A proposal of new concurrency model for Ruby 3

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People love “Concurrency”

dRuby in the last century.
Masatoshi SEKI @m_seki

JA

Improved scalability by relaxing the GVL
Charlie Gracie @crgracie

EN

ErRuby: Ruby on Erlang/OTP
Lin Yu Hsiang @johnlinvc

EN

concurrent-ruby and how it is making Rails concurrent
Vipul A M @vipulnsward

EN

How to create multiprocess server on Windows with Ruby
Ritta Narita @narittan

EN

Ruby Concurrency compared
Anil Wadghule @anildigital

EN

Concurrent RubyKaigi

(at least, there are two parallel sessions)

Why people love (to discuss) “Concurrency”?

- Performance by “Parallel” execution to utilize multiple-cores
- Ruby has thread system, but MRI doesn’t permit to allow parallel execution.

About this presentation

- Show “Why difficult multi-threads programs”
- Propose new concurrent and parallel mechanism idea named **“Guild”**
  - For Ruby 3

Koichi Sasada

- A programmer living in Tokyo, Japan
- Ruby core committer since 2007
  - YARV, Fiber, … (Ruby 1.9)
  - RGenGC, RincGC (Ruby 2…)

Koichi is an Employee

heroku

Difficulty of Multi-threads programming

Programming language evolution

- Trade-off: Performance v.s. Safety/Easily
  - Performance: making faster programs
  - Safety: making bug-free programs
  - Easily: making programs with small efforts

Two example
C language

- String manipulation with pointers
- Memory management without GC

String manipulation with pointers

- C: Using raw pointers to manipulate strings
  - Good: all-purpose and fast
  - Bad: Error-prone
    - Generates strange behavior, such as abnormal termination
- Ruby: Wrap with String class
  - Good: Easy to use
  - Bad: slower than C in some cases

Object management without GC

- C: Free memory objects manually
  - Good: full control (target, timing and so on)
  - Bad: Error-prone
    - double-free/memory-leak, …
- Ruby: Automatic collection with GC
  - Good: nothing to care about object collection
  - Bad: introduce some overhead

Ruby chose “**safety/easily**” approach

- Ruby encourage “**Happy Programming**”
  - Reduce programmer’s cost
  - Nowadays computer is enough faster
  - Implementation techniques overcome performance penalties

Do you want to program without GC?

Muilti-threads programming is difficult

- **Introduce data race, race condition**
- Introduce deadlock, livelock
- Difficulty on debugging because of nondeterministic behavior
  - difficult to reproduce same problem

Difficult to make correct (bug-free) programs

- Difficult to tune performance

Difficult to make fast programs

Data race and race condition

- Bank amount transfer example
  - Quoted from Race Condition vs. Data Race http://blog.regehr.org/archives/490

```
def transfer1 (amount, account_from, account_to)
  if (account_from.balance < amount) return NOPE
  account_to.balance += amount
  account_from.balance -= amount
  return YEP
end
```

Data race

- "account_to.balance += amount" has **Data-race**
  - Assume two threads (T1 and T2) invoke this methods with same bank accounts

```
# interleave two threads (T1: amount = 100, T2: amount = 200)
  T1: t1 = account_to.balance # t1 = 10
  T2: t2 = account_to.balance # t2 = 10
  T2: account_to.balance = t2 + 200 #=> 210
  T1: account_to.balance = t1 + 100 #=> 110 (expected: 310)
```

Race condition

- To avoid data-race with the lock
- But there is another problem yet

```
# Lock with “Thread.exclusive”
def transfer2 (amount, account_from, account_to)
  if (account_from.balance < amount) return NOPE
  Thread.exclusive{ account_to.balance += amount }
  Thread.exclusive{ account_from.balance -= amount }
  return YEP
end
```

Race condition

- To avoid data-race with the lock
- But there is another problem yet

```
# T1 amount = 100, T2 amount = 200, account_from.balance = 250
T1: if (account_from.balance (== 250) < 100) return NOPE # OK, go through
T2: if (account_from.balance (== 250) < 200) return NOPE
T2:  Thread.exclusive{ account_to.balance += 200 }
T2:  Thread.exclusive{ account_from.balance -= 200 } #=> 250-200 => 50
T1:  Thread.exclusive{ account_to.balance += 100 }
T1:  Thread.exclusive{ account_from.balance -= 100 } #=> 50 - 100 => negative number!!
```

Final solution

- Lock whole of method

```
def transfer1 (amount, account_from, account_to)
  Thread.exclusive{
    if (account_from.balance < amount) return NOPE
    account_to.balance += amount
    account_from.balance -= amount
    return YEP
  }
end
```

Another example
Multi-thread quiz

- What happen on this program?

```
ary = [1, 2, 3]
t1 = Thread.new{
  ary.concat [4, 5, 6]
}
t2 = Thread.new{
  p ary # what's happen?
}.join
```

(1) **[1, 2, 3]**
(2) **[1, 2, 3, 4, 5, 6]**
(3) **(1) or (2)**

Another example
Multi-thread quiz

- Answer: (4) depends on an interpreter

```
ary = [1, 2, 3]
t1 = Thread.new{
  ary.concat [4, 5, 6]
}
t2 = Thread.new{
  p ary # what's happen?
}.join
```

On MRI, (3) is correct

It will shows
[1, 2, 3] or
[1, 2, 3, 4, 5, 6]
(depends on thread switching timing)

Another example
Multi-thread quiz

- Answer: (4) depends on an interpreter

```
ary = [1, 2, 3]
t1 = Thread.new{
  ary.concat [4, 5, 6]
}
t2 = Thread.new{
  p ary # what's happen?
}.join
```

On JRuby:

It can cause Java exception because "Array#concat" is not thread safe

On JRuby …

```
# similar program
h = Hash.new(0)
NA = 1_000
10_000.times{
  ary = []
  (1..10).each{
    Thread.new{
      NA.times{|i|
        ary.concat [i]
      }
    }
  }
  t2 = Thread.new{
    s = ary.dup
  }.join
}
```

Unhandled Java exception: java.lang.NullPointerException

```
java.lang.NullPointerException: null
          rbInspect at org/jruby/RubyBasicObject.java:1105
            inspect at org/jruby/RubyObject.java:516
          inspectAry at org/jruby/RubyArray.java:1469
            inspect at org/jruby/RubyArray.java:1497
        cacheAndCall at org/jruby/runtime/callsite/CachingCallSite.java:293
               call at org/jruby/runtime/callsite/CachingCallSite.java:131
       block in t.rb at t.rb:17
         yieldDirect at org/jruby/runtime/CompiledIRBlockBody.java:156
       yieldSpecific at org/jruby/runtime/IRBlockBody.java:73
       yieldSpecific at org/jruby/runtime/Block.java:136
             times at org/jruby/RubyFixnum.java:291
        cacheAndCall at org/jruby/runtime/callsite/CachingCallSite.java:303
          callBlock at org/jruby/runtime/callsite/CachingCallSite.java:141
               call at org/jruby/runtime/callsite/CachingCallSite.java:145
              <top> at t.rb:3
 invokeWithArguments at java/lang/invoke/MethodHandle.java:599
               load at org/jruby/ir/Compiler.java:111
          runScript at org/jruby/Ruby.java:833
          runScript at org/jruby/Ruby.java:825
         runNormally at org/jruby/Ruby.java:760
         runFromMain at org/jruby/Ruby.java:579
       doRunFromMain at org/jruby/Main.java:425
         internalRun at org/jruby/Main.java:313
                run at org/jruby/Main.java:242
               main at org/jruby/Main.java:204
```

jruby 9.1.2.0 (2.3.0) 2016-05-26 7357c8f OpenJDK 64-Bit Server VM 24.95-b01 on 1.7.0_101-b00 +jit [linux-x86_64]
On 8 hardware threads machine

Difficulty of multi-threads programs

- We need to synchronize all sharing mutable objects correctly
  - We need to know **which methods are thread-safe**.
  - Easy to track all on small program
  - Difficult to track on **big programs**, especially on **programs using gems**
- We need to check **all of source codes**, or believe **library documents** (but documents should be correct)
- Multi-threads prog. requires **“completeness”**

Difficulty of multi-threads programs (cont.)

- For debugging, it is difficult to find out the bugs
  - **Backtrace may not work** well because the problem may be placed on another line.
  - Bugs don’t appear frequently with **small data**
  - Difficult to reproduce issues because of **nondeterministic behavior**

FYI:
Why MRI Array#concat is thread-safe?

- MRI uses GVL (Giant/Global VM Lock) to control thread switching timing and C methods (such as Array#concat) are working atomically.
- GVL prohibits parallel thread execution (BAD), however it avoids several severe issues (GOOD).

Thread programming: Performance tuning issue

```
a1 = []; a2 = []
NA = 10_000_000
t1 = Thread.new{
  NA.times{|i| a1 << i }
}.join
t2 = Thread.new{
  NA.times{|i| a2 << i }
}.join
```

Serial program:

real 0m8.568s

user 0m37.816s

sys 0m5.530s

on JRuby

Thread programming: Performance tuning issue

```
a1 = []; a2 = []
NA = 10_000_000
t1 = Thread.new{
  NA.times{|i| a1 << i }
}
t2 = Thread.new{
  NA.times{|i| a2 << i }
}
t1.join; t2.join
```

Parallel program

(2 threads):

real 0m6.411s

user 0m20.527s

sys 0m7.798s

Thread programming: Performance tuning issue

```
a1 = []; a2 = []
NA = 10_000_000
m1, m2  = Mutex.new, Mutex.new
t1 = Thread.new{
  NA.times{|i| m1.synchronize{ a1 << i }}
}
t2 = Thread.new{
  NA.times{|i| m2.synchronize{ a2 << i }}
}
t1.join; t2.join
```

Parallel program with a useless lock 1

(2 threads):

real 0m10.264s

user 0m38.370s

sys 0m4.406s

Thread programming: Performance tuning issue

```
a1 = []; a2 = []
NA = 10_000_000
m = Mutex.new
t1 = Thread.new{
  NA.times{|i| m.synchronize{ a1 << i }}
}
t2 = Thread.new{
  NA.times{|i| m.synchronize{ a2 << i }}
}
t1.join; t2.join
```

Parallel program with a useless lock 2

(2 threads):

real 0m15.163s

user 0m45.317s

sys 0m9.658s

Performance tuning issue

	Execution time
Serial program	**8.568s**
Parallel program	**6.411s**
Parallel program with a useless lock 1	**10.264s**
Parallel program with a useless lock 2	**15.163s**

Thread programming:
Performance tuning issue

We need to use just correct number locks

Not enough → unexpected behavior
Too much → performance penalty

FYI: synchronization mechanism

- Many synchronization mechanisms…
  - Mutual exclusion (Mutex), monitor, critical section
  - Transactional memory (optimistic lock)
  - Atomic instructions
  - Synchronized Queue
  - …
  - Research on many lightweight lock algorithms
- They assume we can use them correctly

Overcome thread difficulty

Key idea

Problem:

Easy to share mutable objects

Idea:

Do not allow to share mutable objects without any restriction

Study from other languages

- Shell script with pipes, Racket (Place)
  - Copy mutable data between processes w/ pipes
- Erlang/Elixir
  - Do not allow mutable data
- Clojure
  - Basically do not allow mutable data
  - Special data structure to share mutable objects
  - Note that it can share mutable objects on Java layer

NOTE: we do not list approaches using “type system”

