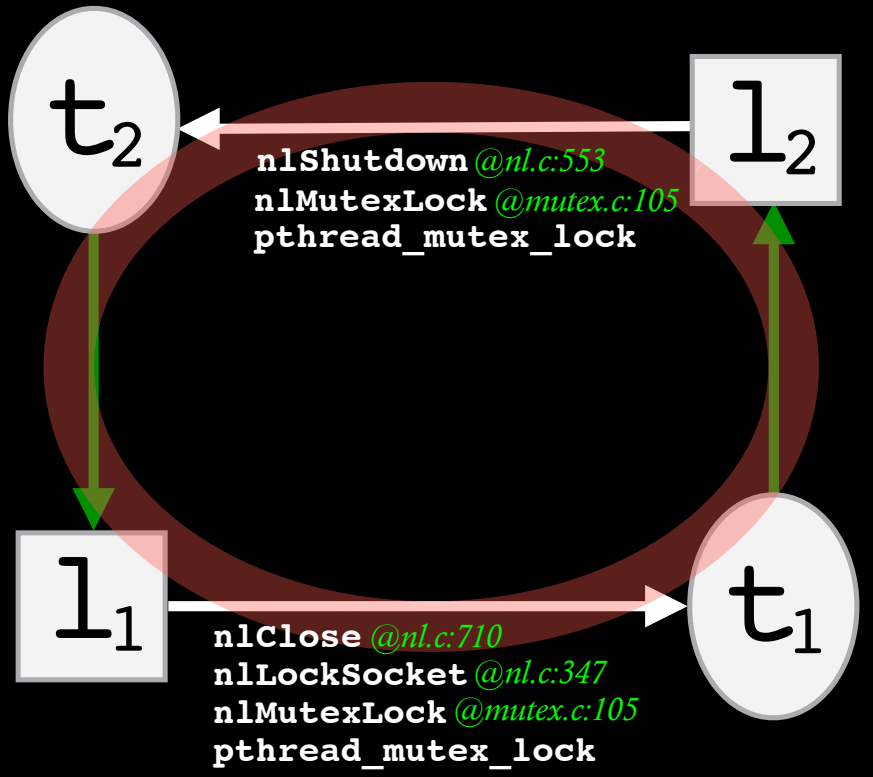
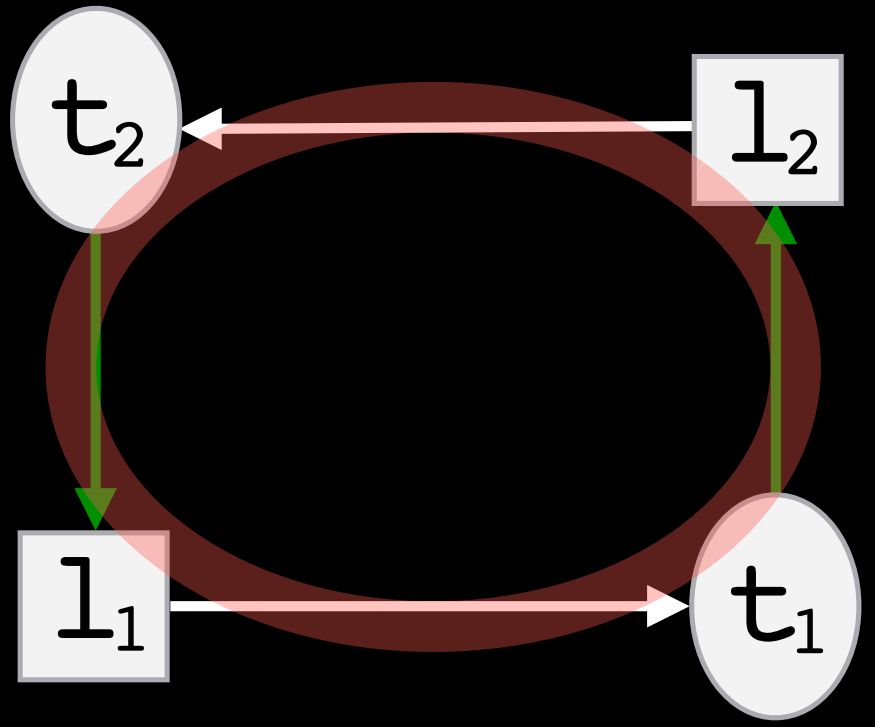


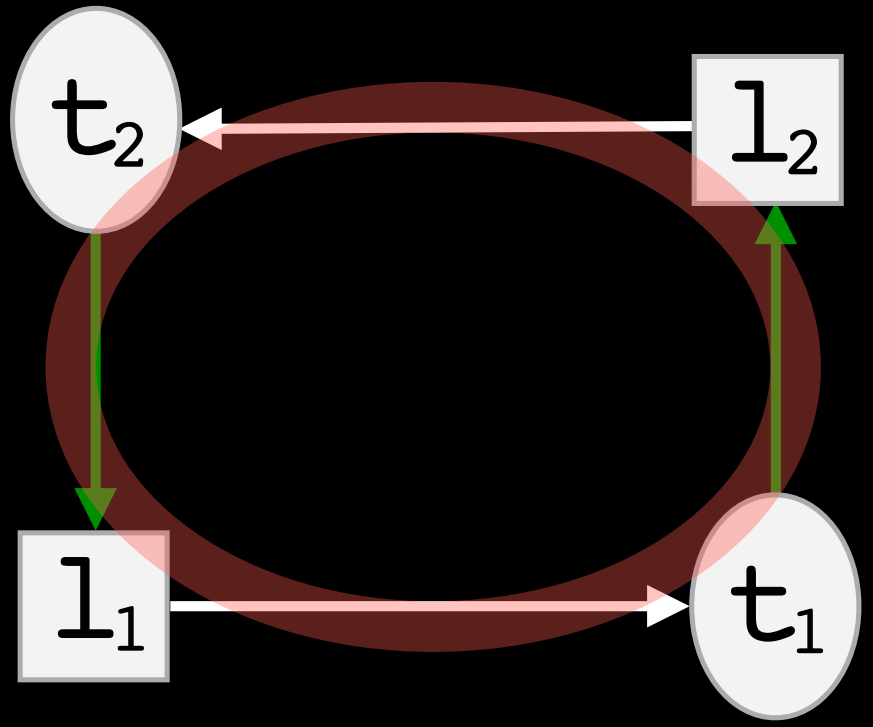
Fingerprinting Deadlocks

```
nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
pthread_mutex_lock
```

```
nlClose @nl.c:710
nlLockSocket @nl.c:347
nlMutexLock @mutex.c:105
pthread_mutex_lock
```



Fingerprinting Deadlocks



Avoidance

Thread 1

nlClose

Thread 2

nlShutdown

nlShutdown *@nl.c:553*
nlMutexLock *@mutex.c:105*
pthread_mutex_lock

nlClose *@nl.c:710*
nlLockSocket *@nl.c:347*
nlMutexLock *@mutex.c:105*
pthread_mutex_lock

Avoidance

Thread 1

```
nlClose
    @ nl.c : 710
    → nlLockSocket
```

```
nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
pthread_mutex_lock
```

```
nlClose @nl.c:710
nlLockSocket @nl.c:347
nlMutexLock @mutex.c:105
pthread_mutex_lock
```

Thread 2

```
nlShutdown
```

Avoidance

Thread 1

```
nlClose
    @ nl.c : 710
    → nlLockSocket
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nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
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```

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nlClose @nl.c:710
nlLockSocket @nl.c:347
nlMutexLock @mutex.c:105
pthread_mutex_lock
```

Thread 2

```
nlShutdown
    @ nl.c : 553
    → nlMutexLock
```

Avoidance

Thread 1

```
nlClose
    @ nl.c : 710
    → nlLockSocket
        @ nl.c : 347
        → nlMutexLock
```

Thread 2

```
nlShutdown
    @ nl.c : 553
    → nlMutexLock
```

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nlShutdown @nl.c:553
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pthread_mutex_lock
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pthread_mutex_lock
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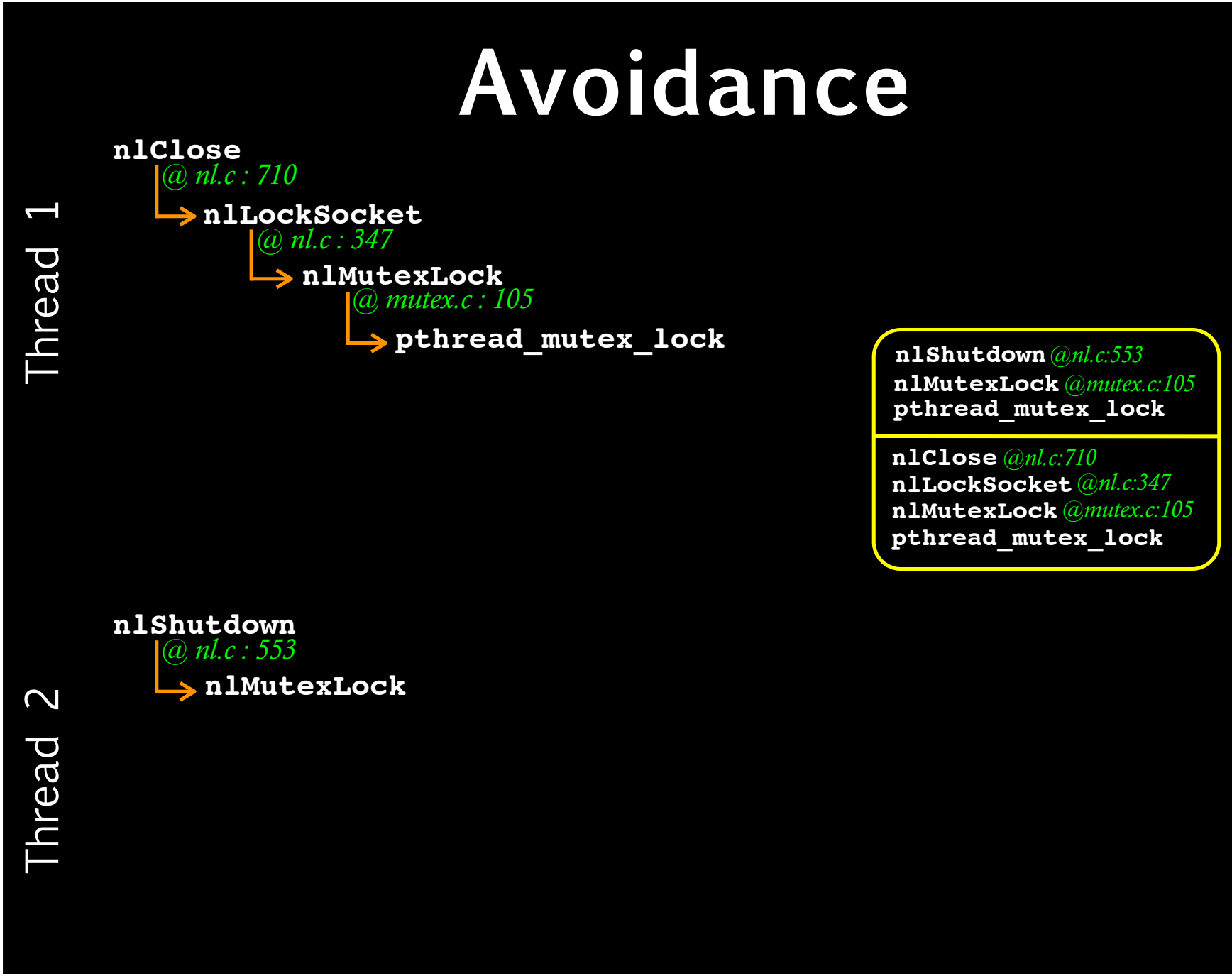
Avoidance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nlShutdown @nl.c:553
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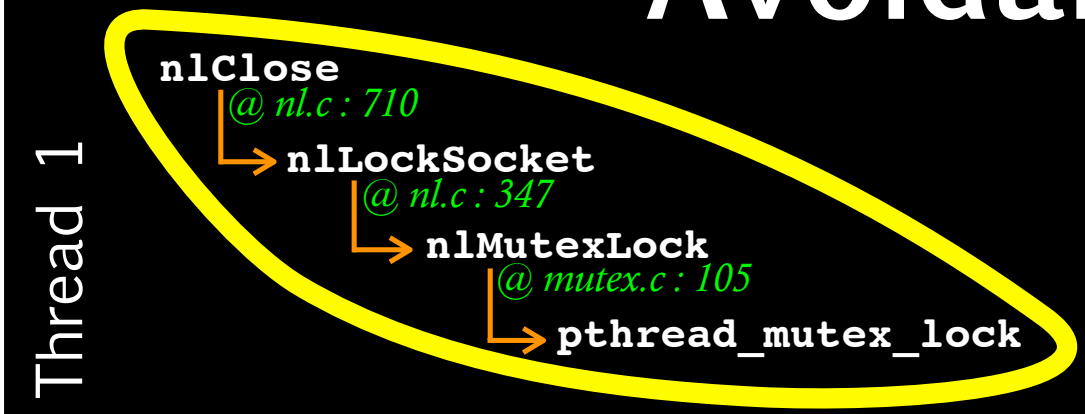
@ nl.c : 553
nlMutexLock

Avoidance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nlShutdown @nl.c:553
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nlMutexLock @mutex.c:105
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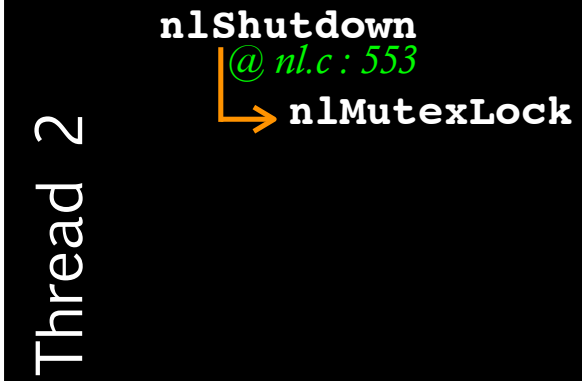
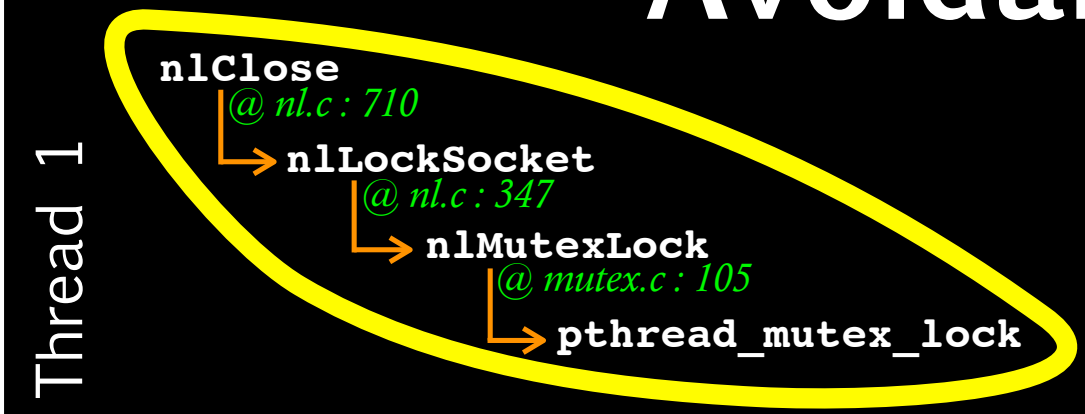

Thread 2
nlShutdown
@ nl.c : 553
nlMutexLock

Avoidance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nlShutdown @nl.c:553
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pthread_mutex_lock
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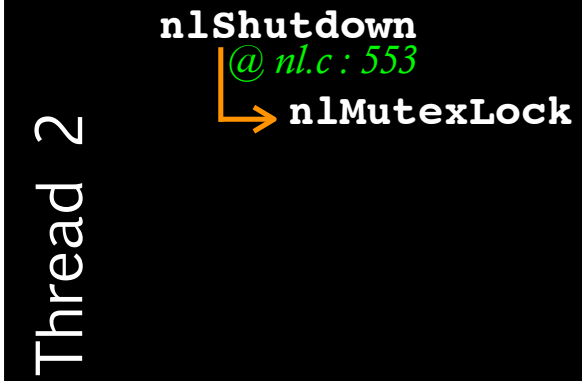
nlLockSocket @nl.c:347
nlMutexLock @mutex.c:105
pthread_mutex_lock


Thread 2
nlShutdown
@ nl.c : 553
nlMutexLock

Avoidance

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```
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    nlLockSocket
      @ nl.c : 347
        nlMutexLock
          @ mutex.c : 105
            pthread_mutex_lock
```

Thread 2