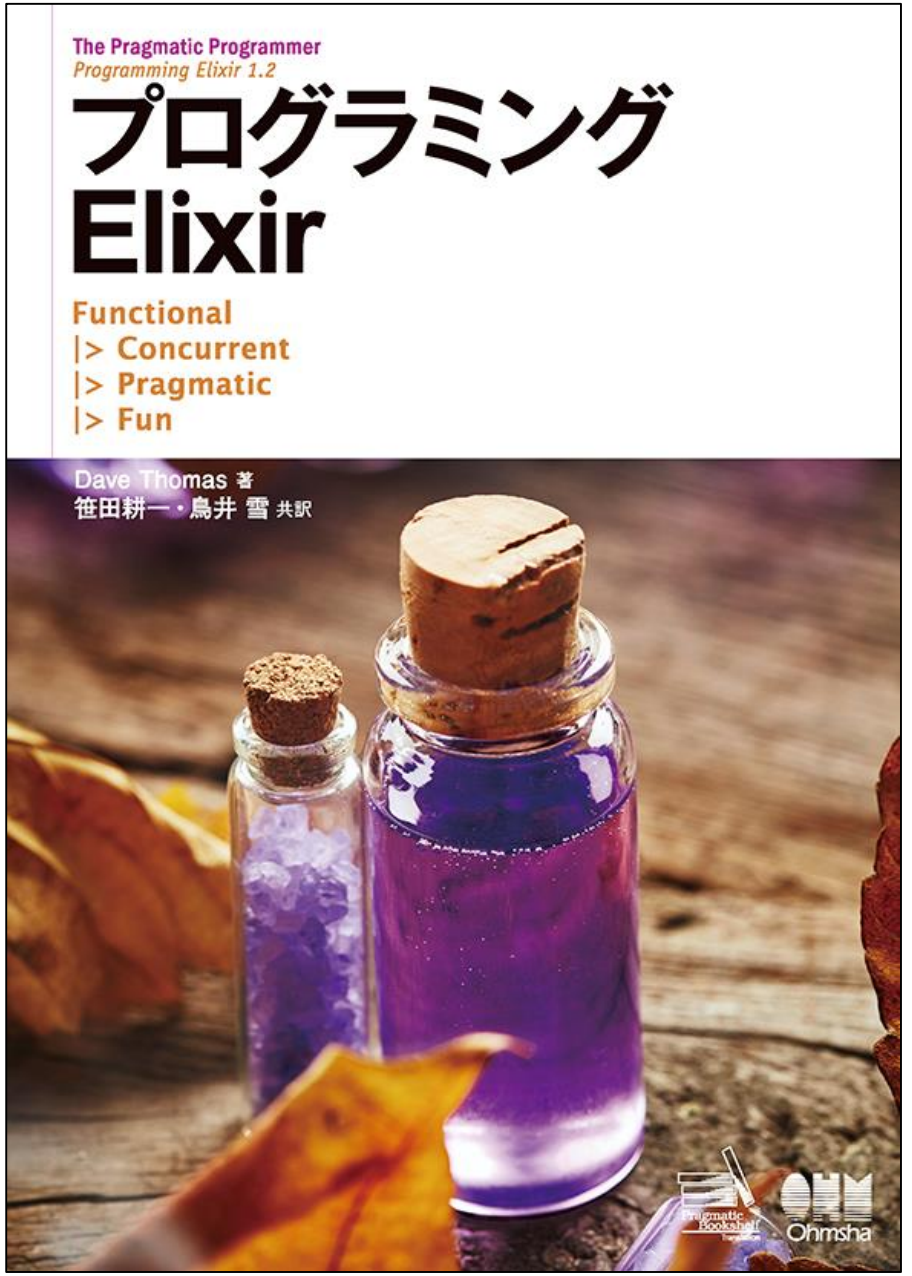
Don’t you know Elixir language?

Programming Elixir 1.2 by Dave Thomas

邦訳:プログラミングElixir
笹田耕一・鳥井雪共訳 2016/08/19

You can buy it TODAY!!

サイン会は明日13時らしいです



Summary of approaches

- Communication with copied data (shell scripts)
  - Good: we don’t need locks
  - Bad: copy everything is **slow**
- Prohibit mutable objects
  - Good: we don’t need locks
  - Bad: Ruby utilizes **many “write” operations**. Unacceptable.
- Provide special data structure to share mutable objects
  - Good: we don’t need locks (who don’t use such special data structures)
  - Bad: Difficult to use special data structures.

Background was finished

Our goal for Ruby 3

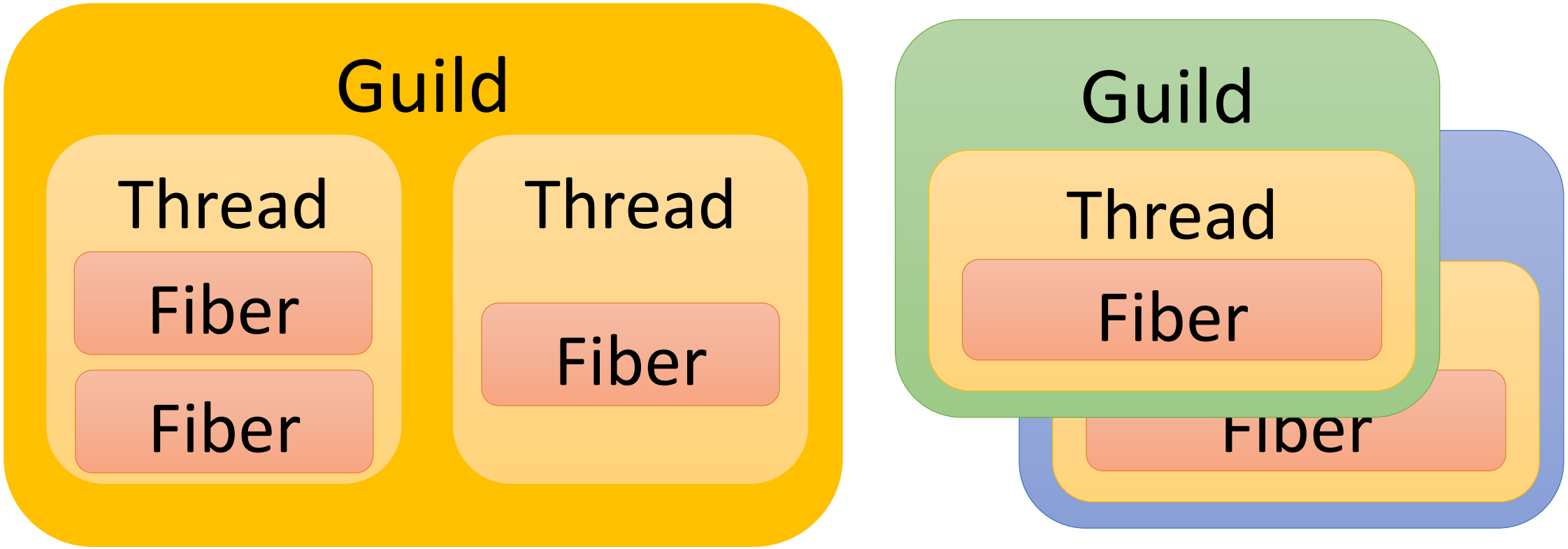
- **We need to keep compatibility** with Ruby 2.
- We can make **parallel program**.
- We **shouldn’t consider** about locks any more.
- We **can share** objects with copy, but **copy operation should be fast.**
- We **should share objects** if we can.
- We can **provide special objects** to share mutable objects like Clojure if we really need speed.

“Guild”

New concurrency model for Ruby 3

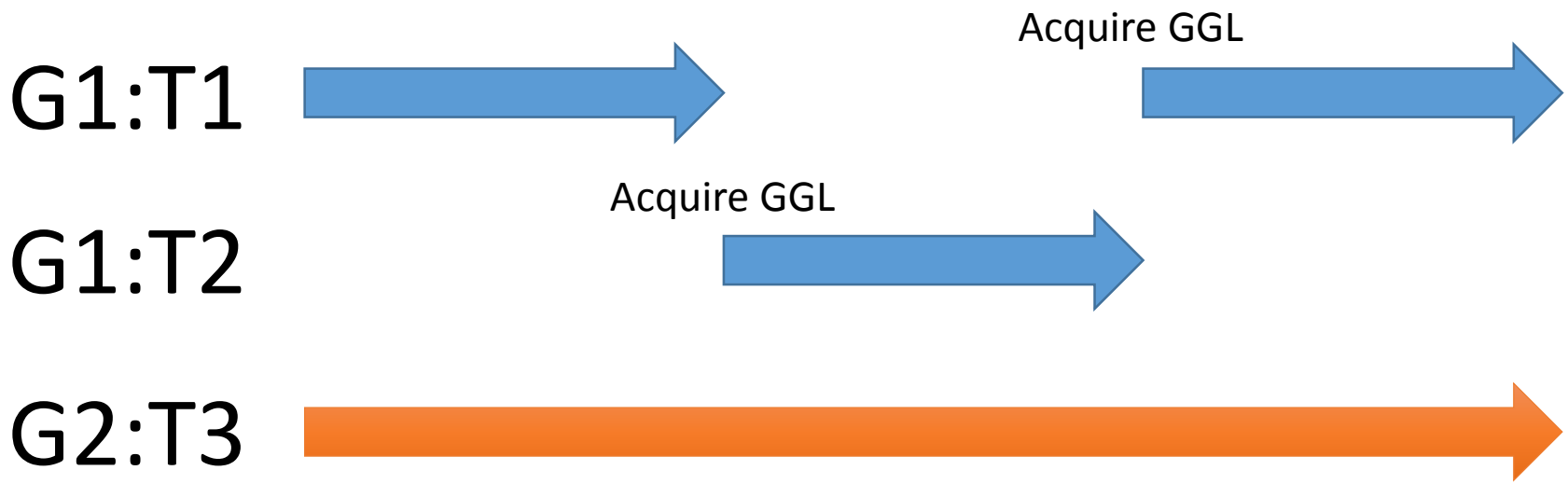
Guild: New concurrency abstraction

- Guild has at least one thread (and a thread has at least one fiber)



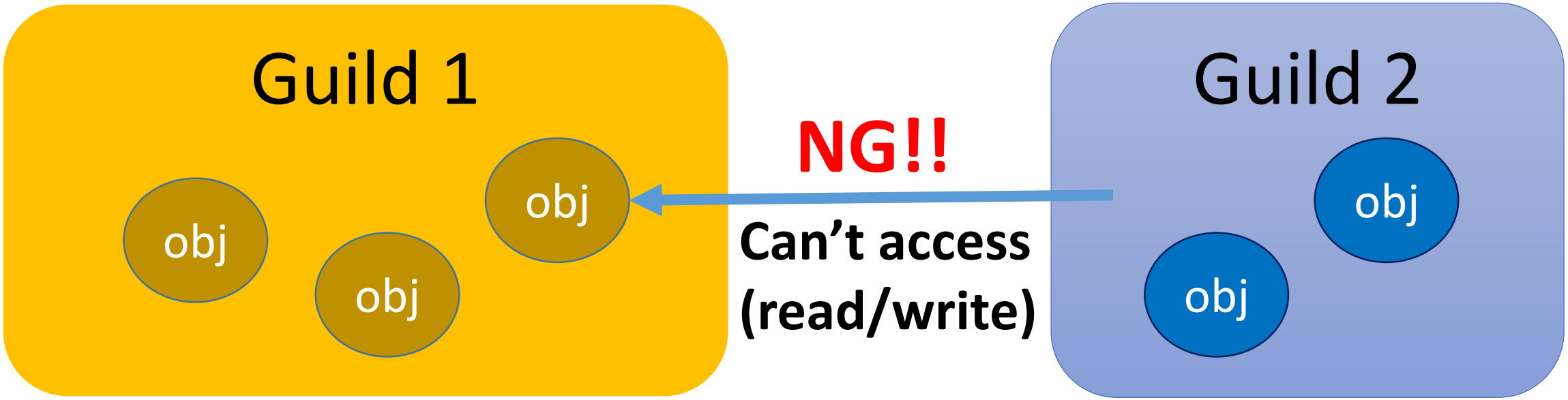
Threads in different guilds can run in Parallel

- Threads in different guilds **can run in parallel**
- Threads in a same guild **can not run in parallel** because of GVL (or GGL: Giant Guild Lock)



Guild and objects:
All objects have their own membership

- All of mutable objects should belong to only one Guild (all mutable objects are member of one guild)
- Other guilds can not access objects



Object membership

Only one guild can access mutable object

→ **We don’t need to consider about locks**

Because:

NO data races and NO race conditions

(if all guilds use only one thread)

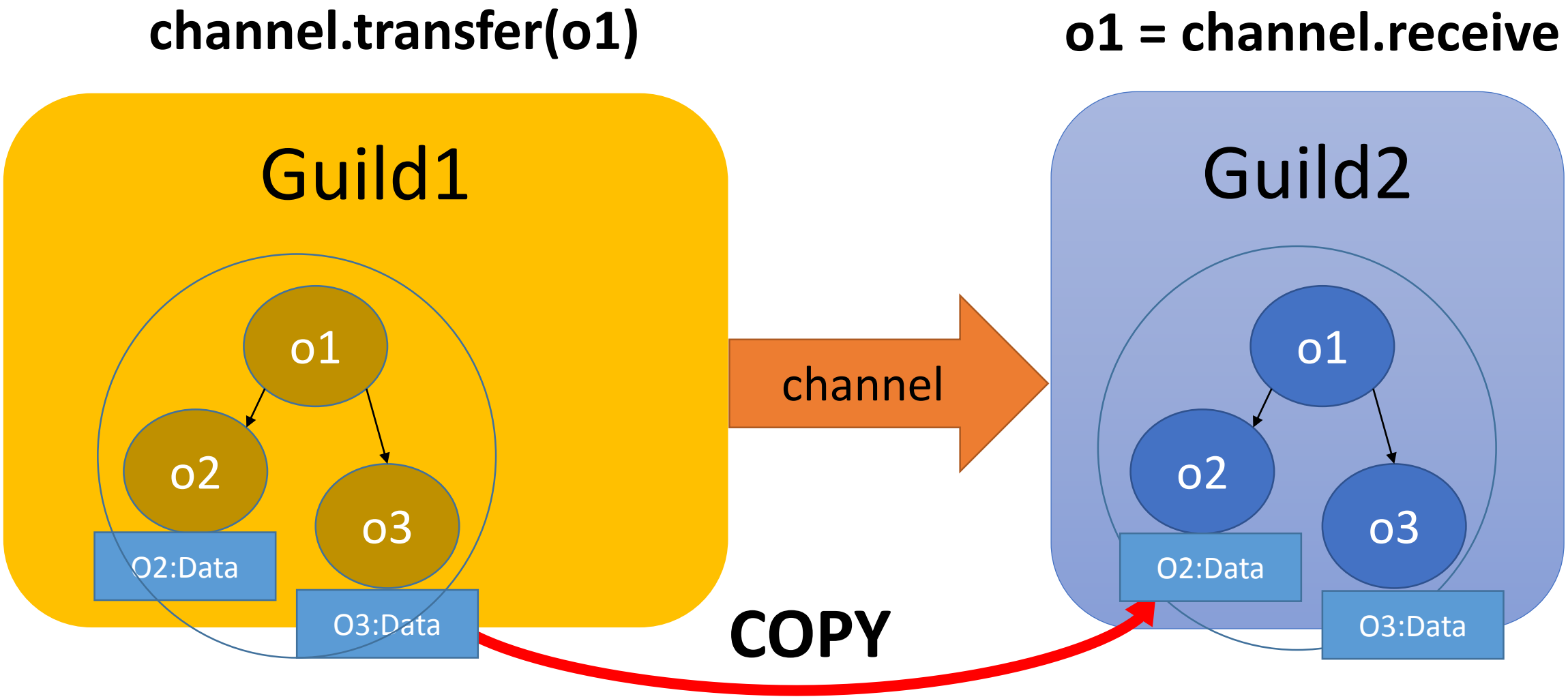
Inter guilds communication

- **“Guild::Channel”** to communicate each guilds
- Two communication methods
  1. **Copy**
  2. **Transfer membership** or **Move** in short

Copy using Channel

- Guild::Channel#transfer(obj) send **deep copied** object(s) to a destination guild.
- dRuby and multi-process system use this kind of communication

Copy using Channel



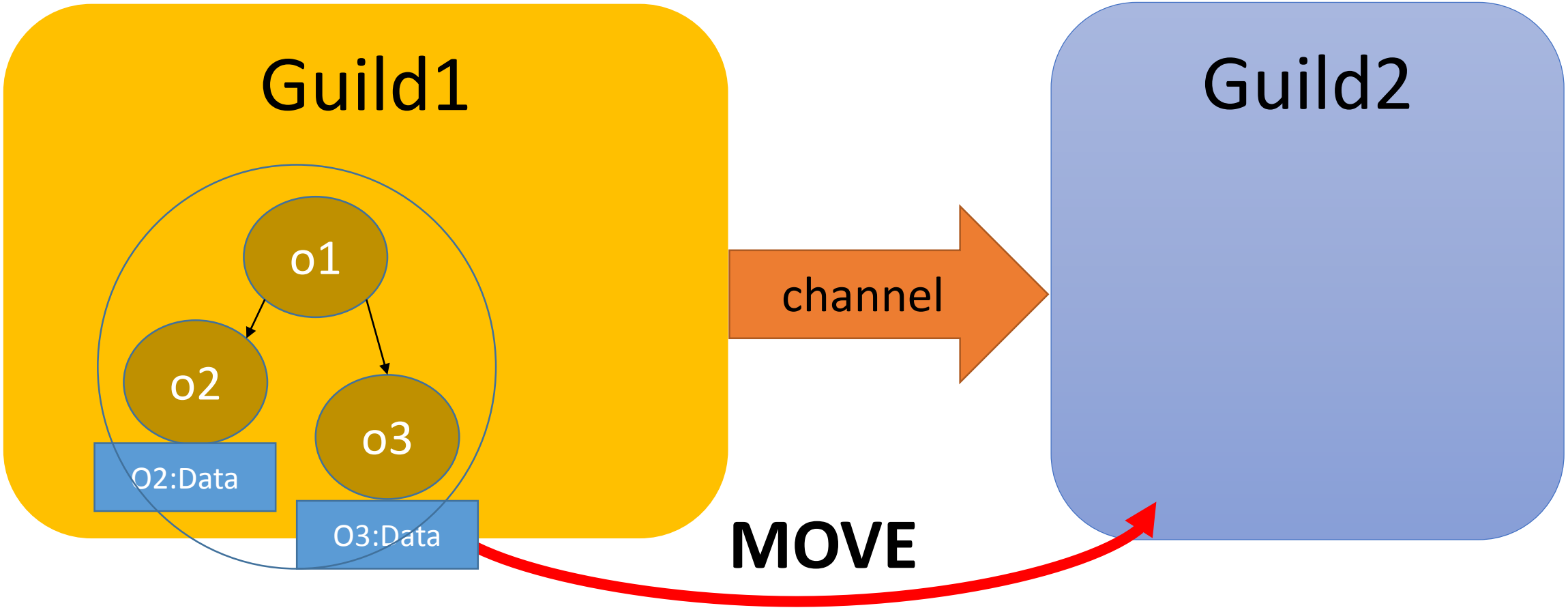
Move using Channel [New technique!!]

- Guild::Channel#transfer_membership(obj) change the membership of object(s)
  - Leave from the source guild
  - Join to the destination guild
- Prohibit accessing to left objects
  - Cause exceptions and so on
  - ex)
```
obj = “foo”
ch.transfer_membership(obj)
obj.upcase      #=> Error!!
p(obj)          #=> Error!!
```

Move using Channel

channel.transfer_membership(o1)

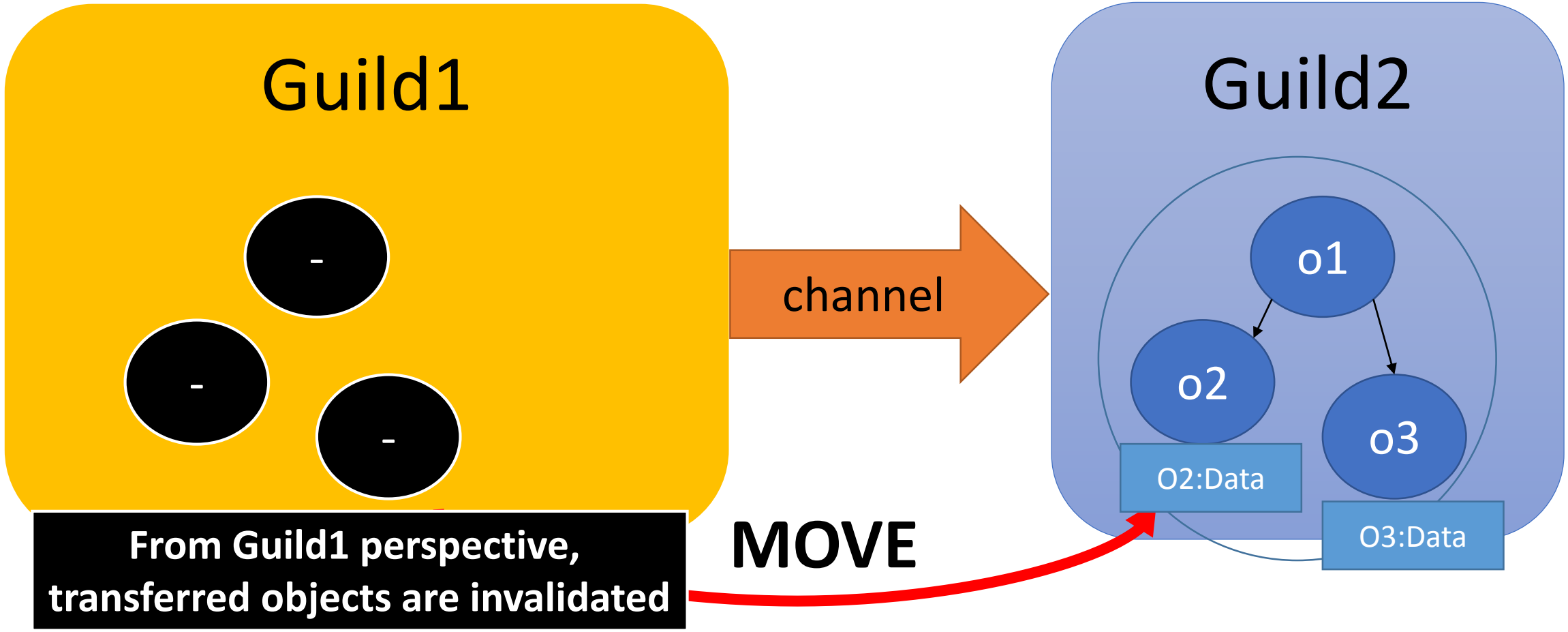
o1 = channel.receive



Move using Channel

channel.transfer_membership(o1)