```
nlShutdown
  @ nl.c : 553
    nlMutexLock
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nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
pthread_mutex_lock
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nlClose @nl.c:710
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Avoidance

Thread 1

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nlClose
    @ nl.c : 710
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        @ nl.c : 347
        → nlMutexLock
            @ mutex.c : 105
            → pthread_mutex_lock
    @ nl.c : 722
    → nlMutexLock
```

Thread 2

```
nlShutdown
    @ nl.c : 553
    → nlMutexLock
```

```
nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
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nlClose @nl.c:710
nlLockSocket @nl.c:347
nlMutexLock @mutex.c:105
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Avoidance

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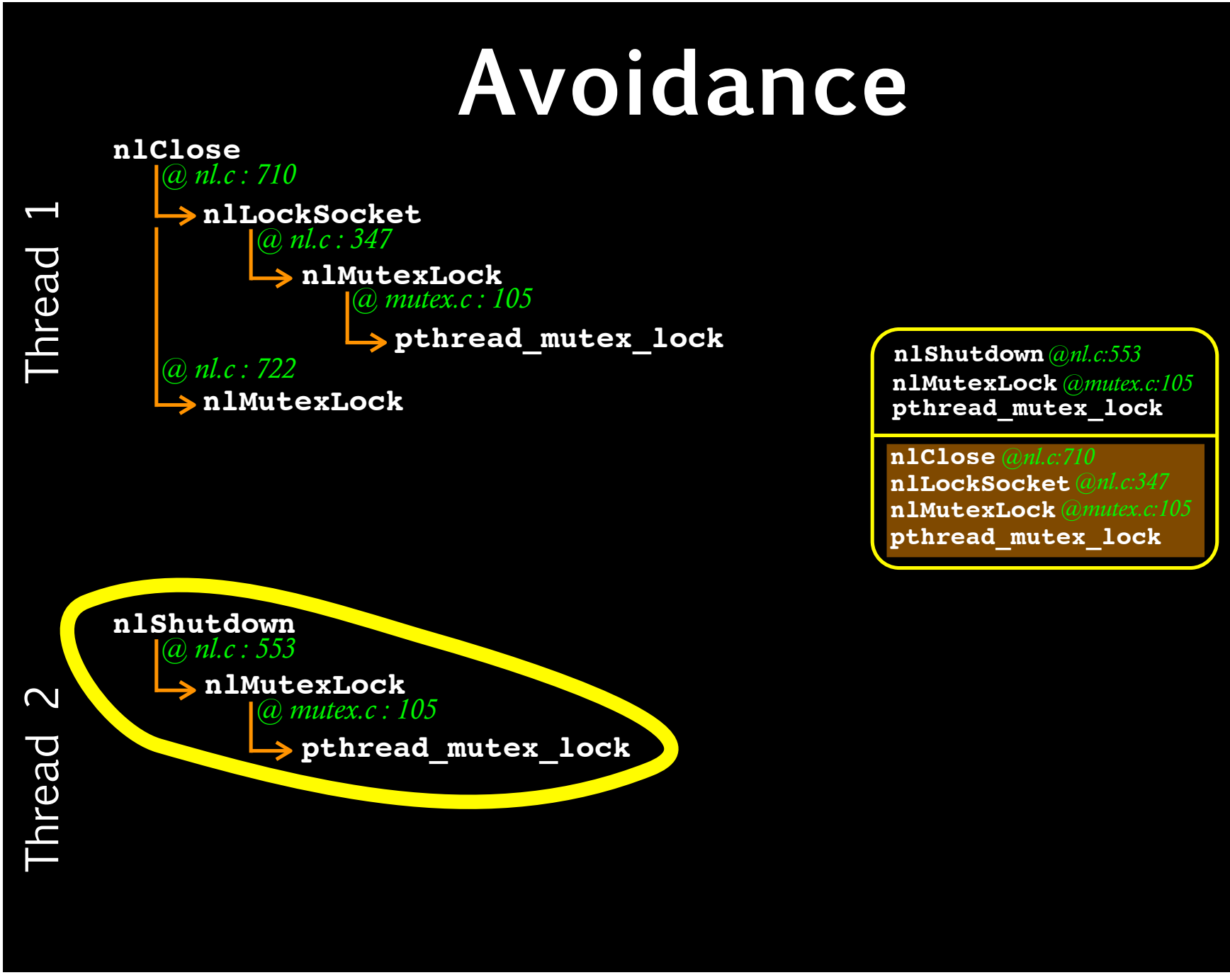
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nlClose
@ nl.c : 710
nlLockSocket
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pthread_mutex_lock
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nlMutexLock
nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
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nlClose @nl.c:710
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nlShutdown
@ nl.c : 553
nlMutexLock
@ mutex.c : 105
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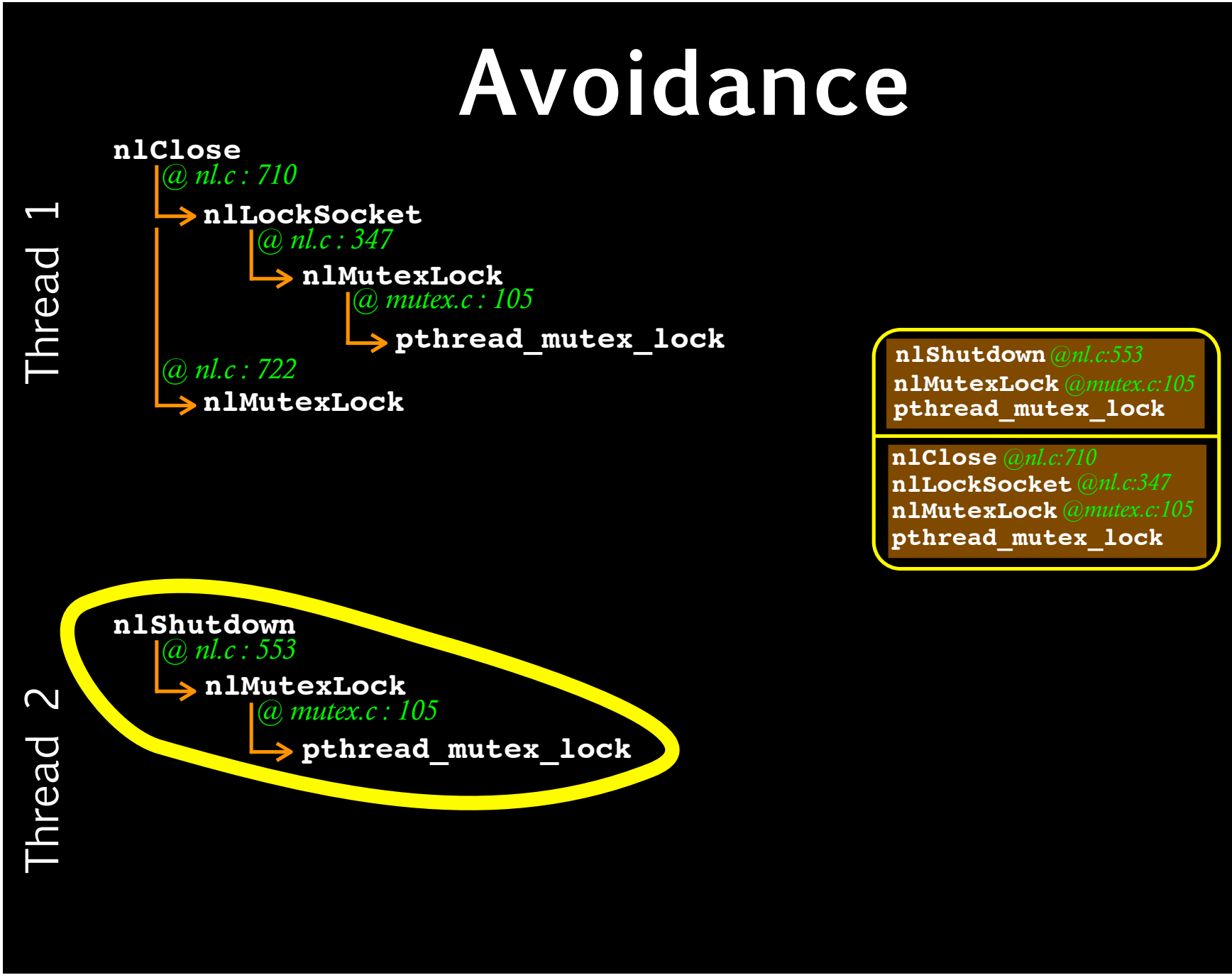
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nlClose
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nlLockSocket
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nlMutexLock
@ mutex.c : 105
pthread_mutex_lock
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nlShutdown
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nlMutexLock
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    @ mutex.c : 105
    pthread_mutex_lock
  pthread_mutex_unlock
```

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    pthread_mutex_lock
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nlLockSocket @nl.c:347
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Avoidance

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nlClose
  @ nl.c : 710
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      → pthread_mutex_lock
  pthread_mutex_unlock
```

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nlShutdown
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  @ nl.c : 710
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    nlMutexLock
      @ mutex.c : 105
      pthread_mutex_lock
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    @ mutex.c : 105
    pthread_mutex_lock
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```

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  @ nl.c : 553
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Avoidance

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  @ nl.c : 710
  nlLockSocket
    @ nl.c : 347
    nlMutexLock
      @ mutex.c : 105
      pthread_mutex_lock
  @ nl.c : 722
  nlMutexLock
    @ mutex.c : 105
    pthread_mutex_lock

  pthread_mutex_unlock
```

Thread 2

```
nlShutdown
  @ nl.c : 553
  nlMutexLock
    @ mutex.c : 105
    pthread_mutex_lock
  @ nl.c : 565
  nlLockSocket
```

```
nlShutdown @nl.c:553
nlMutexLock @mutex.c:105
pthread_mutex_lock
```

```
nlClose @nl.c:710
nlLockSocket @nl.c:347
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Avoidance