o1 = channel.receive

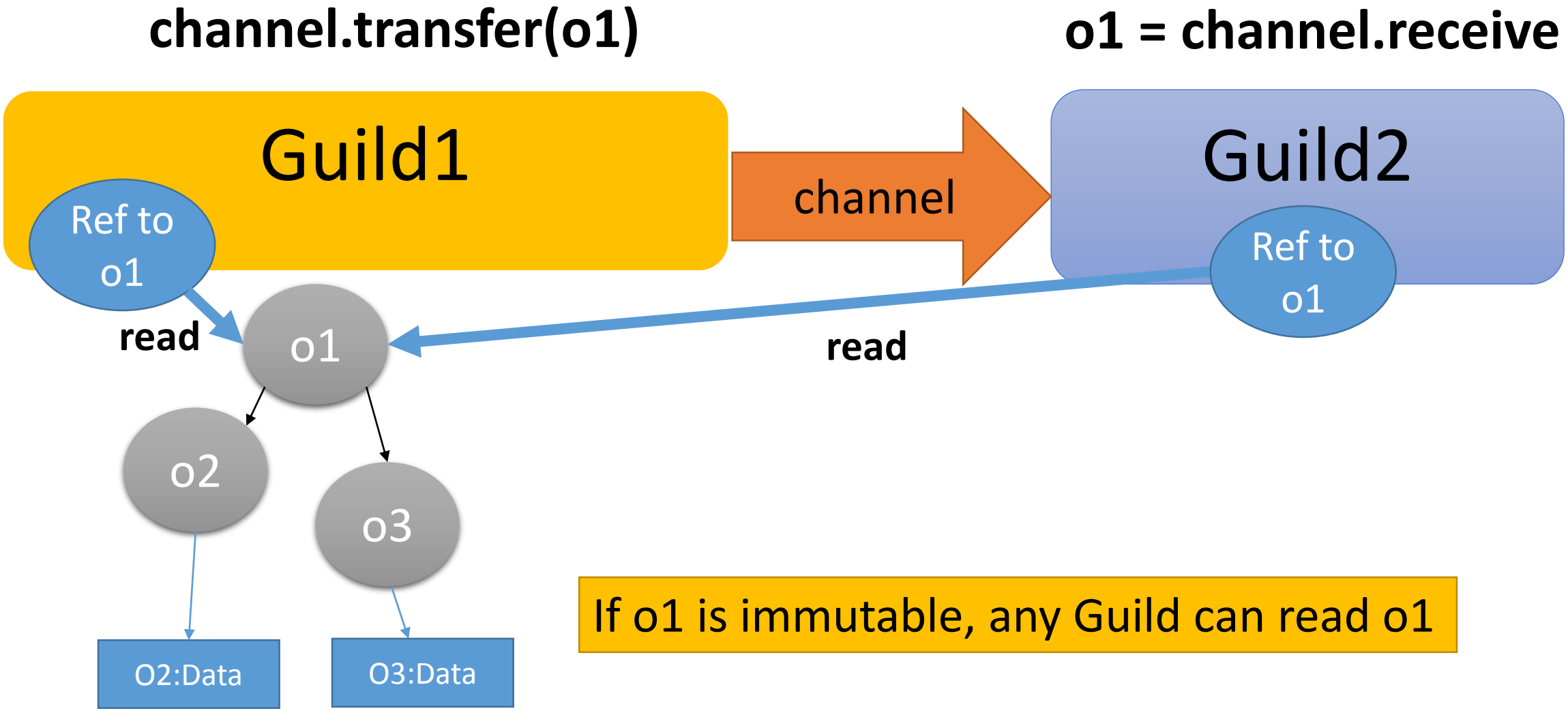


Sharing immutable objects

- **Immutable objects** can be shared with any guilds
  - a1 = [1, 2, 3].freeze: a1 is **Immutable object**
  - a2 = [1, Object.new, 3].freeze: a2 is **not immutable**
- We only need to send references
  - very lightweight, like thread-programming
- **Numeric objects, symbols, true, false, nil** are immutable (from Ruby 2.0, 2.1, 2.2)

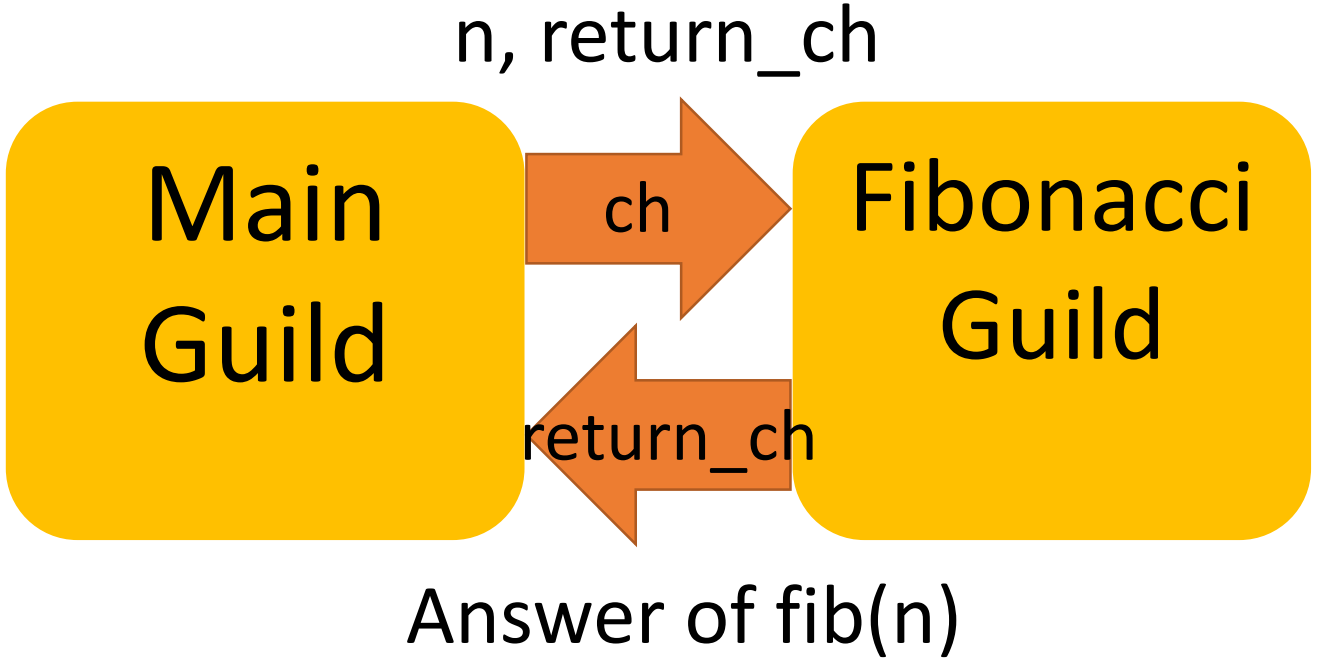
Sharing immutable objects

We can share reference to immutable objects



Use-case 1: master – worker type

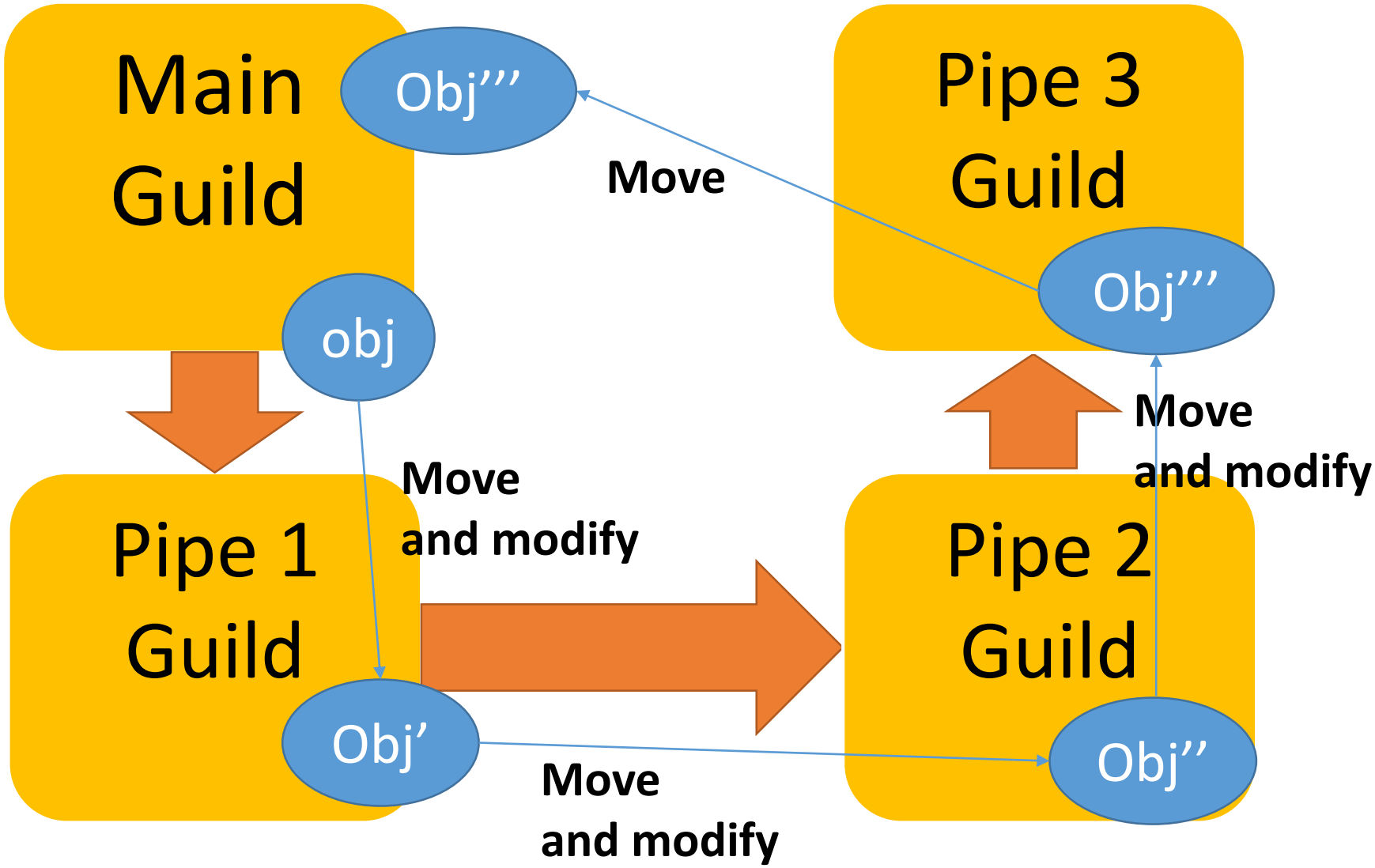
```
def fib(n) ... end
g_fib = Guild.new(script: %q{
  ch = Guild.default_channel
  while n, return_ch = ch.receive
    return_ch.transfer fib(n)
  end
})

ch = Guild::Channel.new
g_fib.transfer([3, ch])
p ch.receive
```