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```
nlClose
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      pthread_mutex_lock
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  nlMutexLock
    @ mutex.c : 105
    pthread_mutex_lock
  pthread_mutex_unlock
```

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```
nlShutdown
  @ nl.c : 553
  nlMutexLock
    @ mutex.c : 105
    pthread_mutex_lock
  @ nl.c : 565
  nlLockSocket
    @ nl.c : 347
    nlMutexLock
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Avoidance

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Thread 2

nlShutdown
@ nl.c : 553
nlMutexLock
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nlLockSocket
@ nl.c : 347
nlMutexLock
@ mutex.c : 105
pthread_mutex_lock

Does It Work ?

- C/C++
  - MySQL
  - SQLite
  - HawkNL
- Java
  - Apache ActiveMQ
  - Limewire
  - MySQL JDBC
  - Sun JDK

System	Bug#	Deadlock Bug Description
MySQL 6.0.4	37080	INSERT and TRUNCATE in two different threads
SQLite 3.3.0	1672	Race condition in custom recursive lock implementation
HawkNL 1.6b3	n/a	nlShutdown() called concurrently with nlClose()
Limewire 4.17.9	1449	Cancel HsqlDB TaskQueue concurrently with program shutdown()
ActiveMQ 3.1	336	Concurrently create listener and actively dispatch messages to consumer
ActiveMQ 4.0	575	Concurrent invocation of Queue.dropEvent() and PrefetchSubscription.add()
MySQL 5.0 JDBC	2147	Connection.close() called concurrently with PreparedStatement.getWarnings()
	14972	Connection.prepareStatement() called concurrently with Statement.close()
	31136	PreparedStatement.executeQuery() called concurrently w/ Connection.close()
	17709	Statement.executeQuery() concurrent with Connection.prepareStatement()

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Avoids real deadlocks in real systems

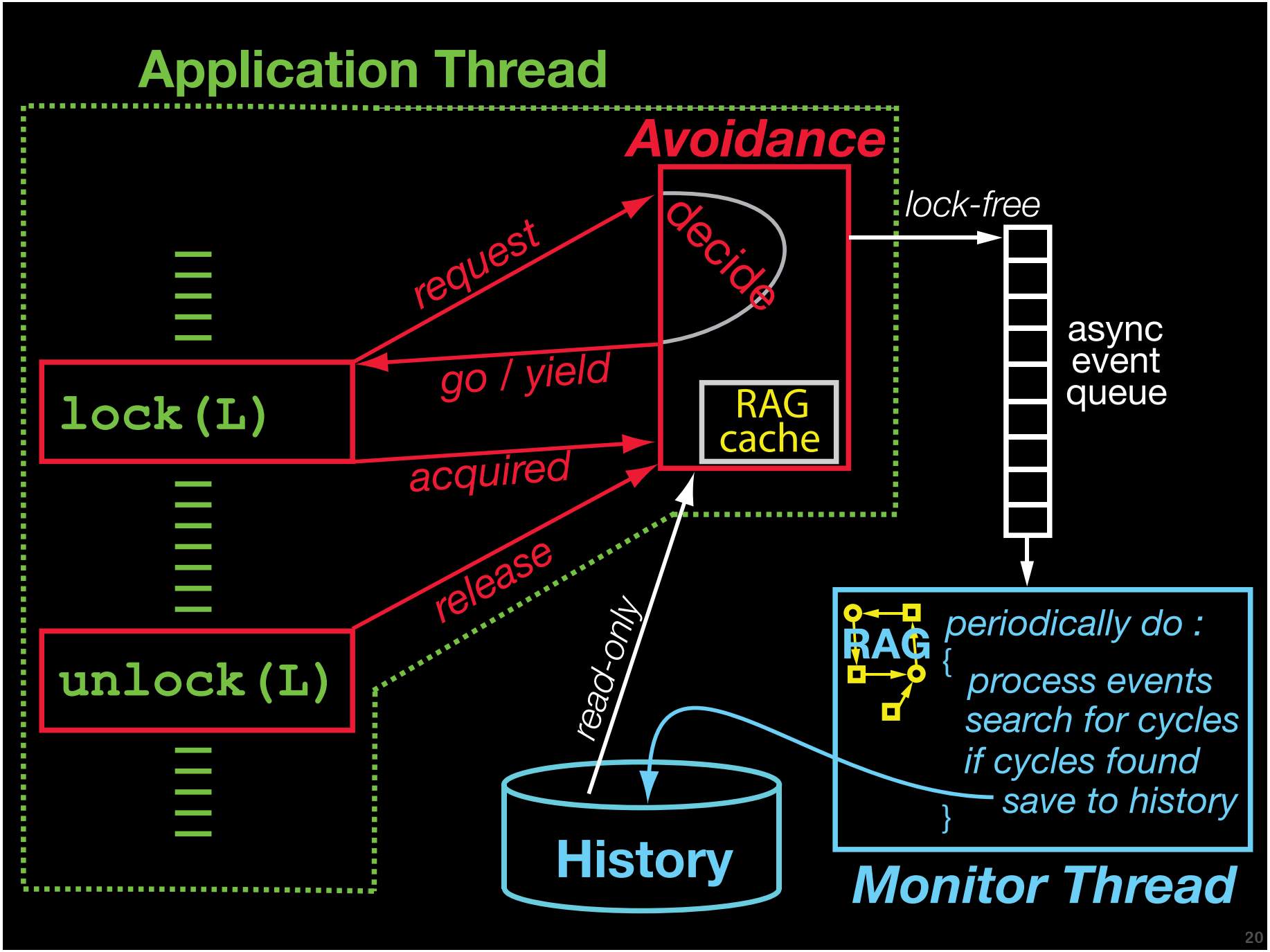
Challenges

1. Performance
2. Induced Starvation
3. Precision Calibration

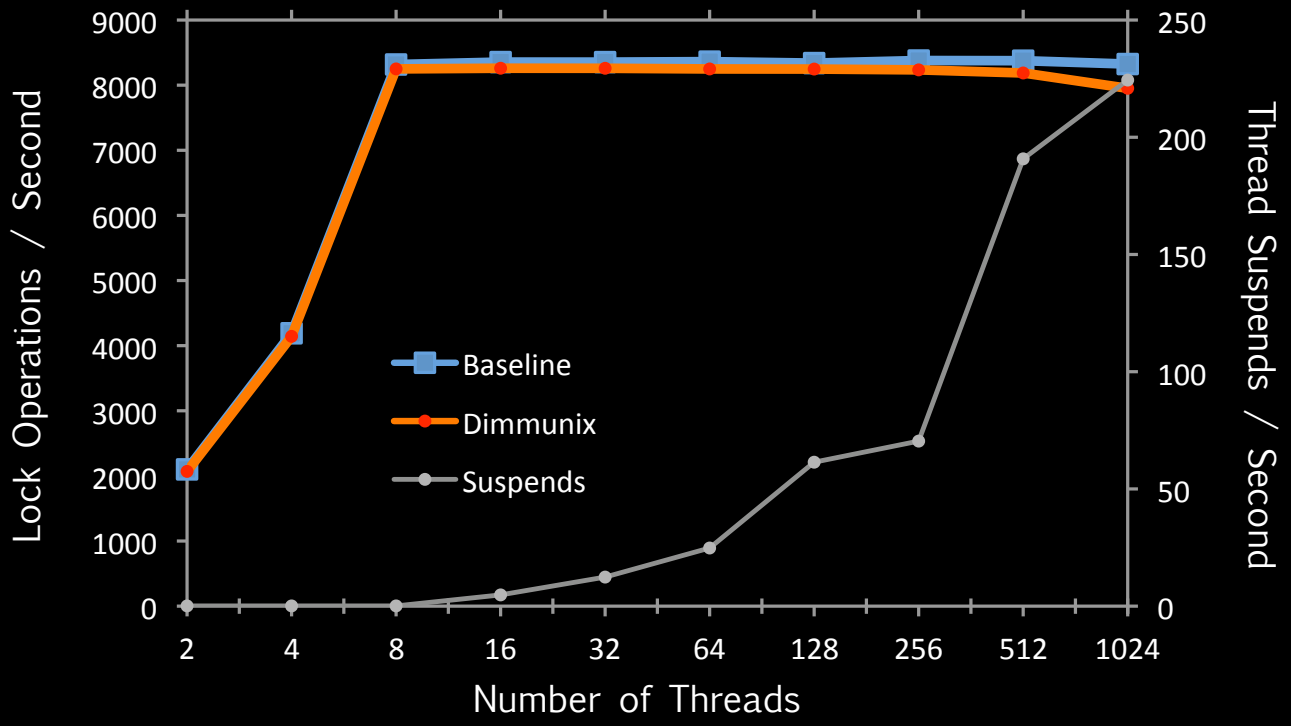
- *See paper for...*
  - Weak vs. strong immunity
  - Software upgrades
  - Evaluation of false positives

1. Performance

- Potential overhead
  - Intercept every call to lock/unlock
  - Update resource allocation graph
  - Find cycles + make suspend/resume decisions
- Solution: asynchronous architecture
  - Do expensive work in a separate thread
  - Take advantage of multi-core CPU
  - Lock-free data structures


Application Thread
Avoidance
request
decide
go / yield
lock(L)
RAG
cache
acquired
lock-free
async
event
queue
release
unlock(L)
read-only
RAG
periodically do :
{
process events
search for cycles
if cycles found
save to history
}
History
Monitor Thread

1. Performance



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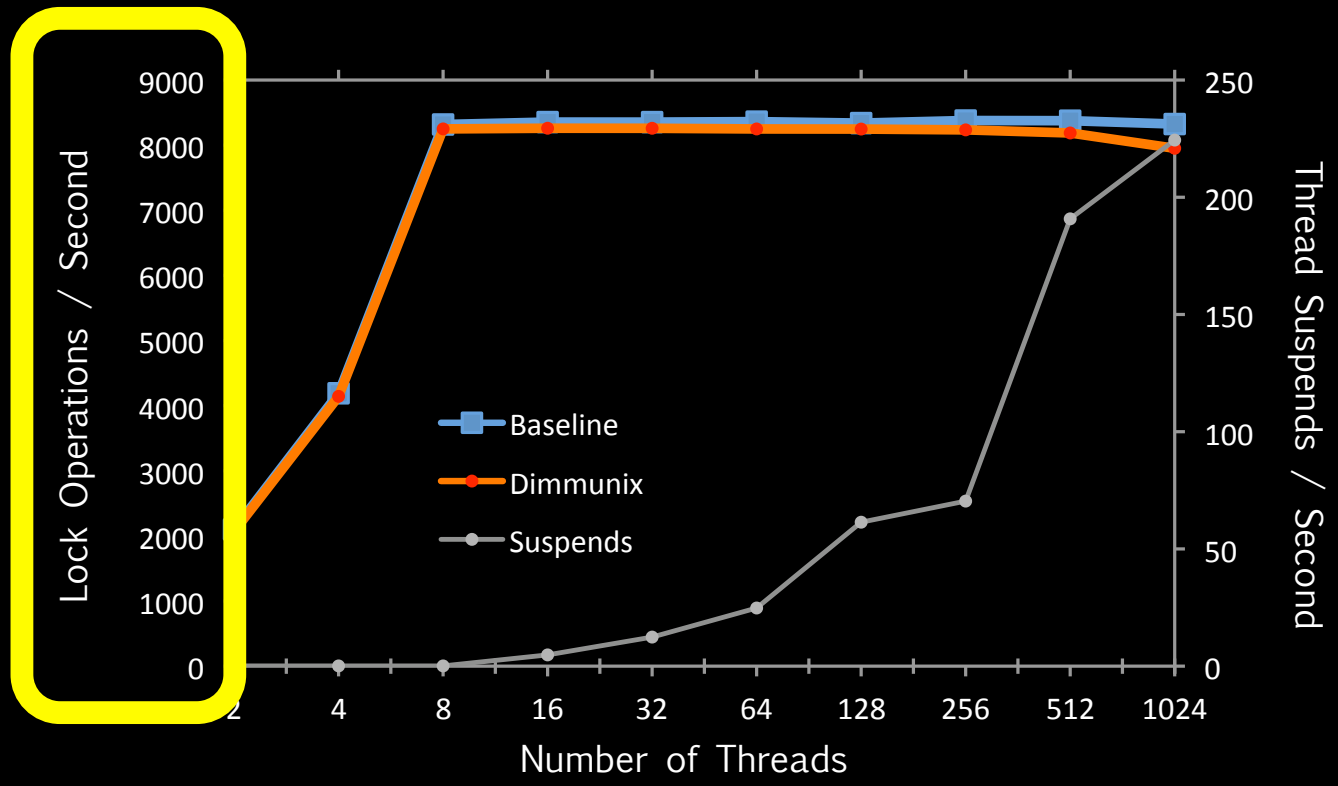