NOTE: Making other Fibonacci guilds, you can compute fib(n) in parallel

Use-case 2: pipeline

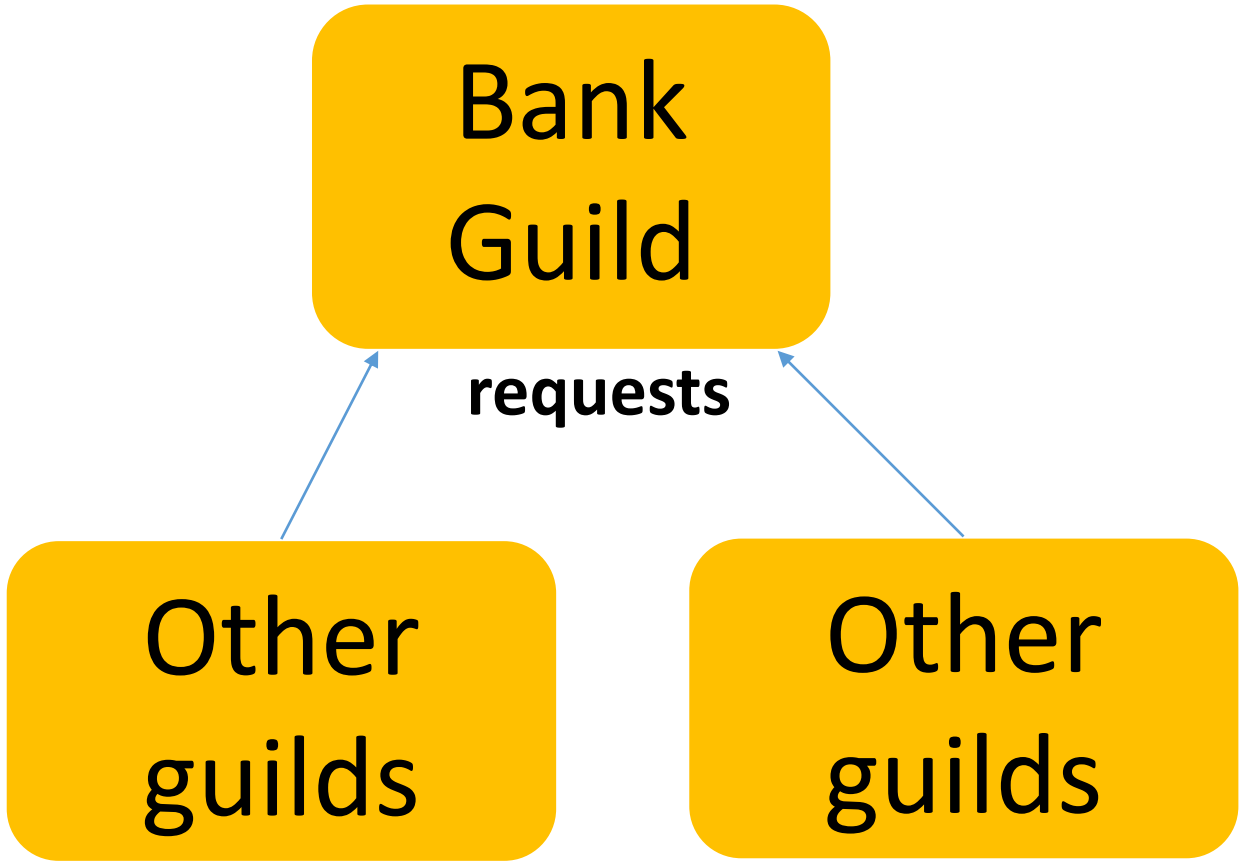
```
result_ch = Guild::Channel.new
g_pipe3 = Guild.new(script: %q{
  while obj = Guild.default_channel.receive
    obj = modify_obj3(obj)
    Guild.argv[0].transfer_membership(obj)
  end
}, argv: [result_ch])
g_pipe2 = Guild.new(script: %q{
  while obj = Guild.default_channel.receive
    obj = modify_obj2(obj)
    Guild.argv[0].transfer_membership(obj)
  end
}, argv: [g_pipe3])
g_pipe1 = Guild.new(script: %q{
  while obj = Guild.default_channel.receive
    obj = modify_obj1(obj)
    Guild.argv[0].transfer_membership(obj)
  end
}, argv: [g_pipe2])

obj = SomeClass.new

g_pipe1.transfer_membership(obj)
obj = result_ch.receive
```



Use-case:
Bank example

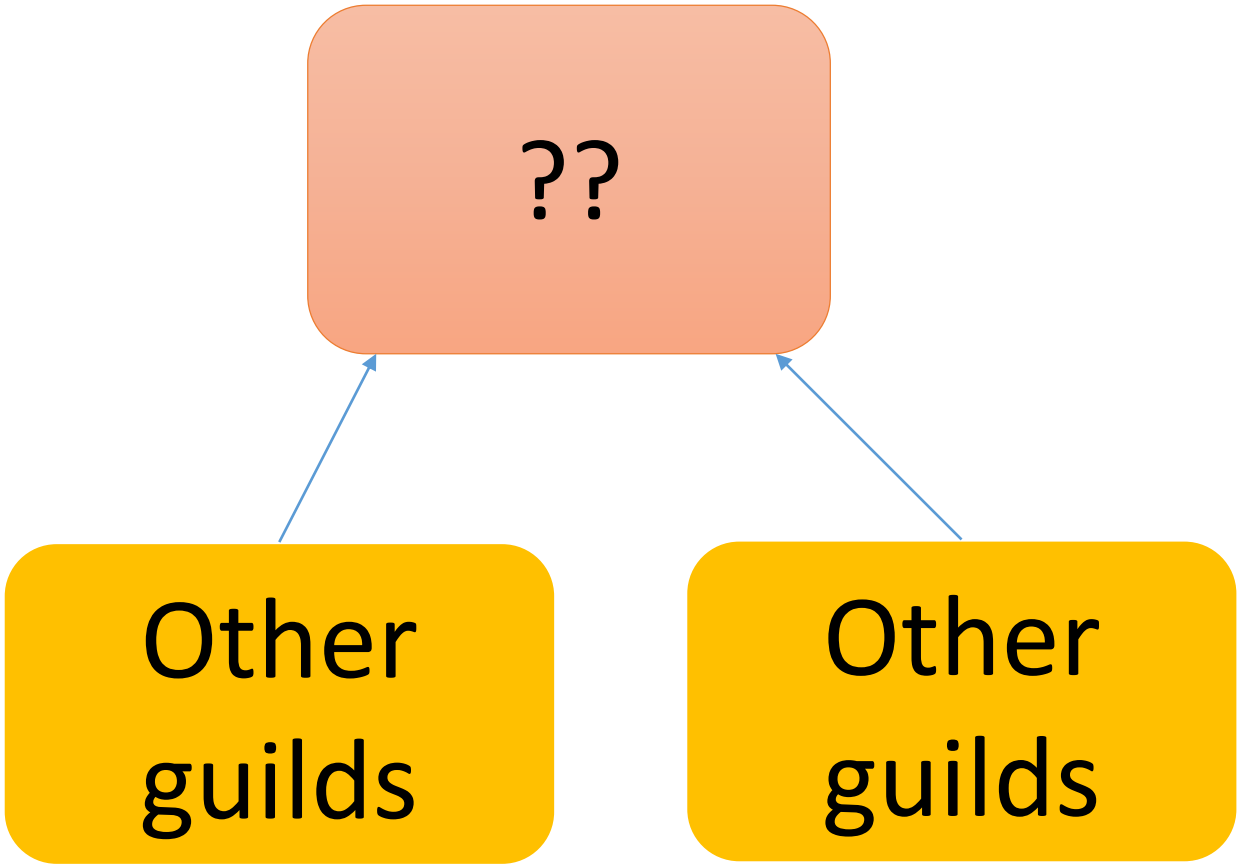
```
g_bank = Guild.new(script: %q{
  while account_from, account_to, amount,
            ch = Guild.default_channel.receive
    if (Bank[account_from].balance < amount)
      ch.transfer :NOPE
    else
      Bank[account_to].balance += amount
      Bank[account_from].balance -= amount
      ch.transfer :YEP
    end
  end
})
…
```

Only bank guild maintains bank data



Use-case:
Introduce special data structure

- Ideas of special data structure to share mutable objects
  - Use external RDB
  - In process/external Key/value store
  - Software transactional memory
  - …



Summary of use cases

- Making multiple workers and compute in parallel
  - Requests and responses are communicate via channels
  - You can send it with copy or move
  - Maybe web application can employ this model
- Making Pipeline structures and compute in parallel
  - Each task has own Guild
  - Receive target object, modify it and send it next pipeline
  - You will send it with move (transfer membership)
  - It will help applications like applying several filters for input data
- Own responsibility by one Guild
  - All accesses are managed by one responsible Guild
  - If you want to share mutable objects, we need special data structures
  - External RDBs or key/value stores are also good idea for this purpose

Communication strategy

[Upper is better]

- Passing immutable objects
- Copy mutable objects
- If you have performance problem, move (transfer membership) mutable objects
- If you have performance problem too, use special data structure to share mutable objects

Compare between Thread model and Guild model

- On threads, it is **difficult to find out** which objects are shared mutable objects
- On Guilds, there are **no shared mutable objects**
  - If there are special data structure to share mutable objects, we only need to check around this code

→ Encourage “Safe” and “Easy” programming

Compare between Thread model and Guild model

- On threads, inter threads communication is very fast.
- On guilds, inter guilds communication introduce overhead
  - “Move” (transfer membership) technique can reduce this kind of overheads

Trade-off: Performance v.s. Safety/Easily

Which do you want to choose?

Digression: The name of “Guild”

- “Guild” is good metaphor for “object’s membership”
- Check duplication
  - First letter is not same as other similar abstractions
    - For variable names
    - P is for Processes, T is for Threads, F is for Fibers
  - There are no duplicating top-level classes and modules in all of rubygems

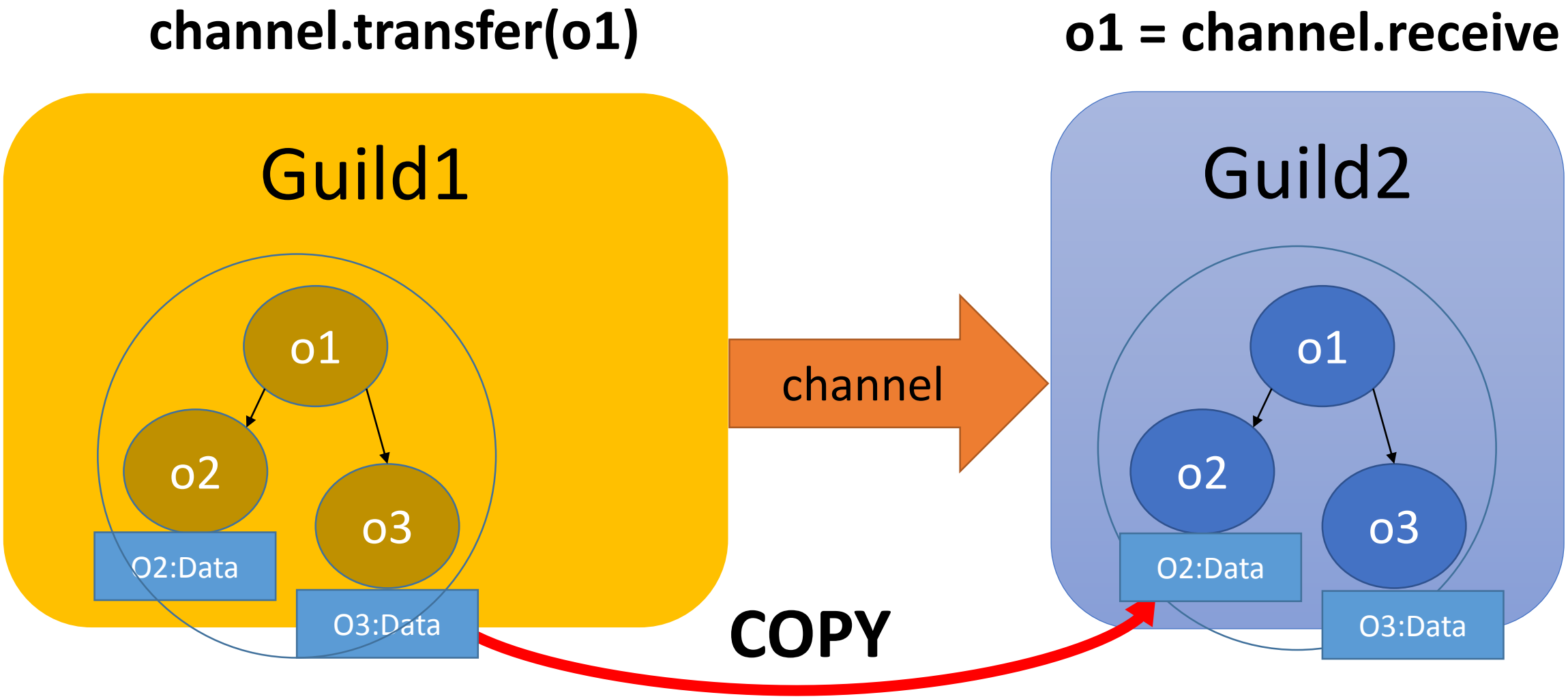
Implementation of “Guild”

- How to implement inter Guilds communication
- How to isolate process global data