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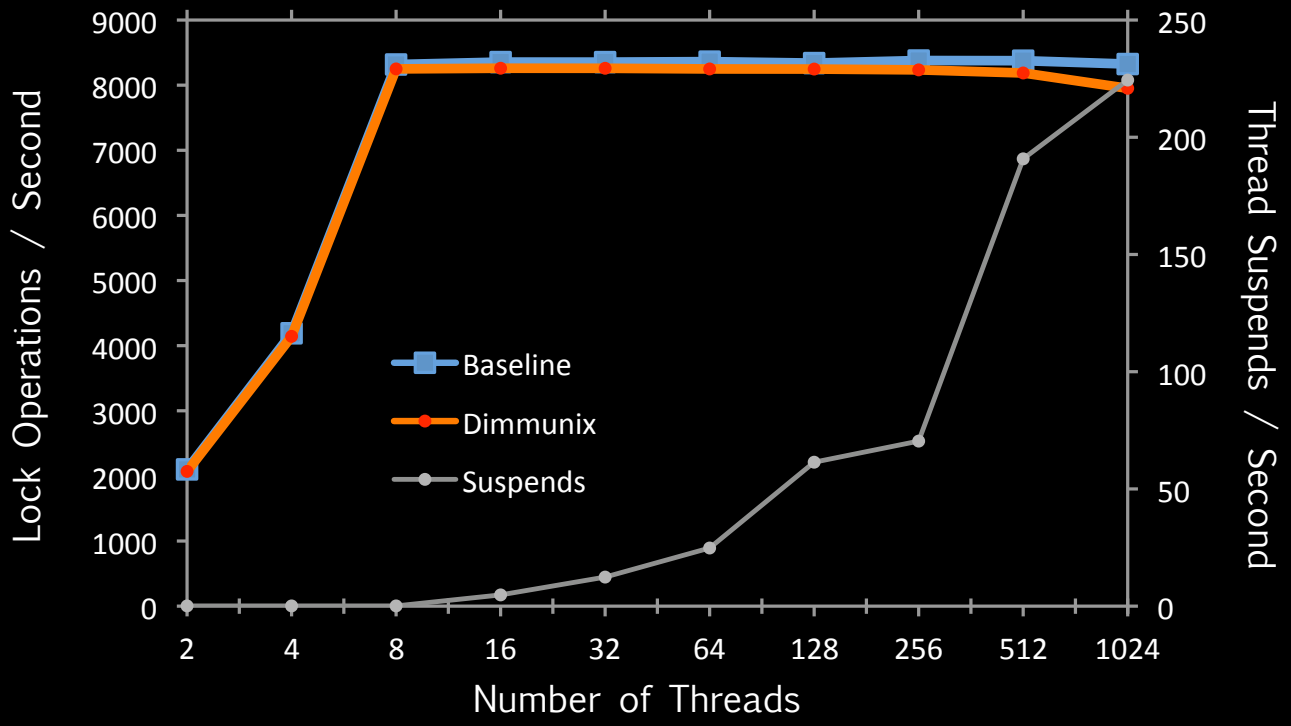

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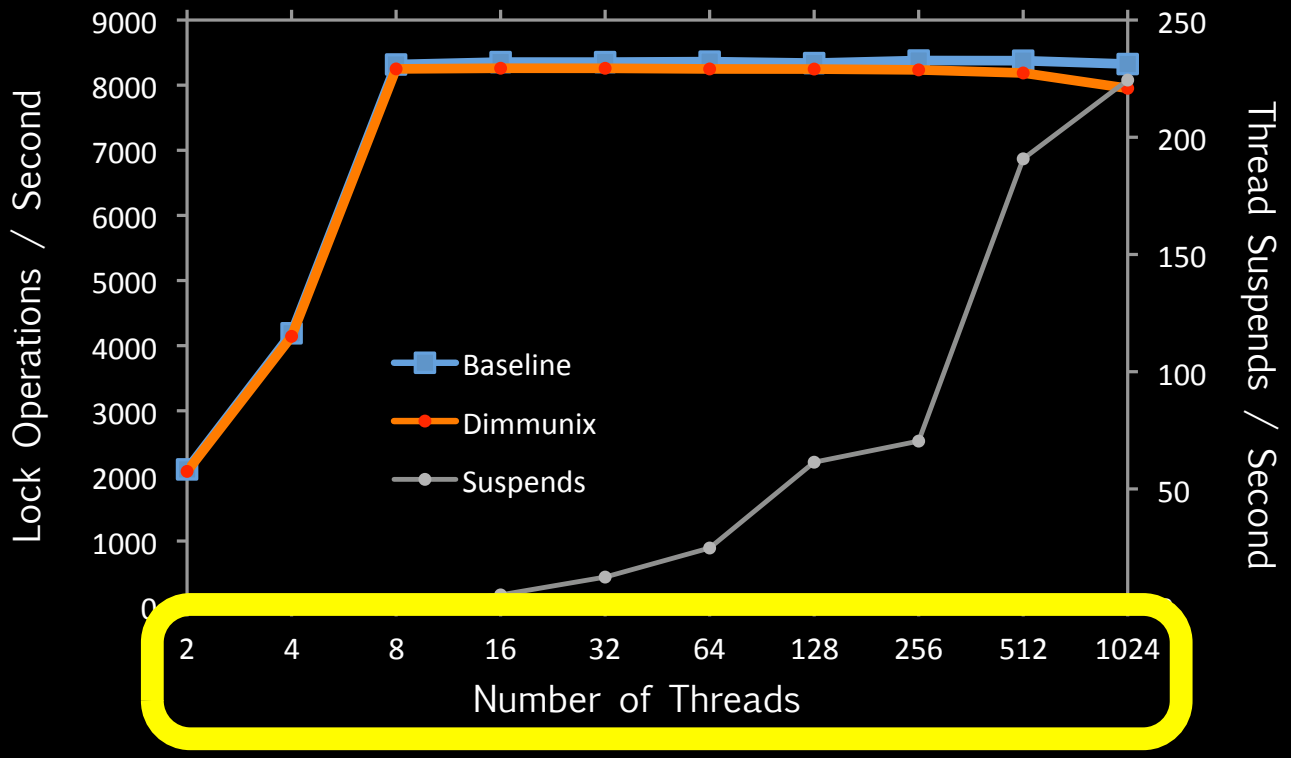

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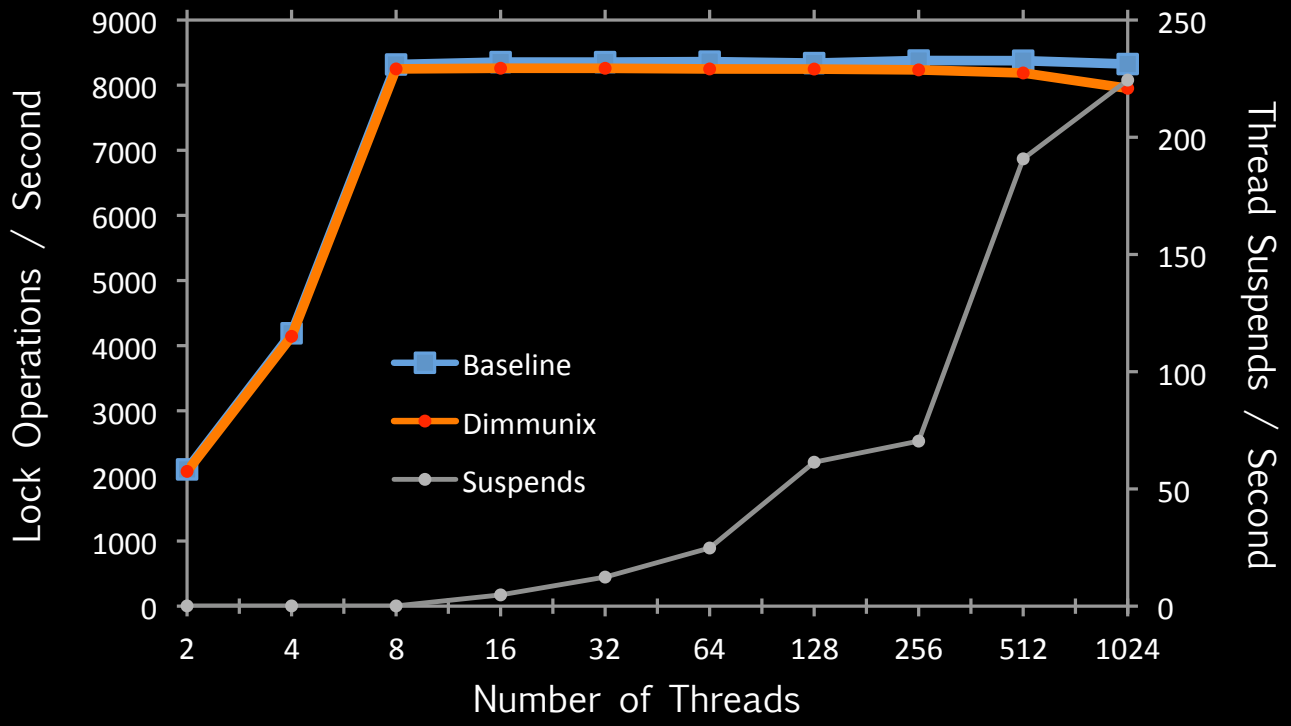

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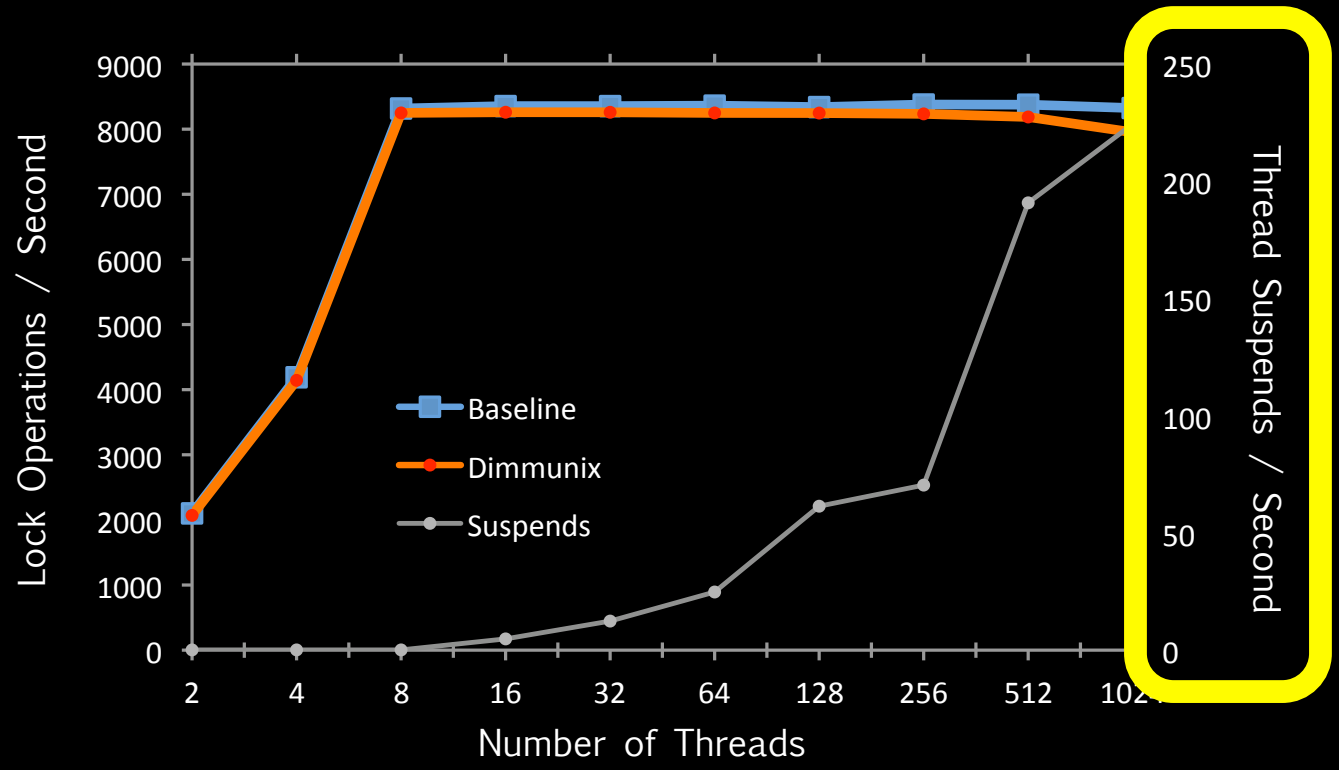

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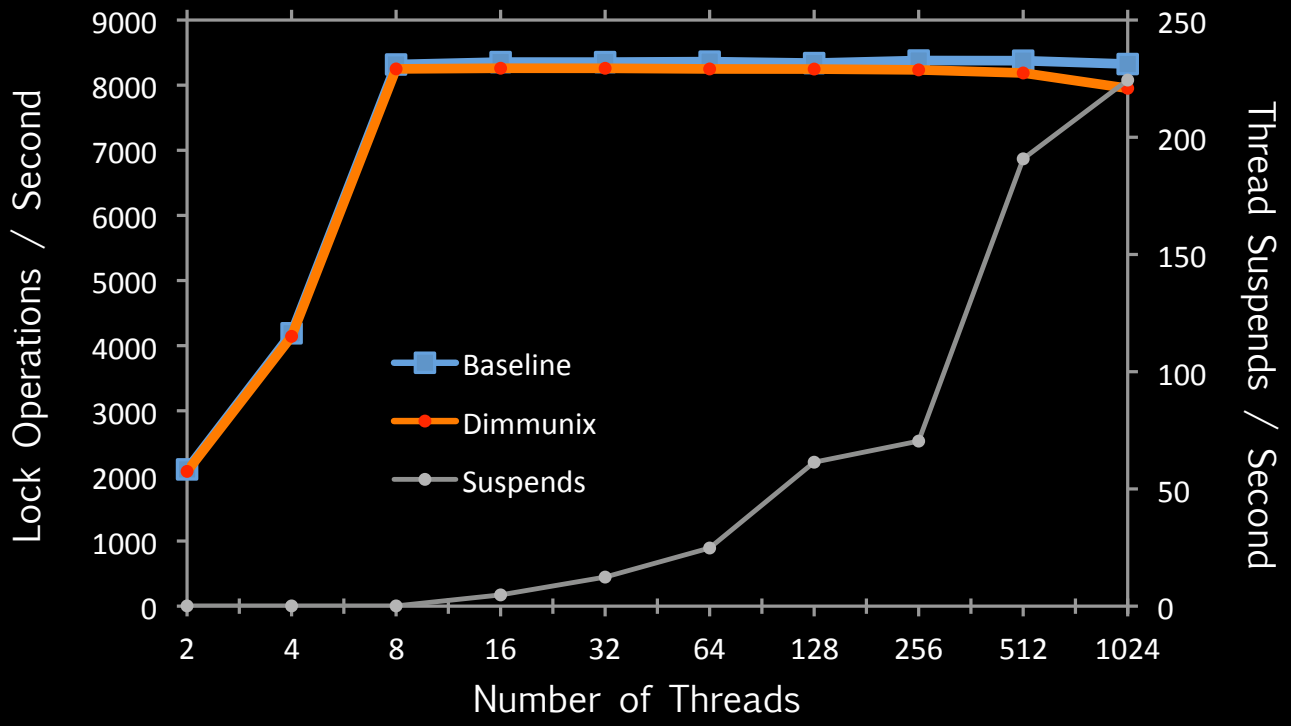

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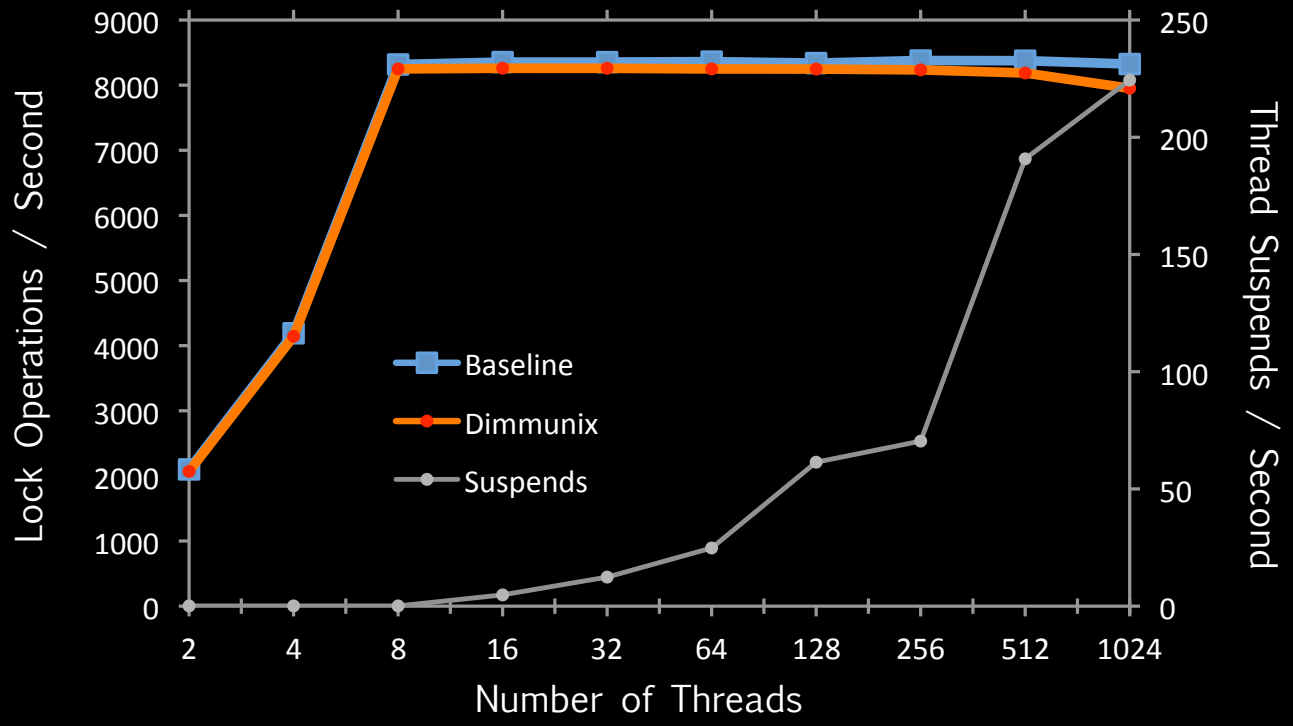

Overhead = **0.6% - 4.5%**

1. Performance

- Matching signatures from history
  - Hash call stacks and index into precomputed tables
  - Thread-local cache of data structures

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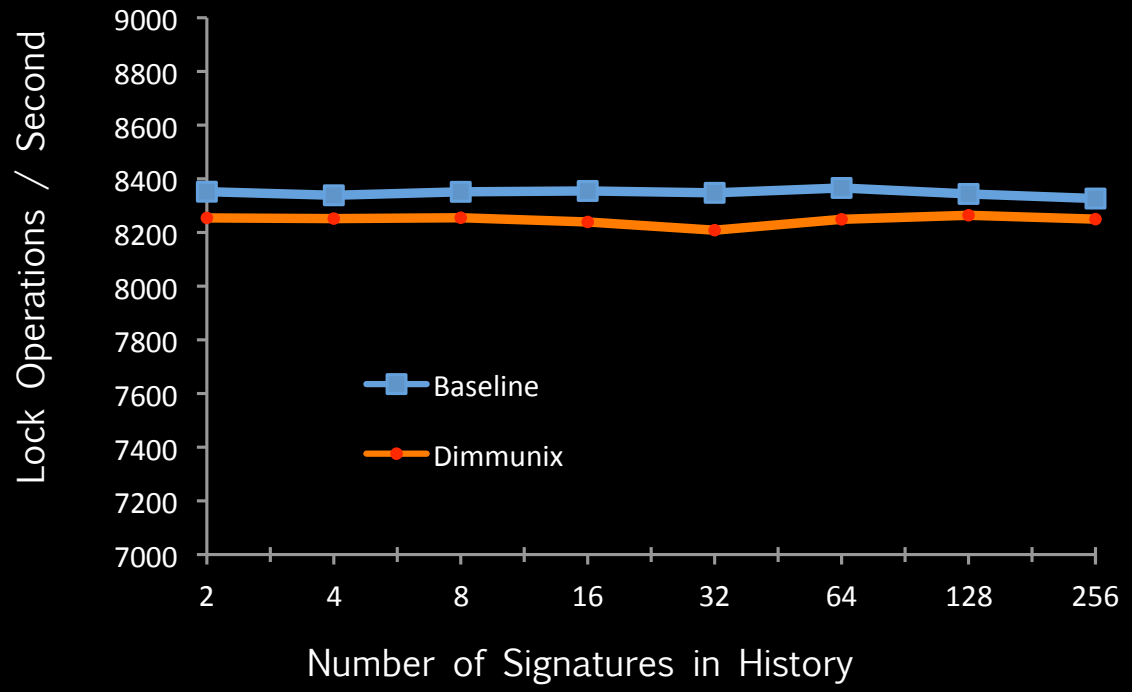

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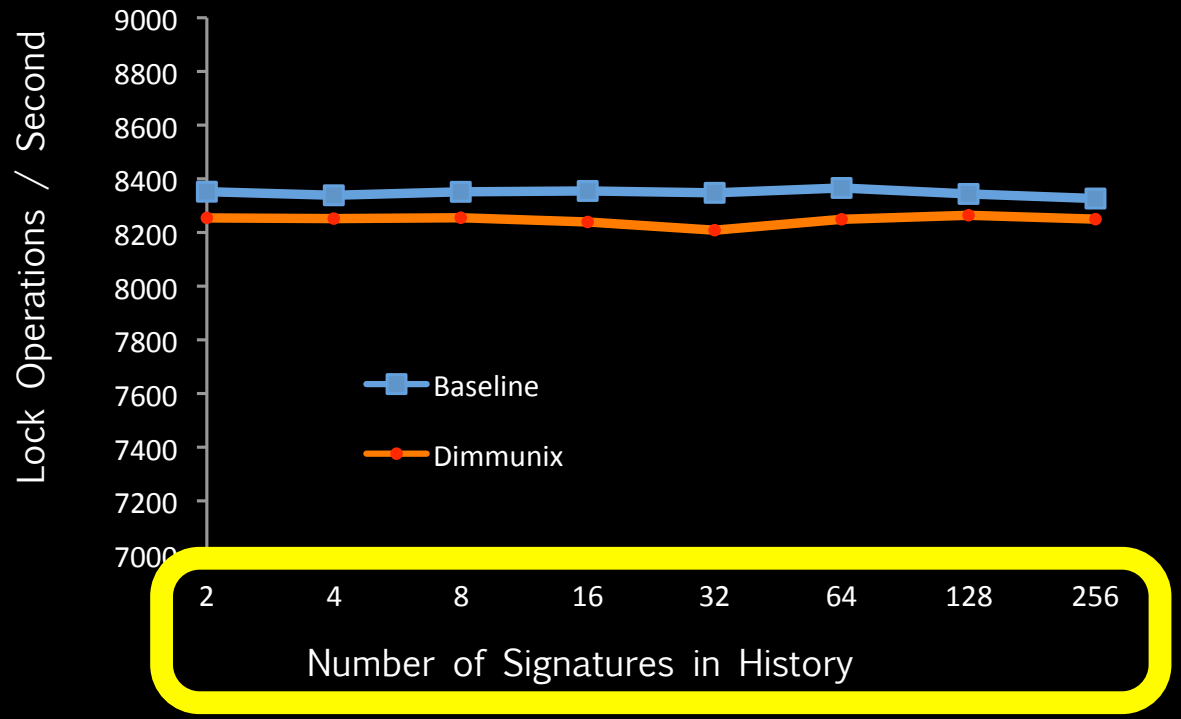

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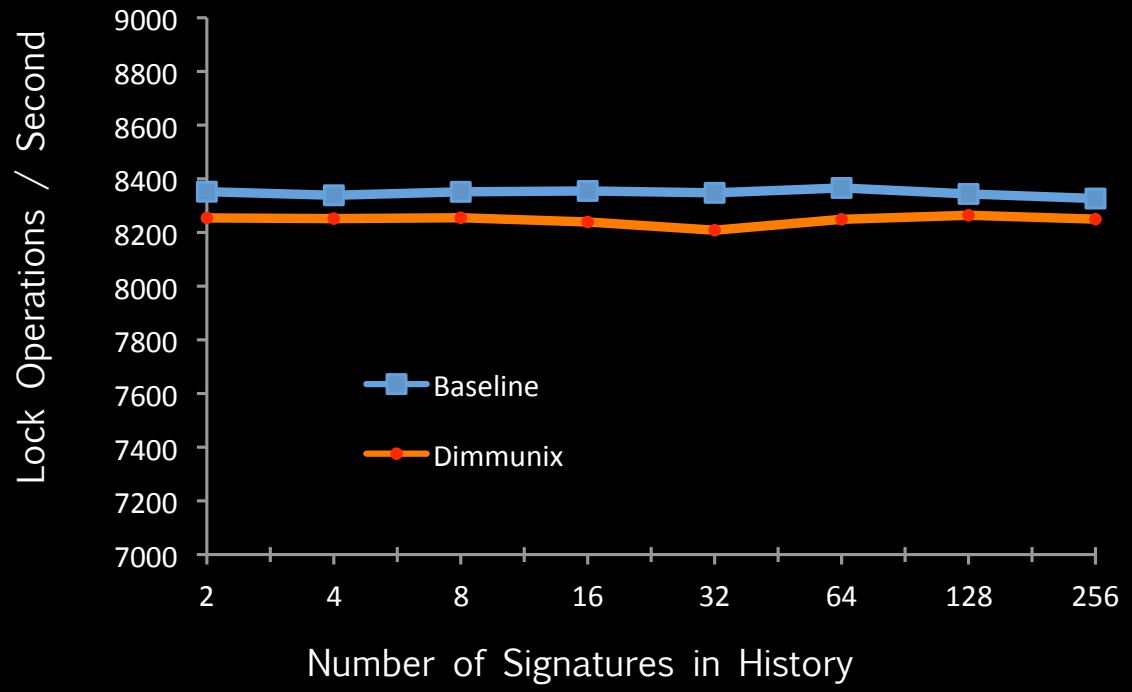
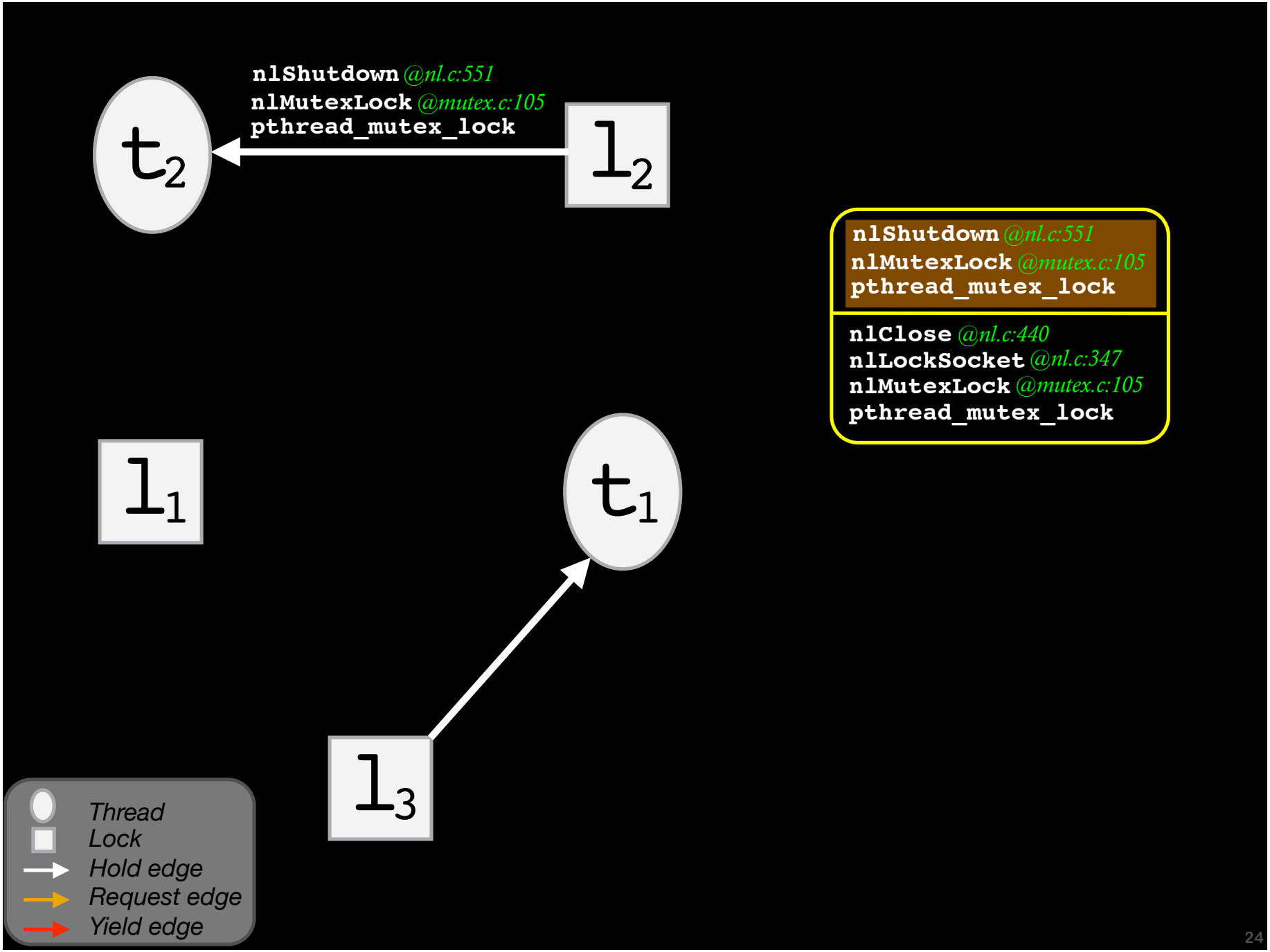


2. Induced Starvation

- All approaches based on yield/suspend can induce starvation
  - i.e., a thread actively yields, waiting for a blocked thread to make progress
- Never encountered in our tests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l1