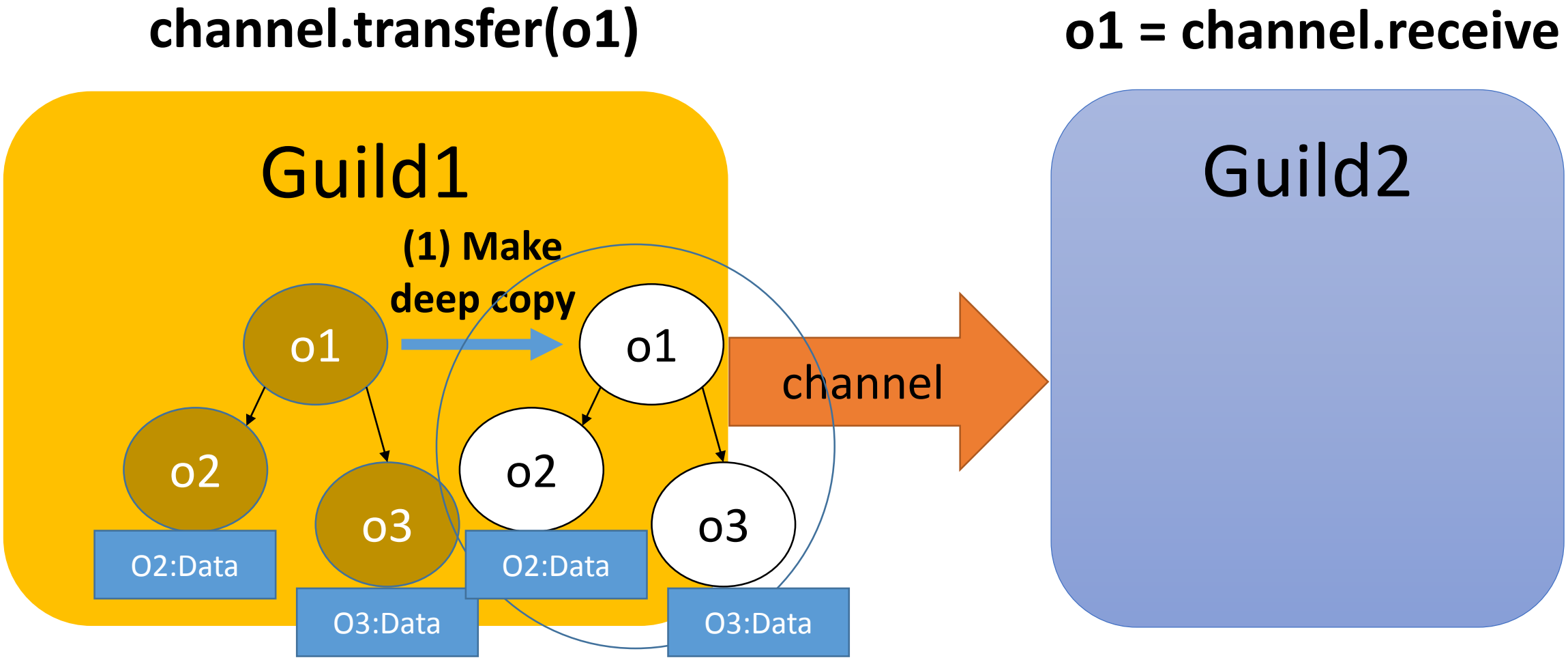
How to implement inter Guilds communication

- Copy
- Move (transfer membership)

Copy using Channel



Copy using Channel Implementation

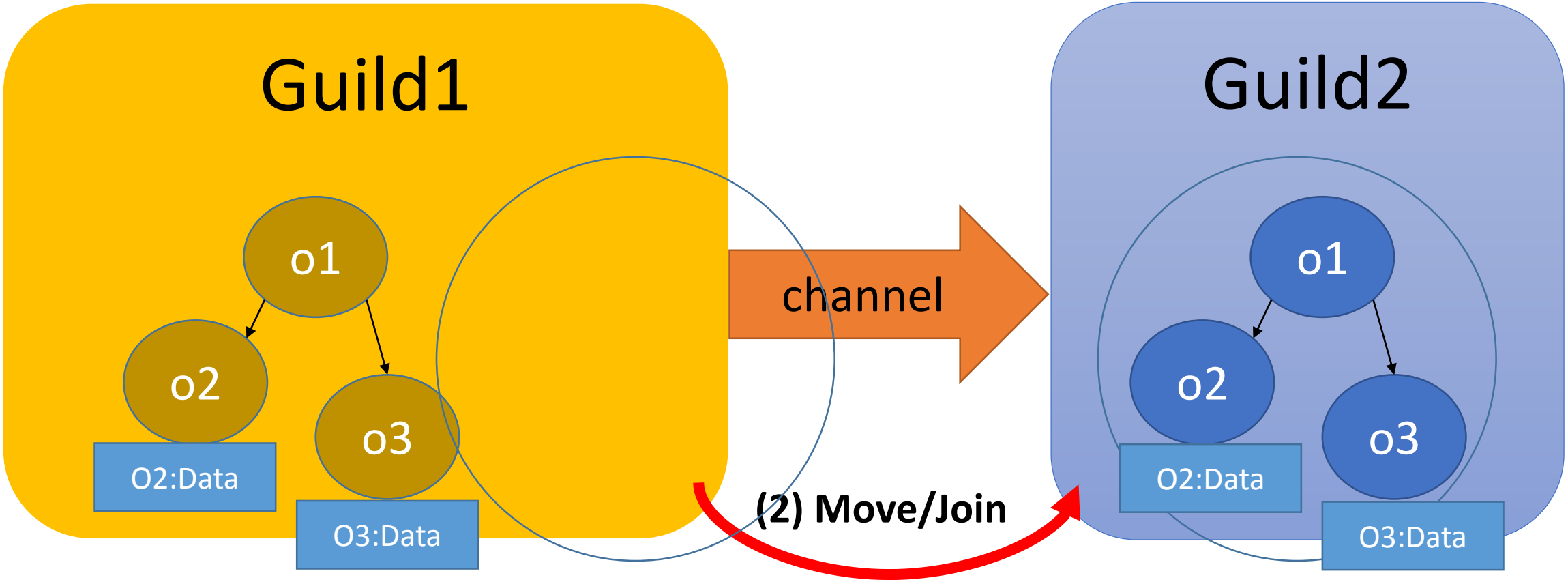


Copy using Channel Implementation

We can use CoW technique for data

channel.transfer(o1)

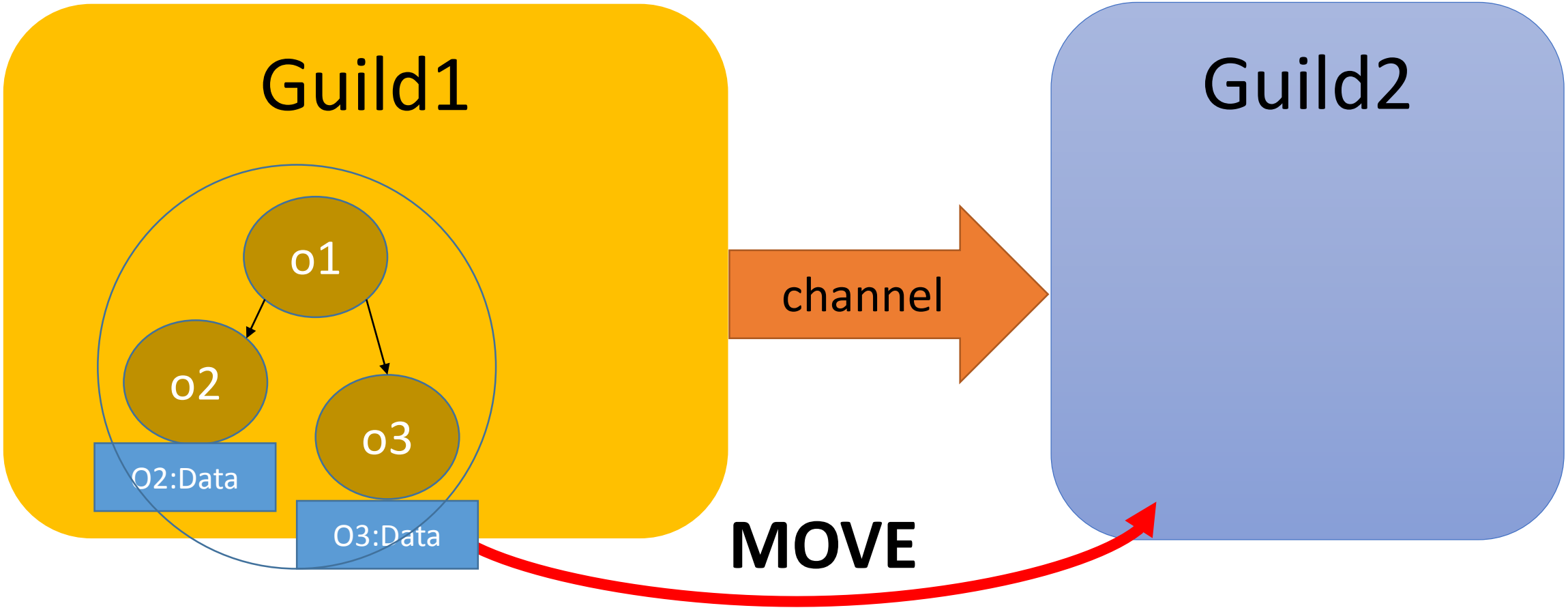
o1 = channel.receive



Move using Channel

channel.transfer_membership(o1)