t1
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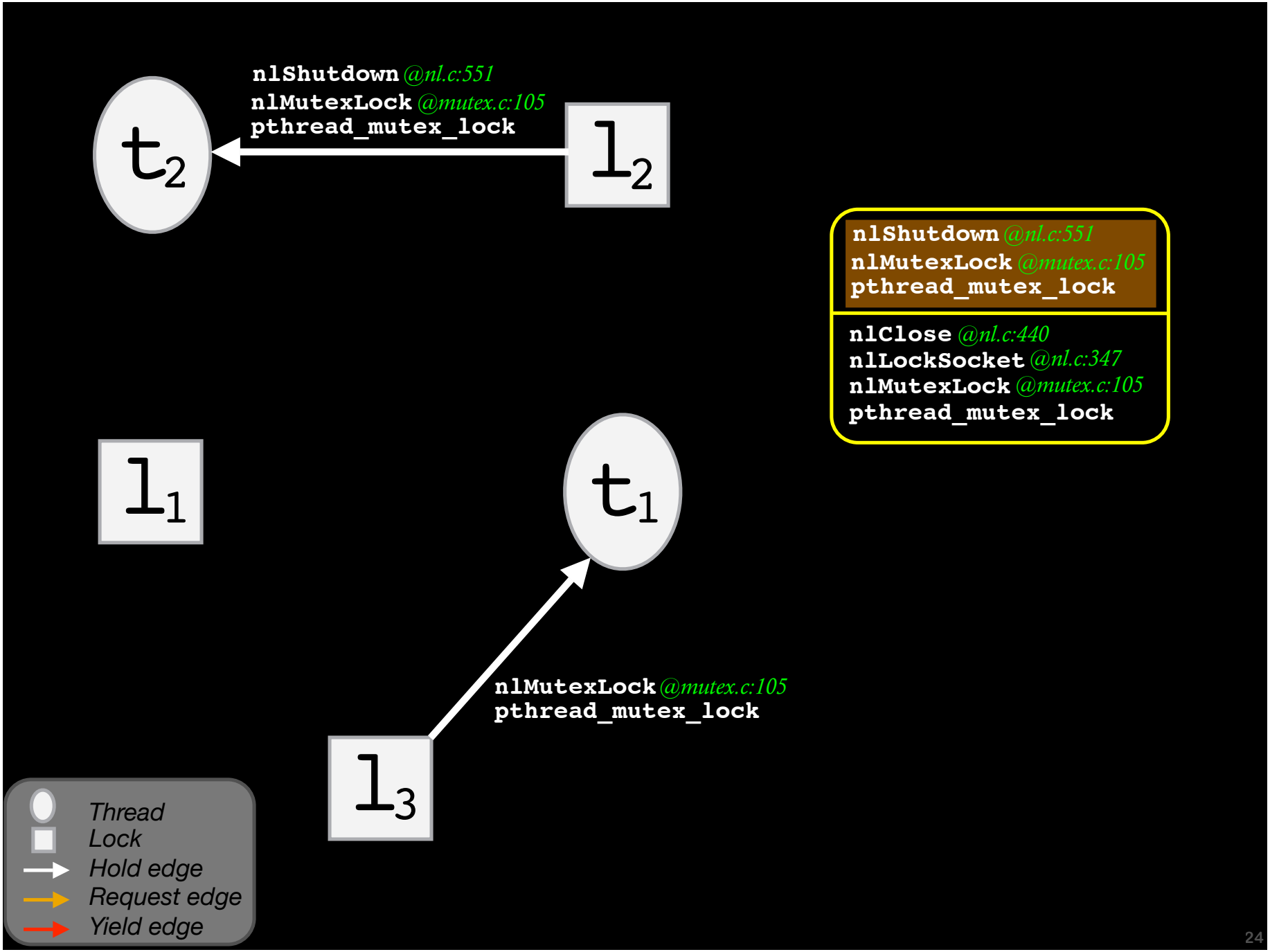
Request edge
Yield edge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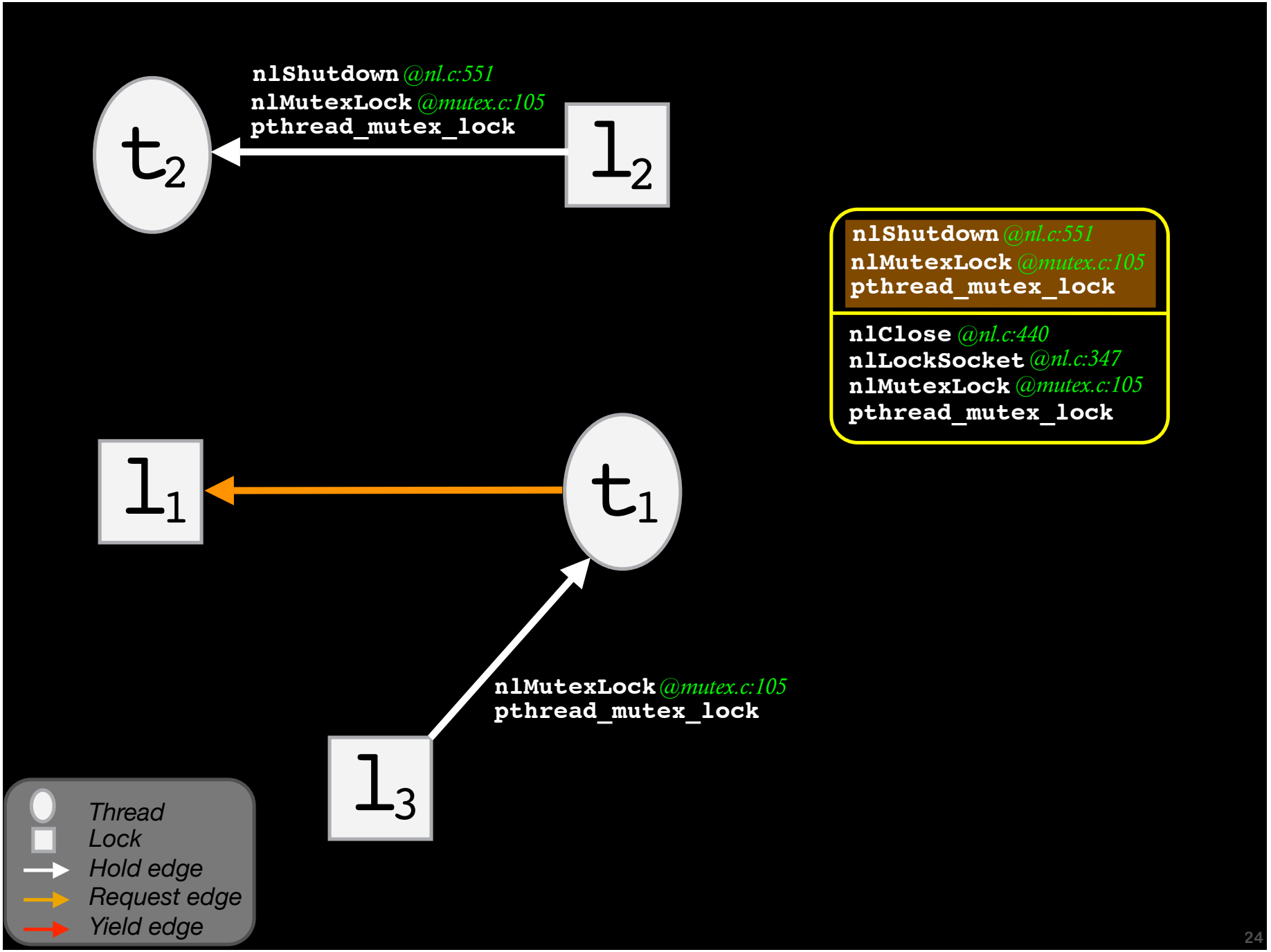
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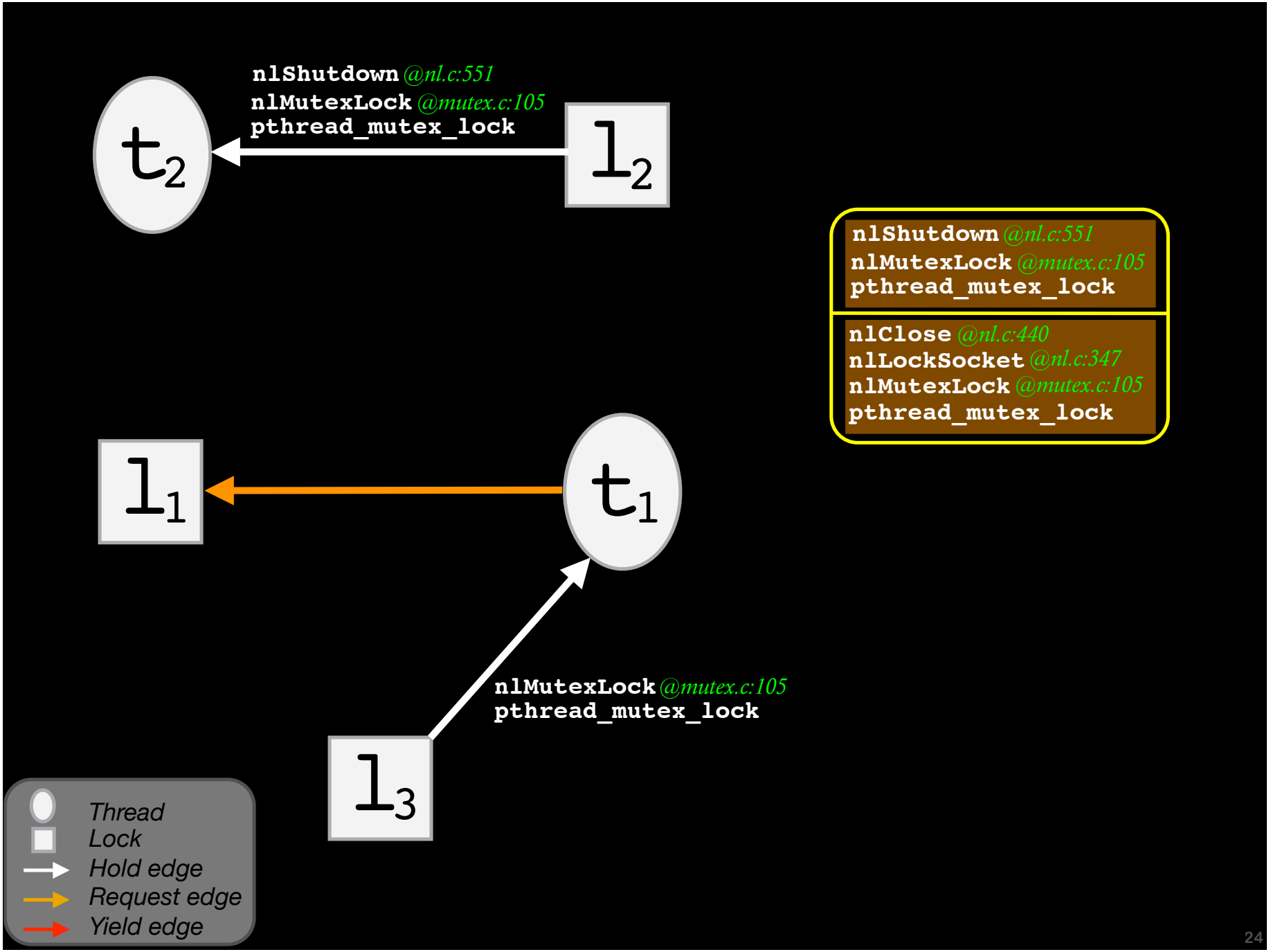
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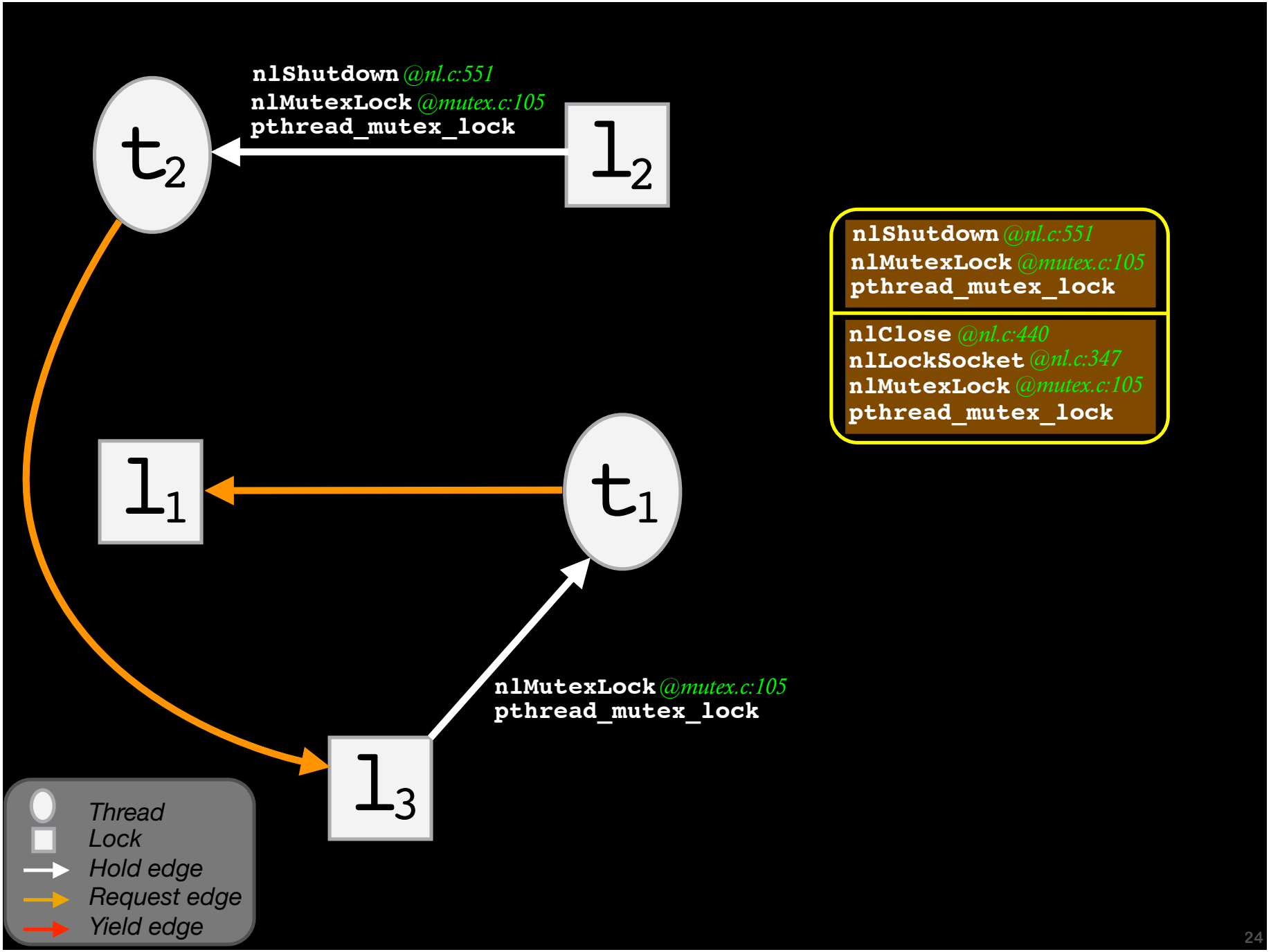
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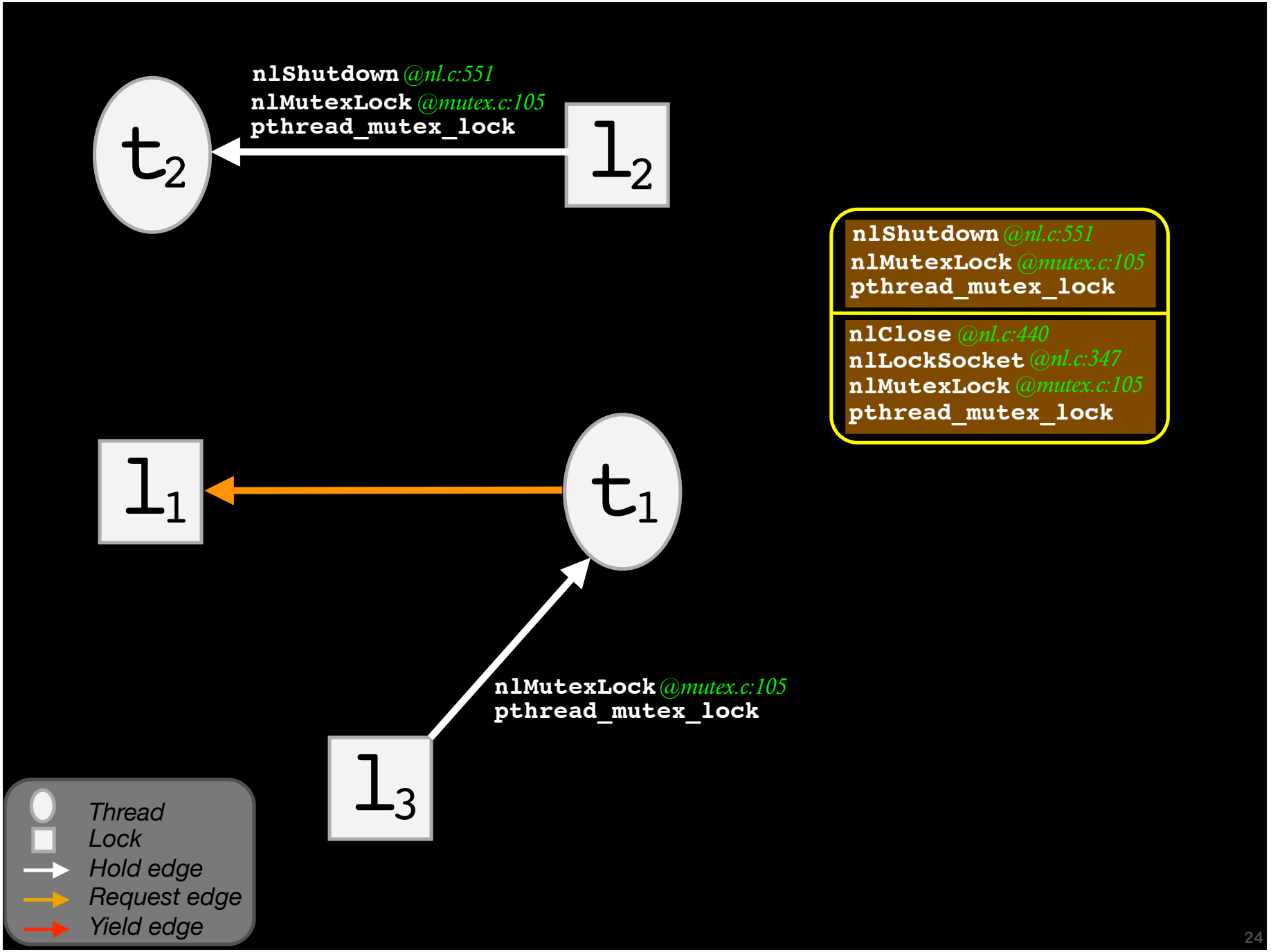
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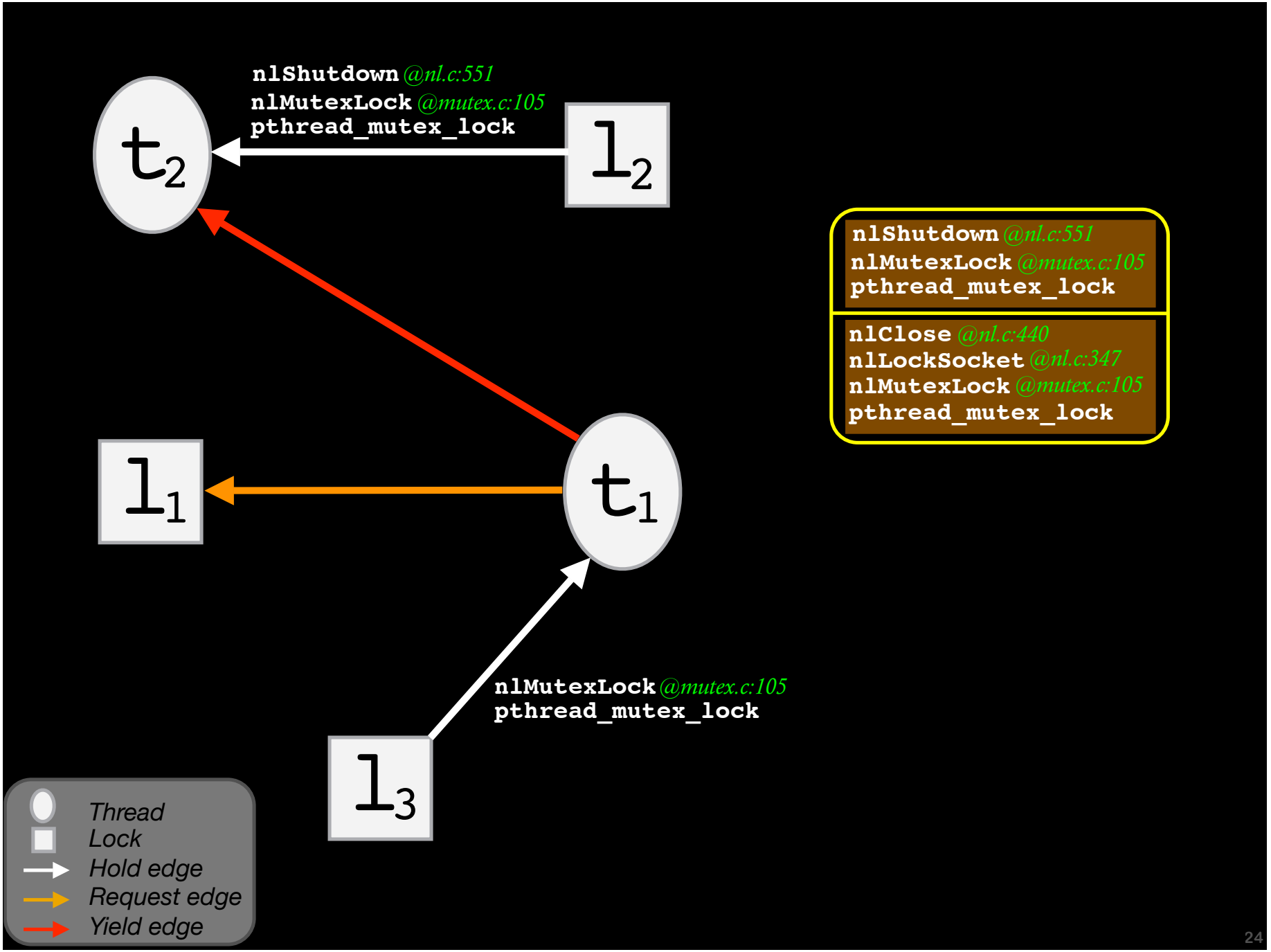
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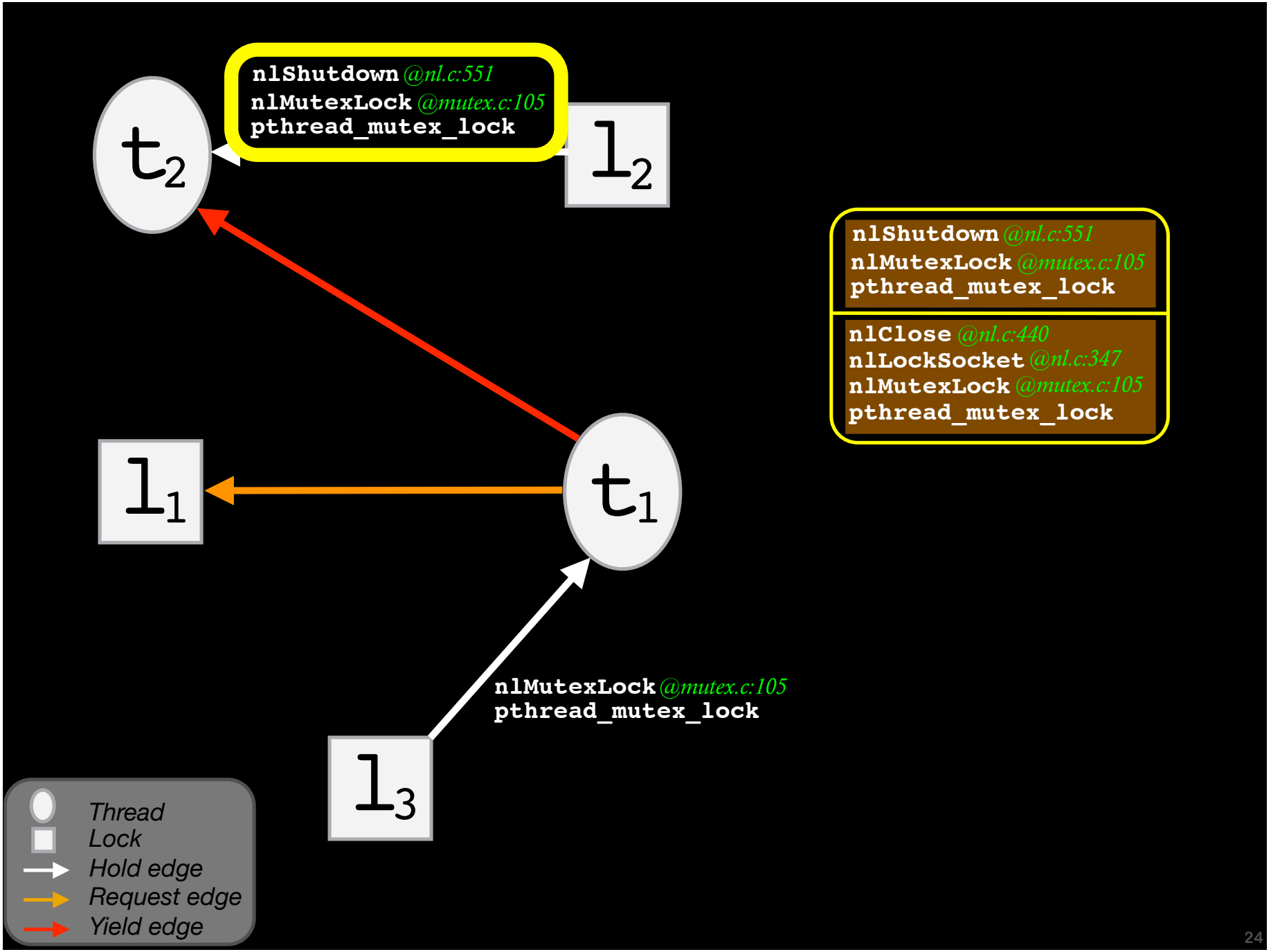
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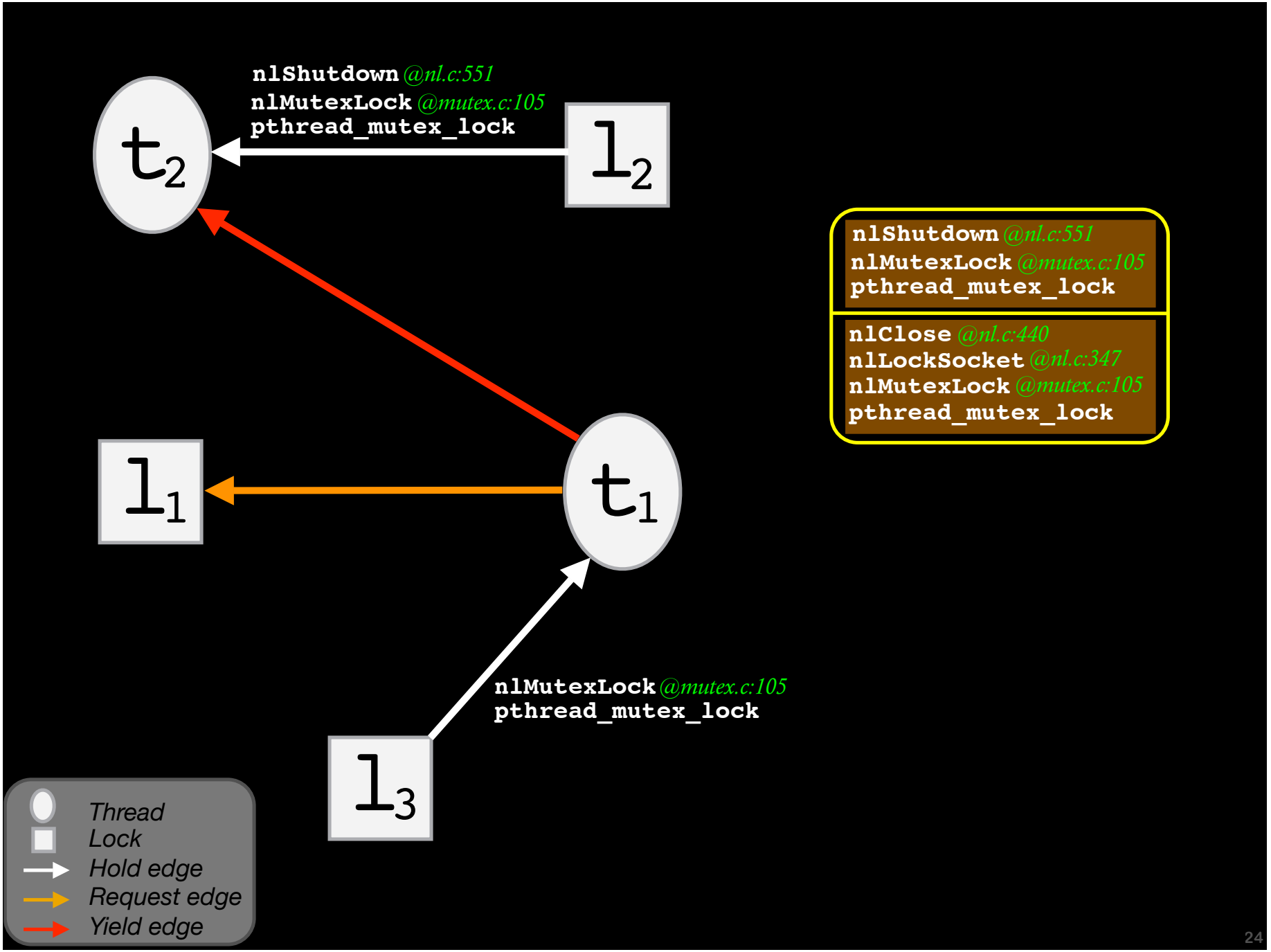
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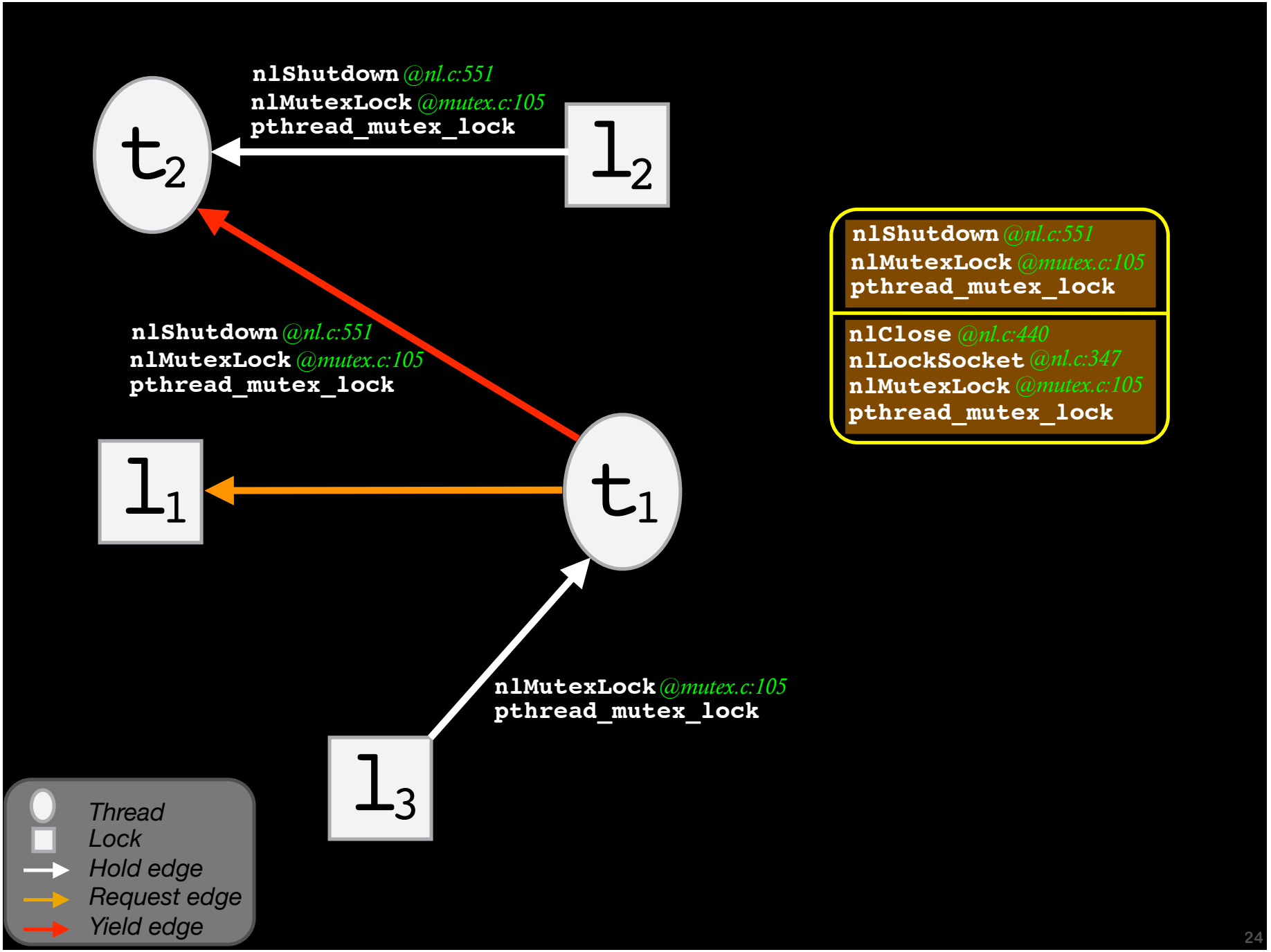
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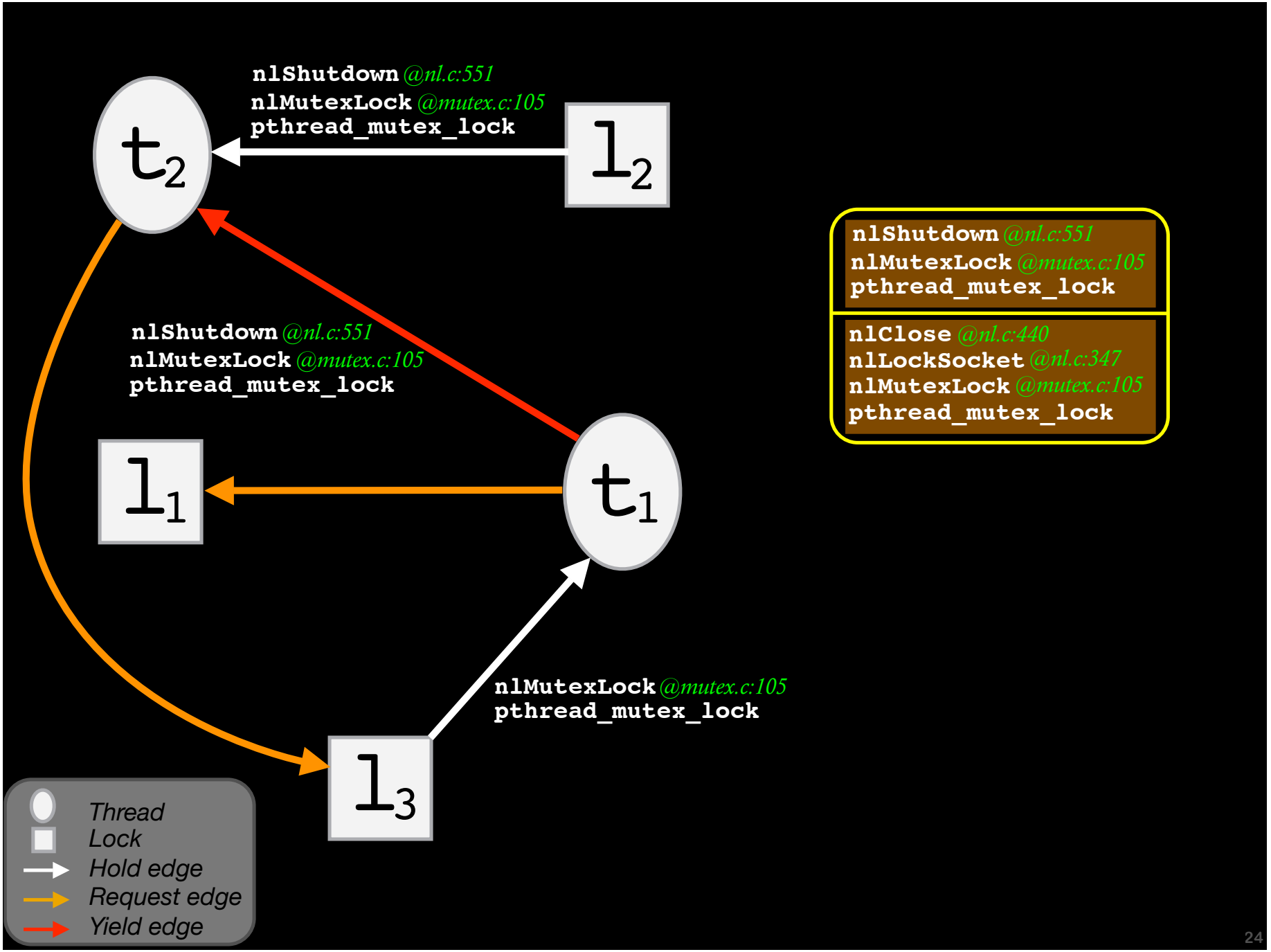
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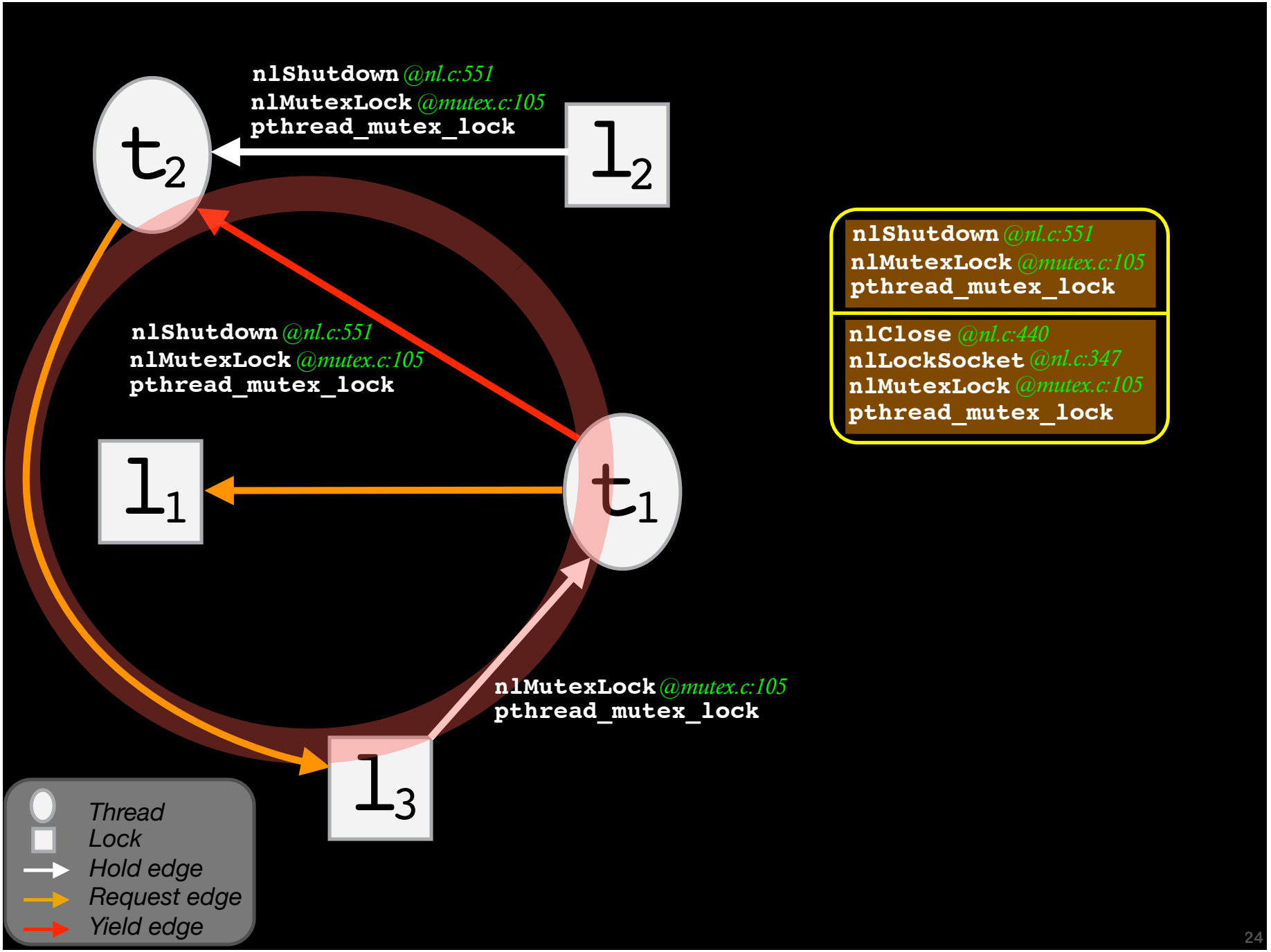
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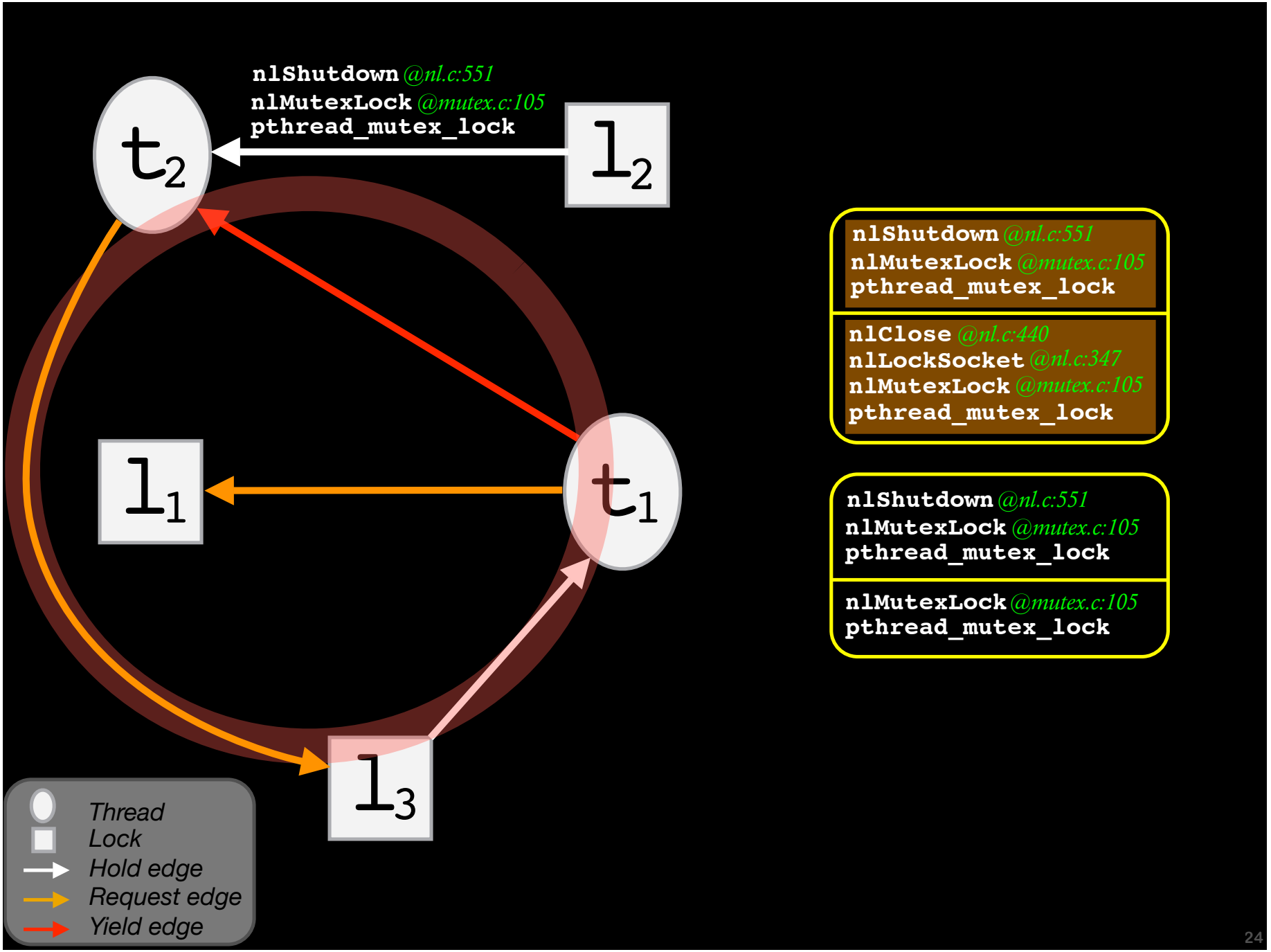
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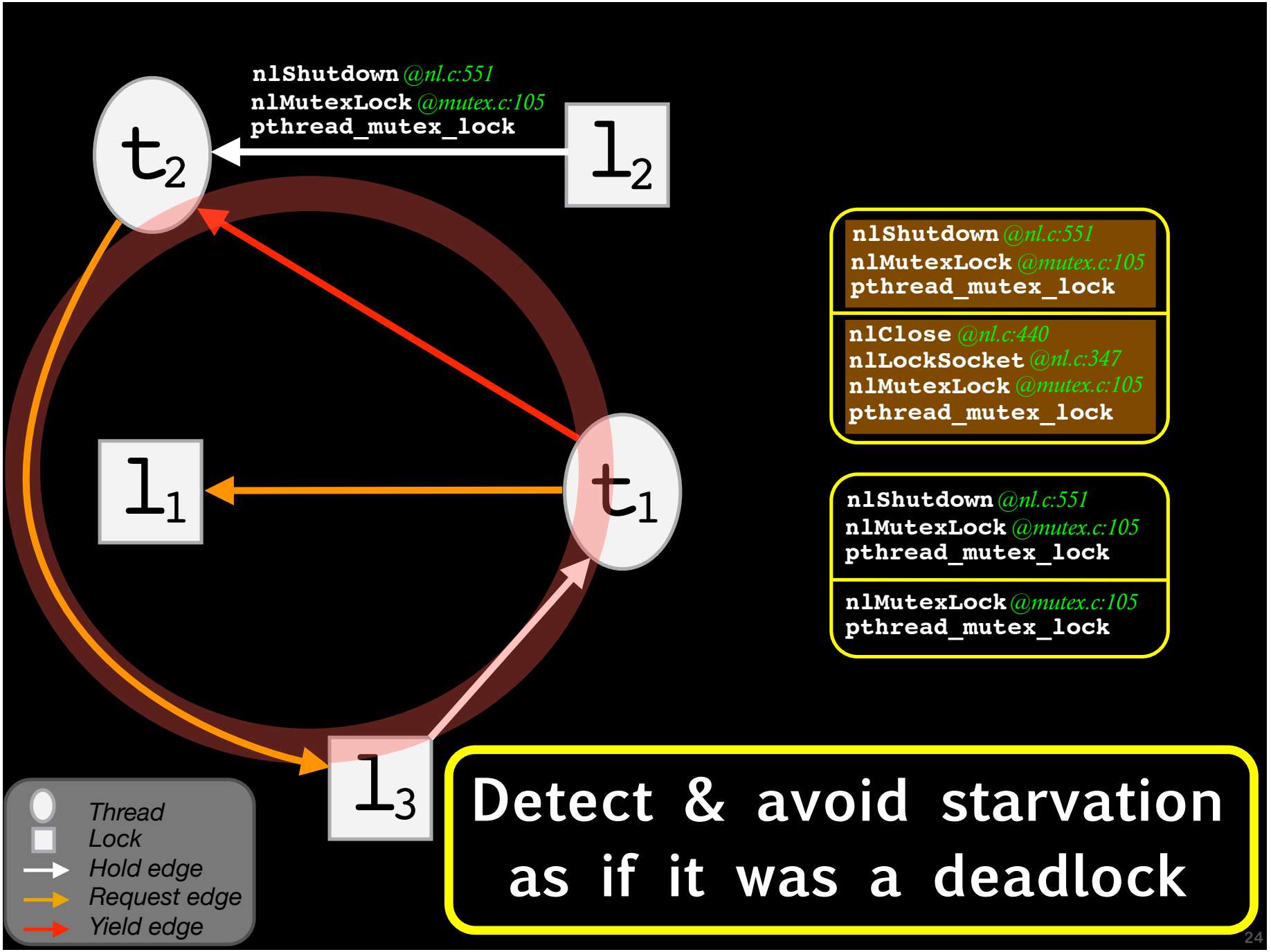
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Thread
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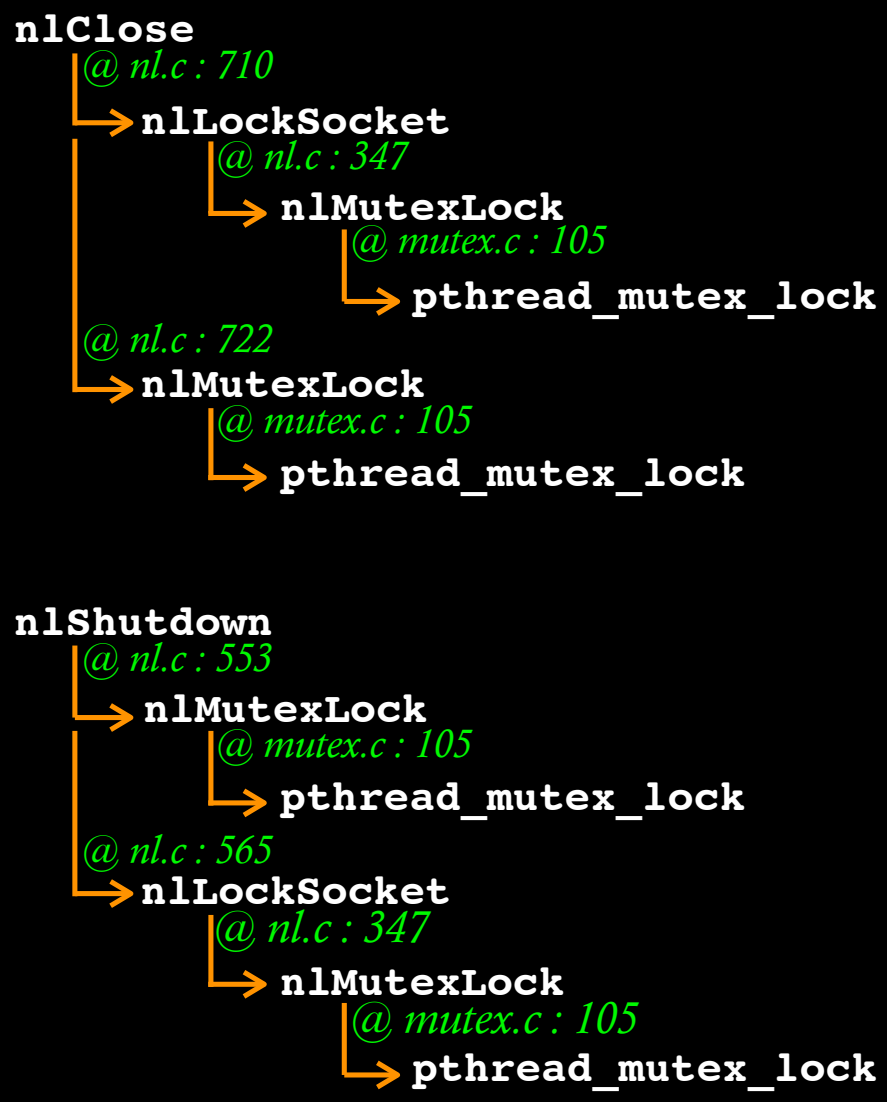
Detect & avoid starvation as if it was a deadlock

3. Precision Calibration

- False positive = avoiding a deadlock that would not have occurred
- Two sources:
  - Matching signatures too generally
  - Input dependencies


nlClose
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@ nl.c : 347
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@ mutex.c : 105
pthread_mutex_lock
@ nl.c : 722
nlMutexLock
@ mutex.c : 105
pthread_mutex_lock
nlShutdown
@ nl.c : 553
nlMutexLock
@ mutex.c : 105
pthread_mutex_lock
@ nl.c : 565
nlLockSocket
@ nl.c : 347
nlMutexLock
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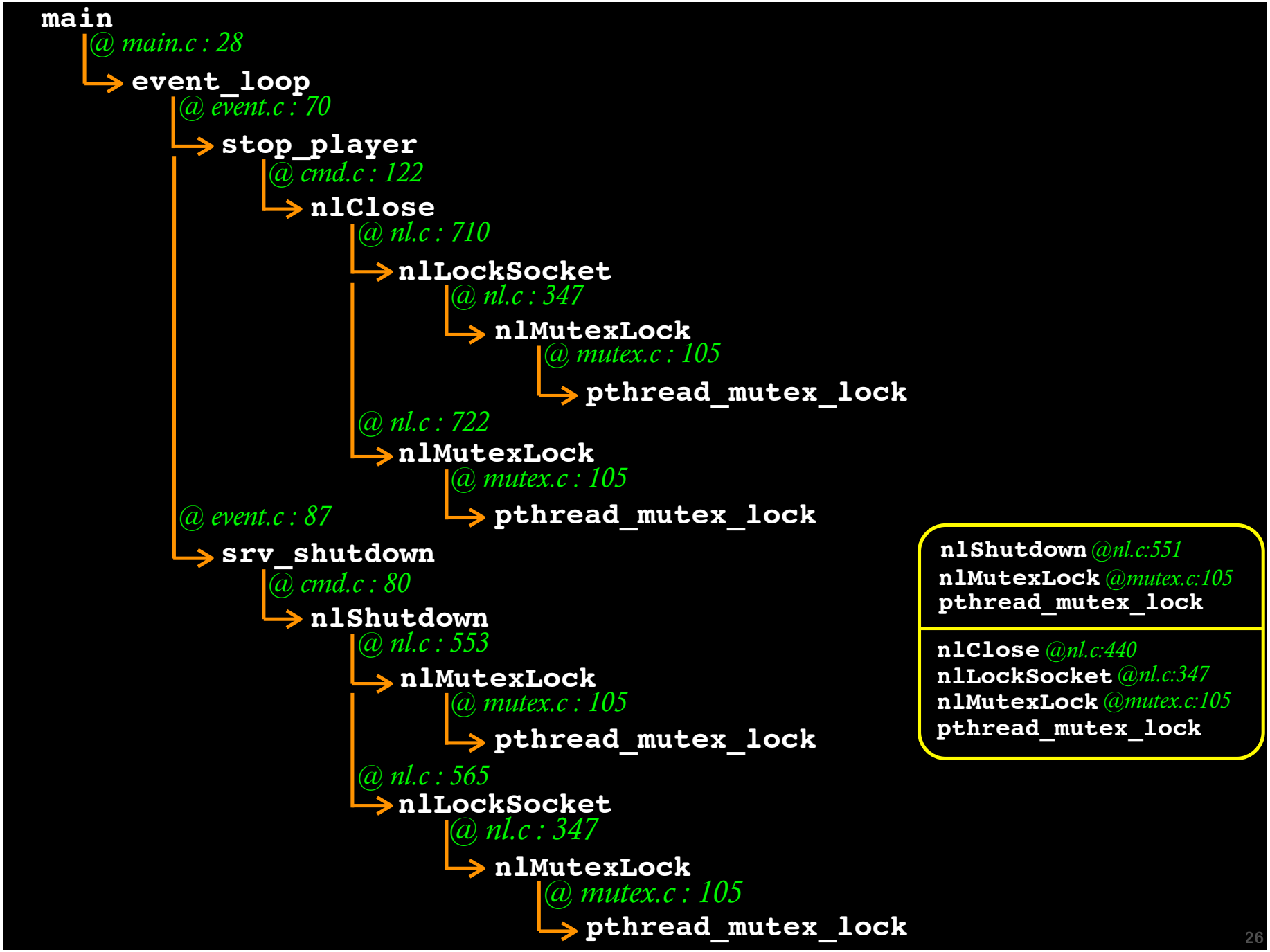
main
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event_loop
@ event.c : 70
stop_player
@ cmd.c : 122
nlClose
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nlLockSocket
@ nl.c : 347
nlMutexLock
@ mutex.c : 105
pthread_mutex_lock
@ nl.c : 722
nlMutexLock
@ mutex.c : 105
pthread_mutex_lock
@ event.c : 87
srv_shutdown
@ cmd.c : 80
nlShutdown
@ nl.c : 553
nlMutexLock
@ mutex.c : 105
pthread_mutex_lock
@ nl.c : 565
nlLockSocket
@ nl.c : 347
nlMutexLock
@ mutex.c : 105
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nlShutdown @nl.c:551
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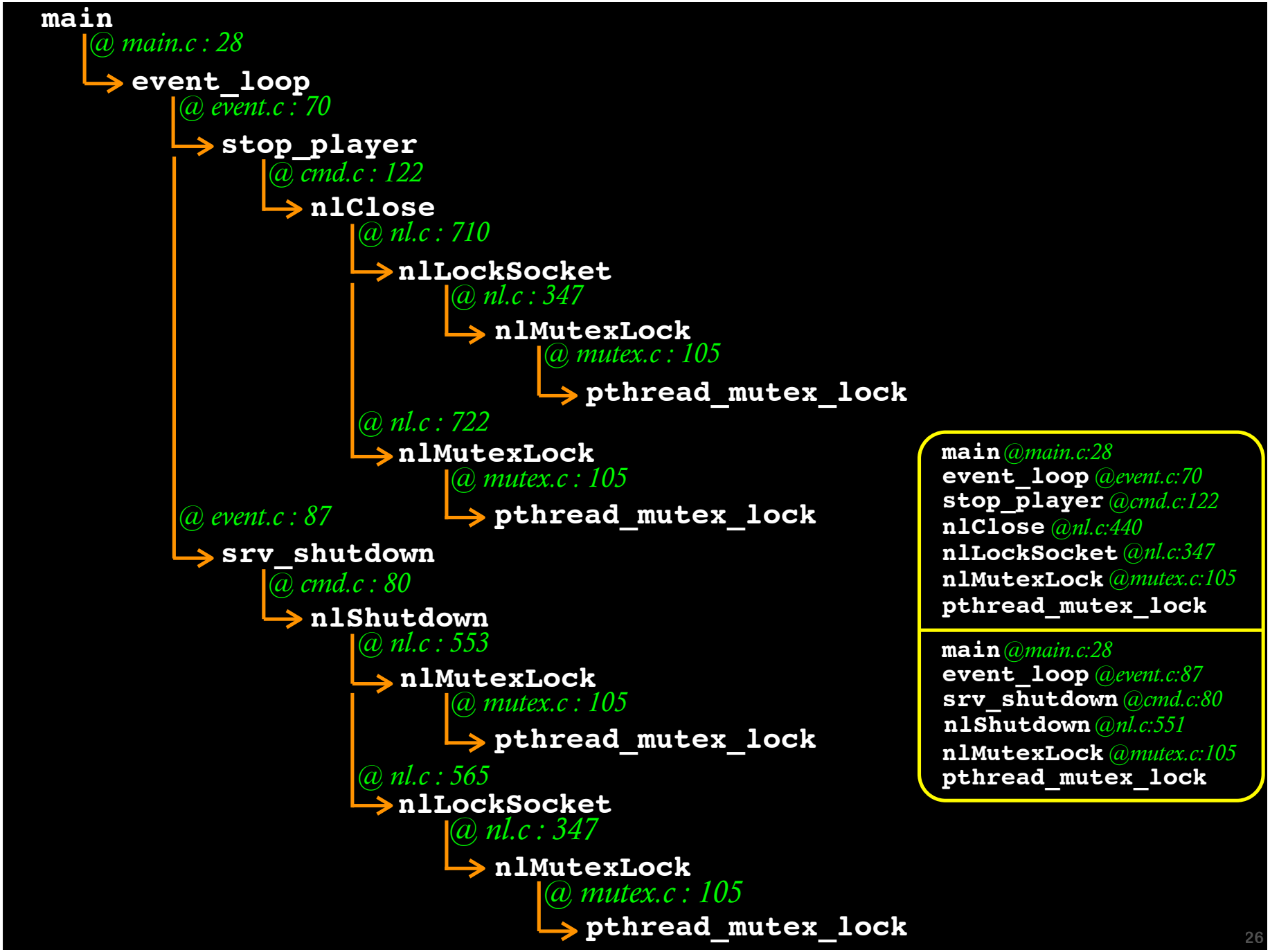