o1 = channel.receive



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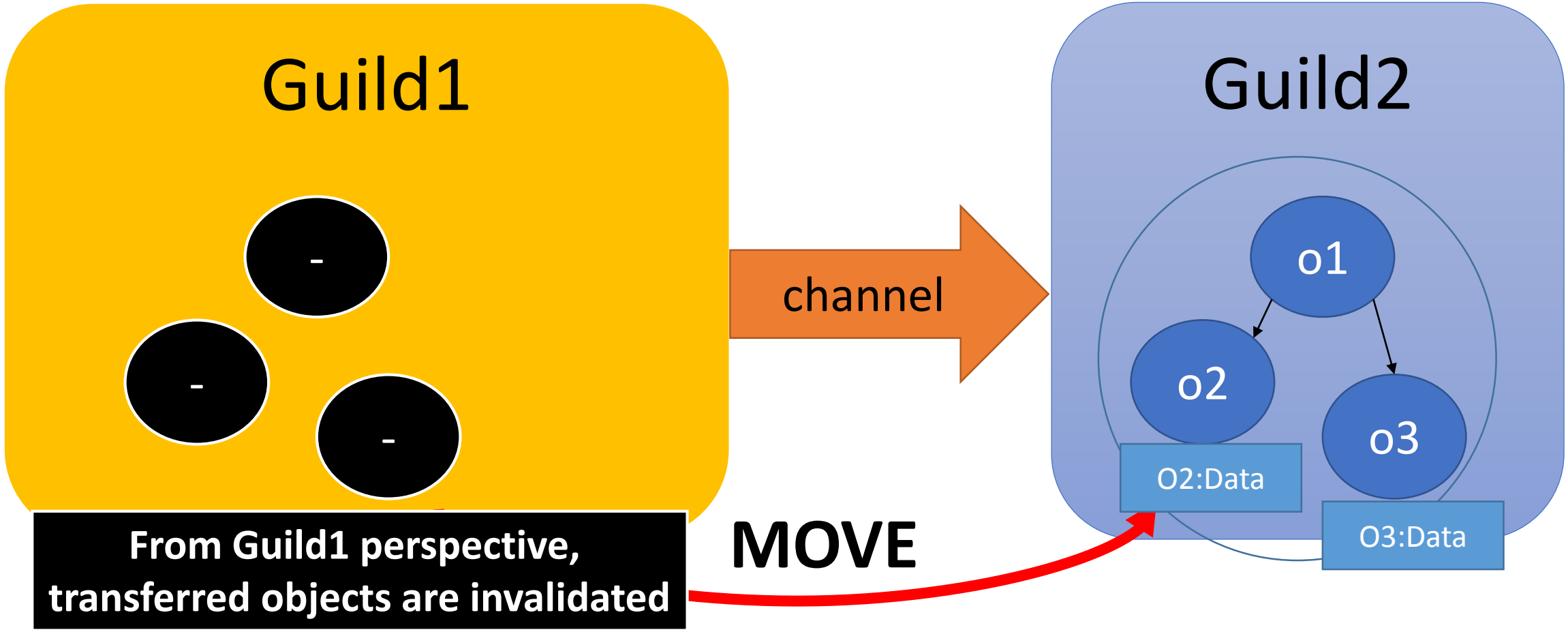
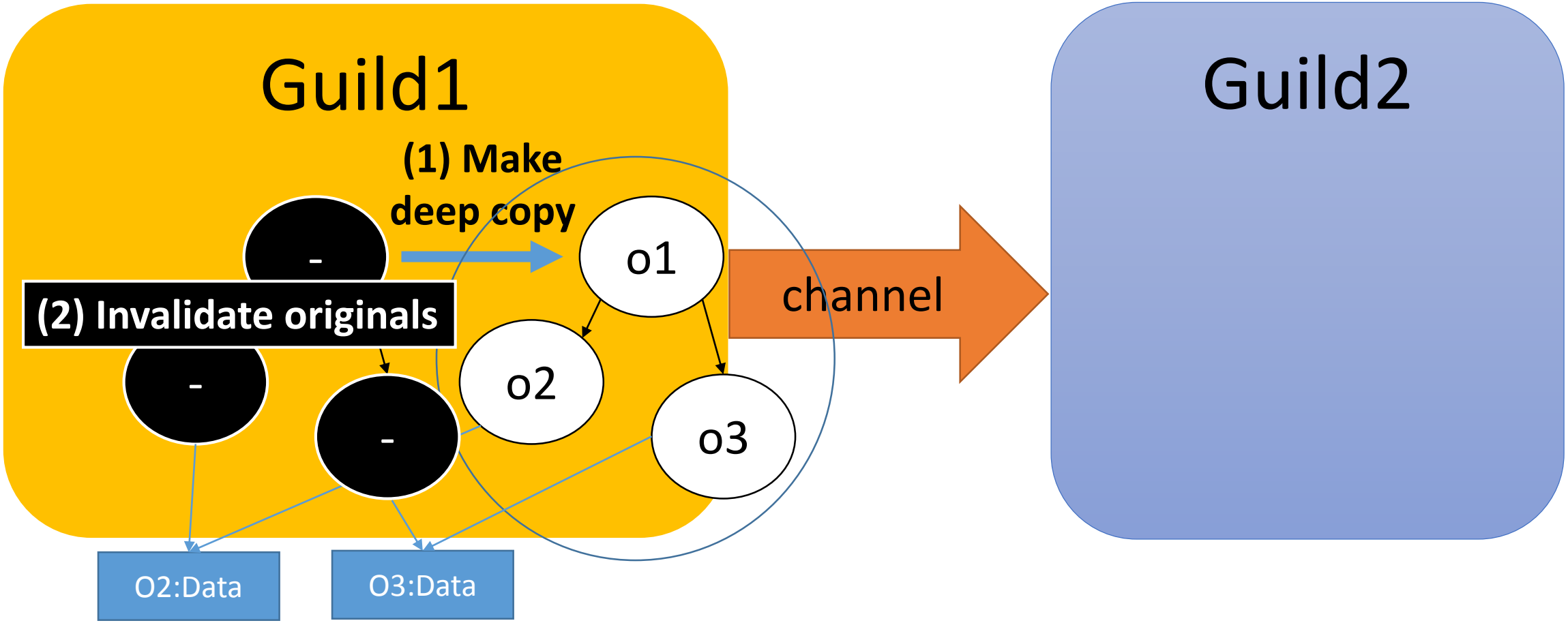


Move using Channel Implementation

channel.transfer_membership(o1)

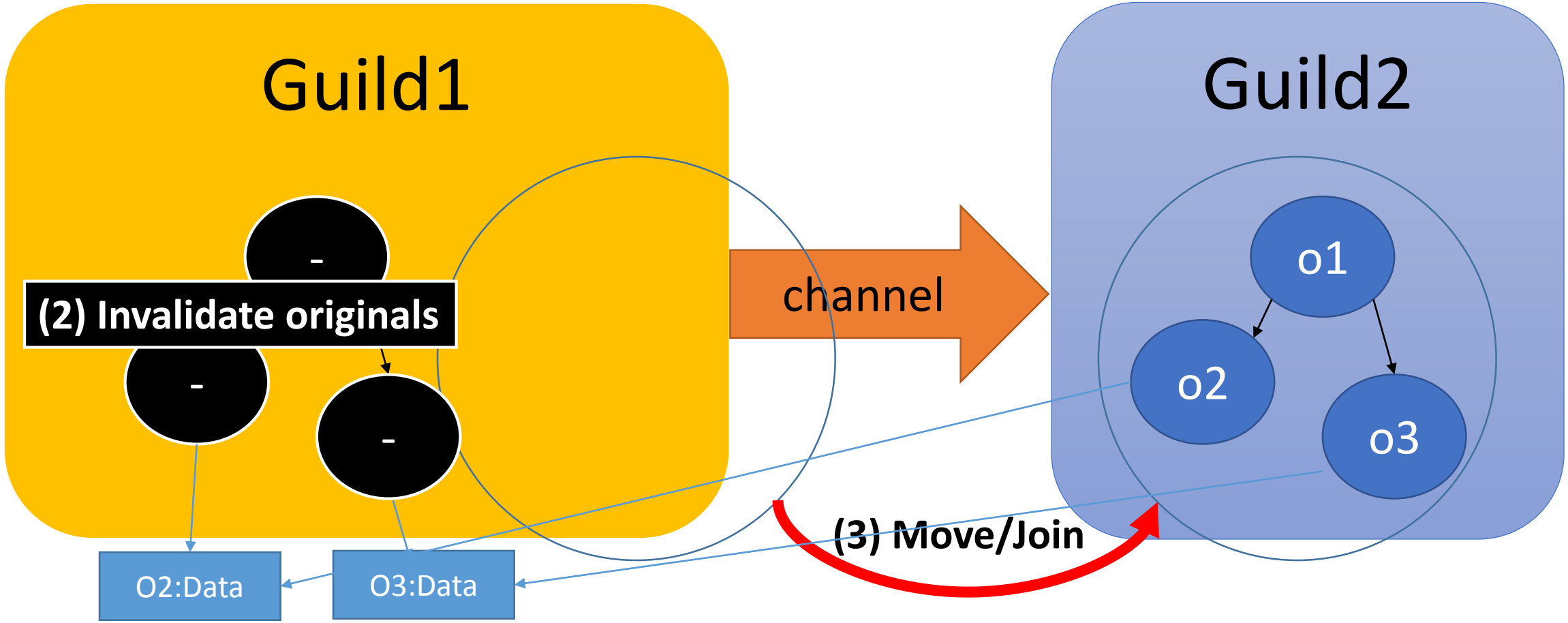
o1 = channel.receive



Move using Channel Implementation

channel.transfer_membership(o1)

o1 = channel.receive



Ruby global data

Keep compatibility with Ruby 2

- Global variables ($foo)
  - Change them to Guild local variables
- Class and module objects
  - Share between guilds
- Class variables
  - Change them to guild local. So that it is guild/class local variables
- Constants
  - Share between guilds
  - However if assigned object is not a immutable object, this constant is accessed only by setting guilds. If other guilds try to access it, them cause error.
- Instance variables of class and module objects
  - Difficult. There are several approaches.
- Proc/Binding objects
  - Make it copy-able with env objects or env independent objects
- ObjectSpace.each_object
  - OMG

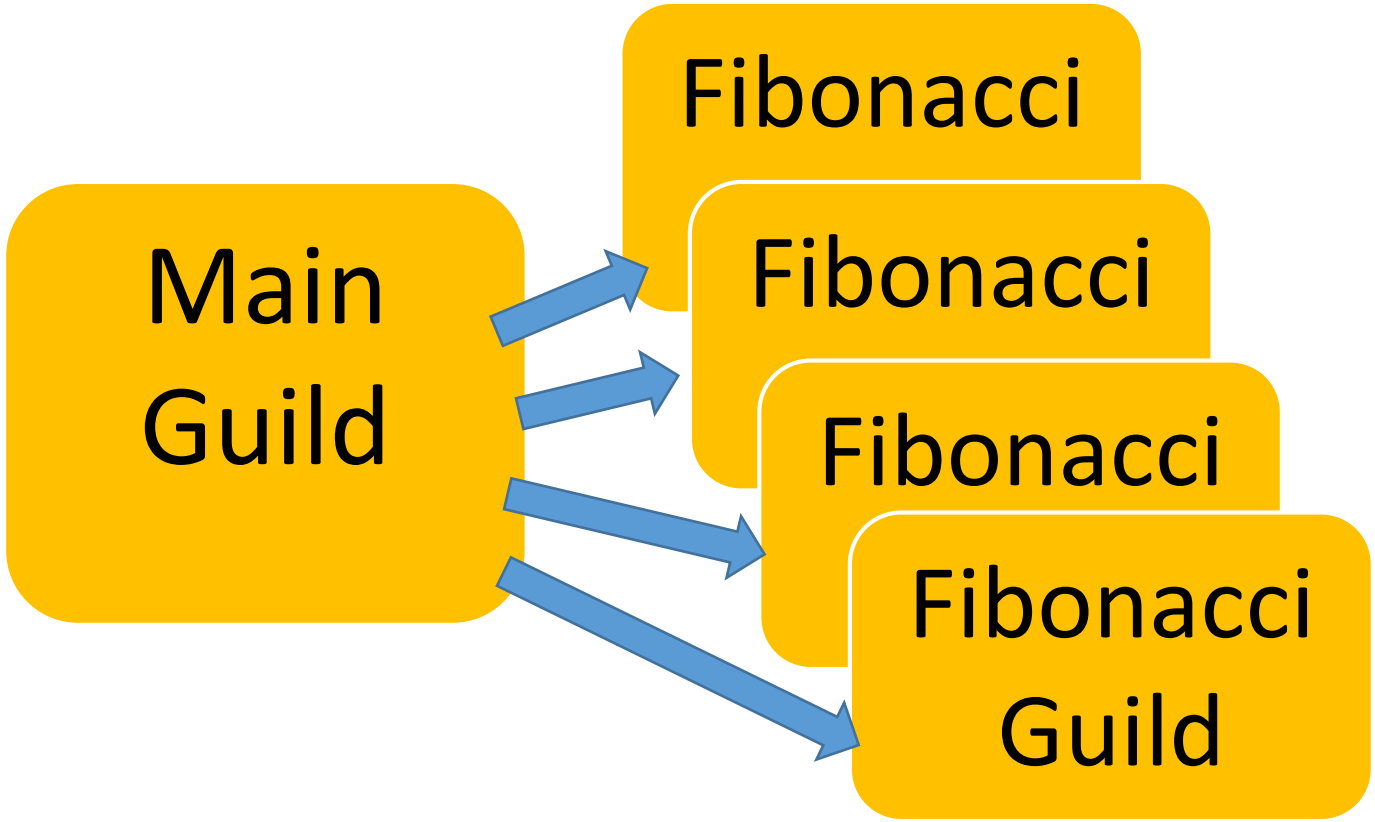
Interpreter process global data

- GC/Heap
  - Share it. Do stop the world parallel marking- and lazy concurrent sweeping.
  - Synchronize only at page acquire timing. No any synchronization at creation time.
- Inline method cache
  - To fill new entry, create an inline cache object and update atomically.
- Tables (such as method tables and constant tables)
  - Introduce mutual exclusions.
- Current working directory (cwd)
  - Each guild should have own cwd (using openat and so on).
- Signal
  - Design new signal delivery protocol and mechanism
- C level global variables
  - Avoid them.
  - Main guild can use C extensions depends on them
- Current thread
  - Use TLS (temporary), but we will change all of C APIs to receive context data as first parameter in the future.