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3. Precision Calibration

- Solution: Automatic precision adjustment
  - Post-factum what-if analysis
  - Heuristic: look for potential lock inversions
- Input dependencies not captured
  - Dimmunix focused 100% on control flow
  - This is a requisite for portability of signatures, i.e., for immunity

Outline

- Immunity Against Deadlocks
- Dimmunix Overview
- Challenges & Solutions
- Discussion & Conclusions

Dimmunix Properties

1. Someone will experience first occurrence
   - Afterward can vaccinate all others
2. Cannot affect deadlock-free programs
3. Cannot induce incorrect outputs (non-RT)
4. Must be aware of all synch mechanisms

Related Work

- **Complements other reliability techniques**
  - **Static analysis** [*Flanagan & Leino*] [*Engler & Ashcraft*]
  - **Modelchecking** [*Henzinger et al.*] [*Havelund et al.*]
  - **Transactional Memory** [*Herlihy & Moss*]
- **Improves upon previous approaches by increasing avoidance precision**
  - **Program transformations** [*Boronat & Cholvi*]
  - **Ghostlocks** [*Zeng & Martin*]
  - **Gatelocks** [*Buchbinder et al.*]

Dimmunix

- Failure immunity applied to deadlocks
- Effective for both Java and C/C++
- Low overhead (4.5% for 1024 threads)
- Needs no assistance & no source code
- Can use as band-aid and vaccine

http://dimmunix.epfl.ch/