Performance evaluation

- On 2 core virtual machine
  - Linux on VirtualBox on Windows 7
- Now, we can’t run Ruby program on other than main guild, so other guilds are implemented by C code

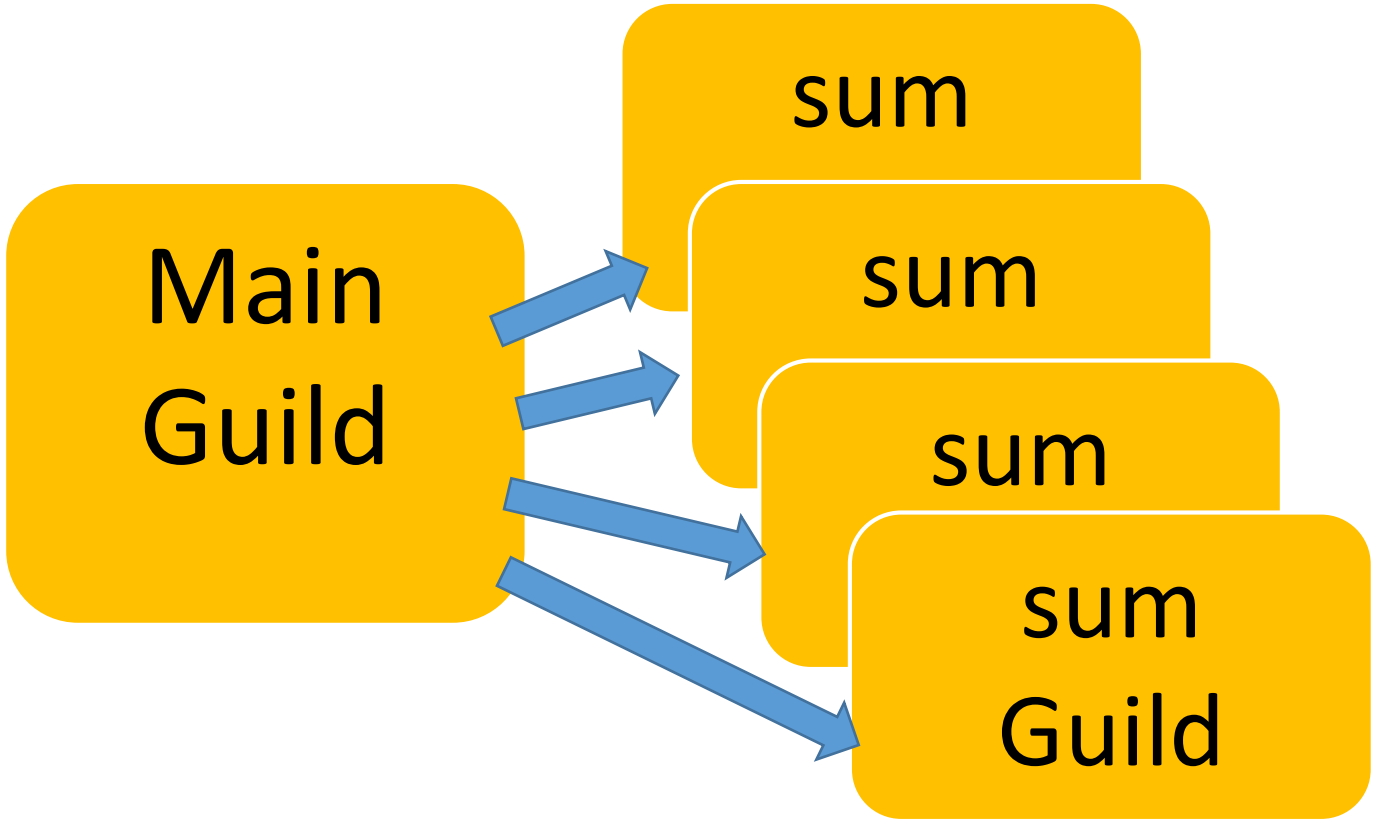
Performance evaluation
Simple numeric task in parallel



	Execution time (sec)
Single-Guild	19.45
Multi-Guild	10.45

Total 50 requests to compute fib(40)
Send 40 (integer) in each request

Performance evaluation Copy/Move

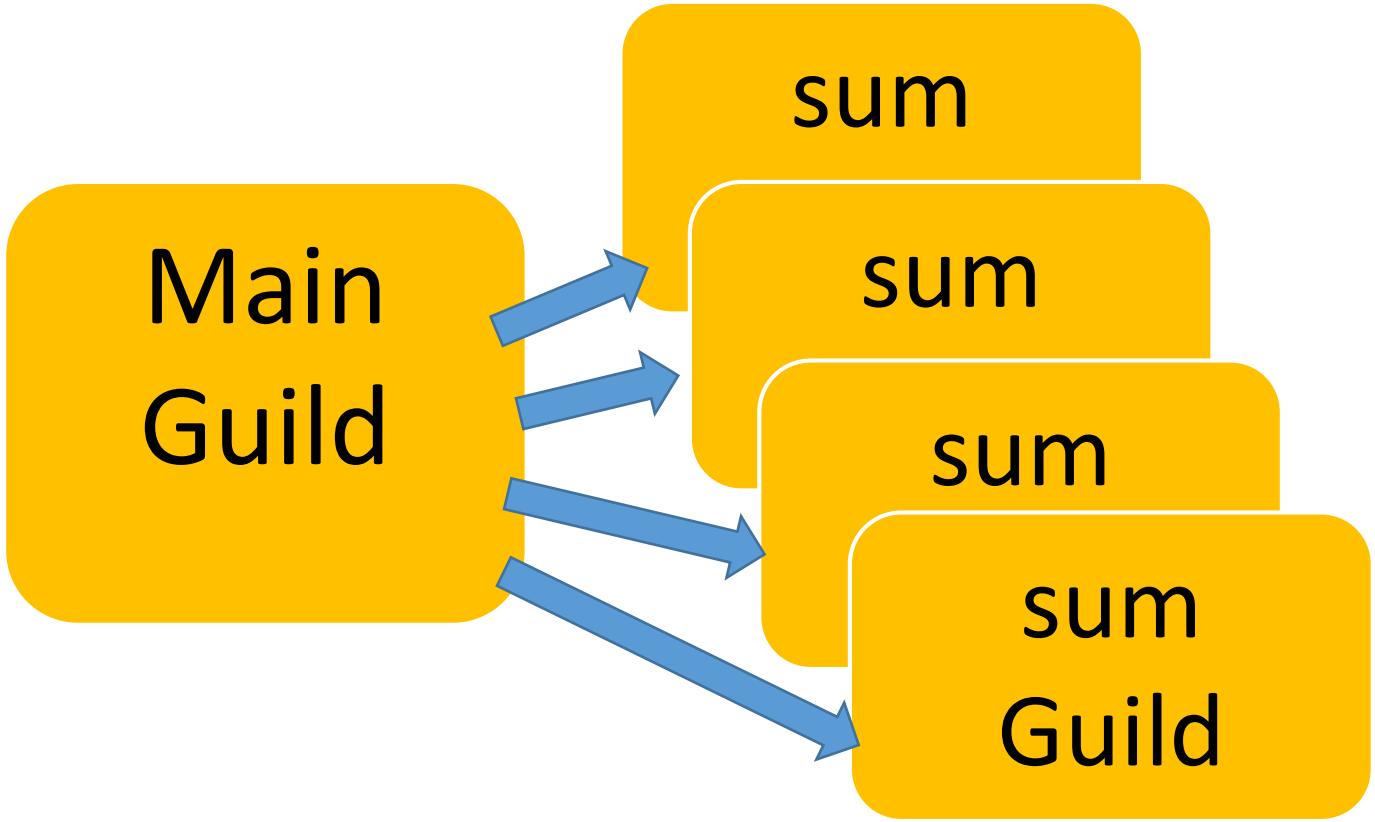


	Execution time (sec)
Single-Guild	1.00
Multi/ref	0.64
Multi/move	4.29
Multi/copy	5.16

Total 100 requests to compute sum of array
Send (1..10_000_000).to_a in each request

Too slow!!
Because “move” need to check all of elements

Performance evaluation Copy/Move



	Execution time (sec)
Single-Guild	1.00
Multi/ref	0.64
Multi/move	0.64

If we know this array only has immutable objects,
we don’t need to check all elements => special data structure

Check our goal for Ruby 3

- **We need to keep compatibility** with Ruby 2.
  - **OK:** Only in main guild, it is compatible.
- We can make **parallel program**.
  - **OK:** Guilds can run in parallel.
- We **shouldn't consider** about locks any more.
  - **OK:** Only using copy and move, we don't need to care locks.
- We **can share** objects with copy, but **copy operation should be fast.**
  - **OK:** Move (transfer membership) idea can reduce overhead.
- We **should share objects** if we can.
  - **OK:** We can share immutable objects fast and easily.
- We can **provide special objects** to share mutable objects like Clojure if we really need speed.
  - **OK:** Yes, we can provide.

Satisfied!

Summary

- Introduce “why threads are very difficult”
- Propose new concurrency abstraction “Guild” for Ruby 3
  - Not implemented everything yet, but I show key ideas and preliminary evaluation

Thank you for your attention

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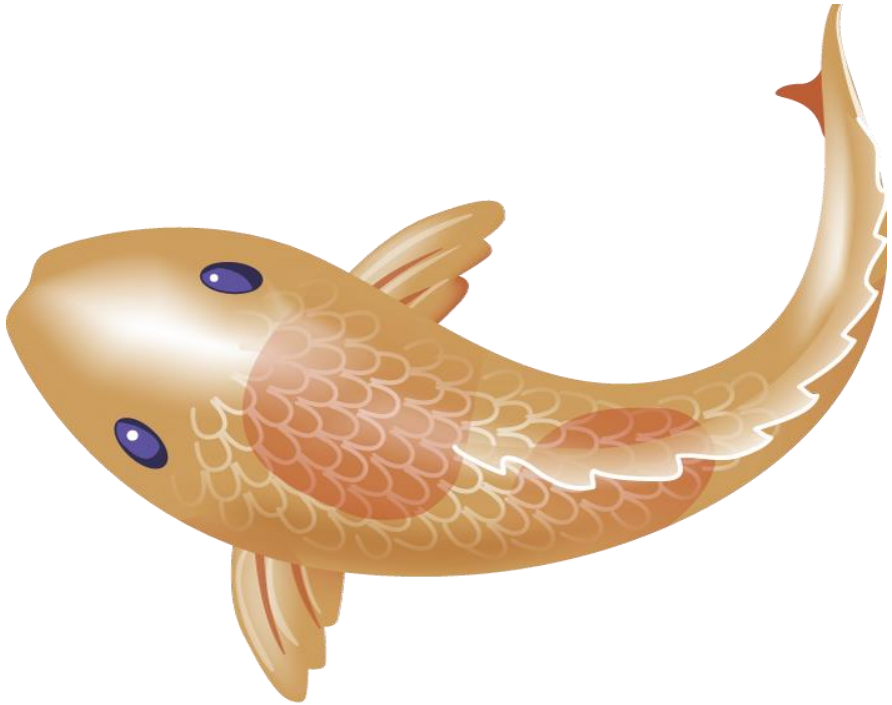

Approach comparison

	Process/MVM	Place (Racket)	Guild (copy/move)	Thread
Heap	Separate	Separate	Share	Share
Communication Mutable objects	Copy	Copy	Copy/Move	Share
Communication Frozen object	Copy	Share (maybe)	Share	Share
Lock	Don’t need	Don’t need	(mostly) Don’t need	Required
ISeq	Copy	Share	Share	Share
Class/Module	Copy	Copy (fork)	Share	Share