# GHC(STG,Cmm,asm) illustrated

for hardware persons

*exploring some mental models and implementations*

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Rev. 0.02.0
WIP

"Any sufficiently advanced technology is indistinguishable from magic."

Arthur C. Clarke

NOTE

- This is not an official document by the ghc development team.
- Please don't forget “semantics”.  It's very important.
- This is written for ghc 8.0.

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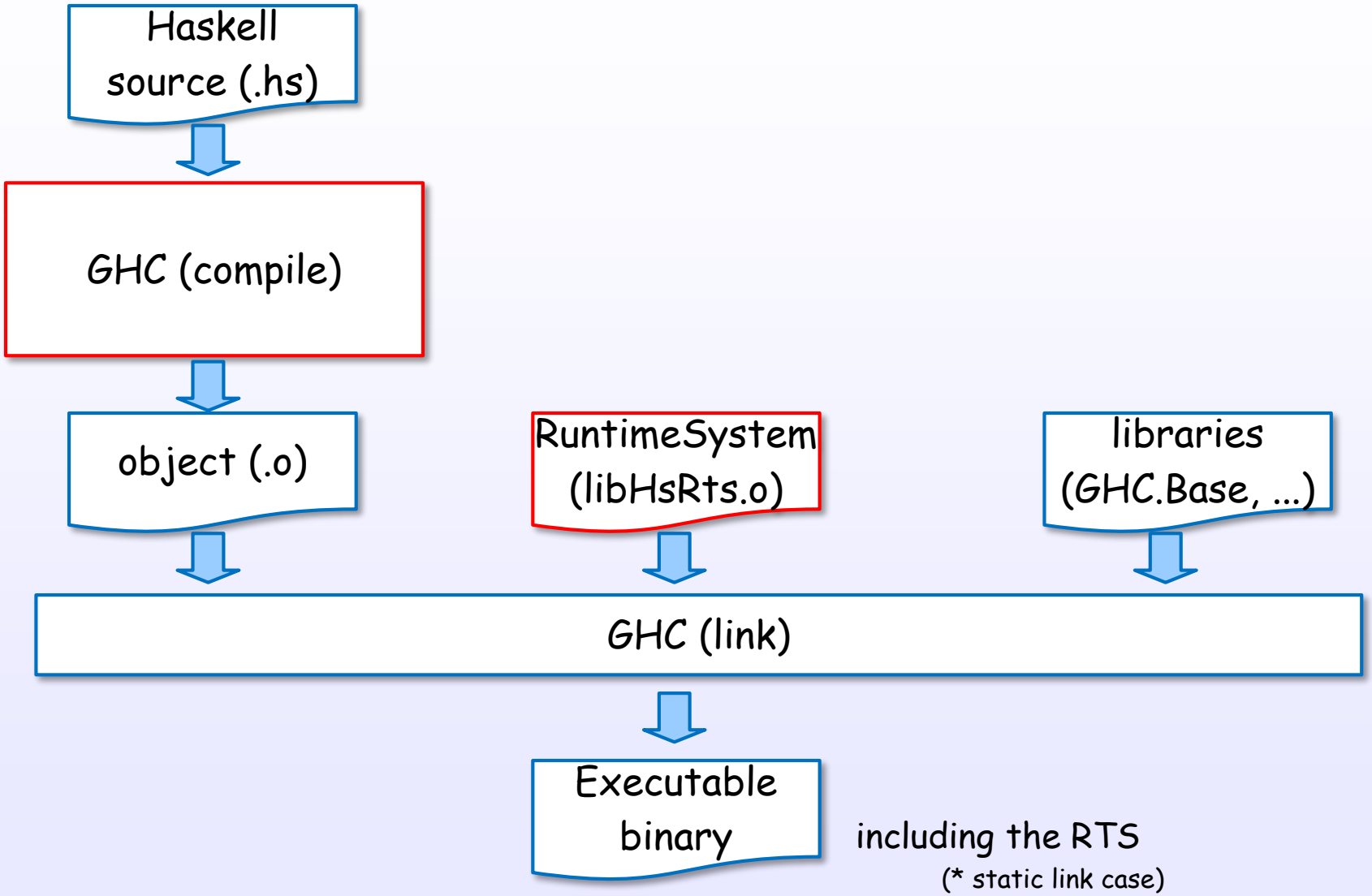
Executable binary

# The GHC = Compiler + Runtime System (RTS)

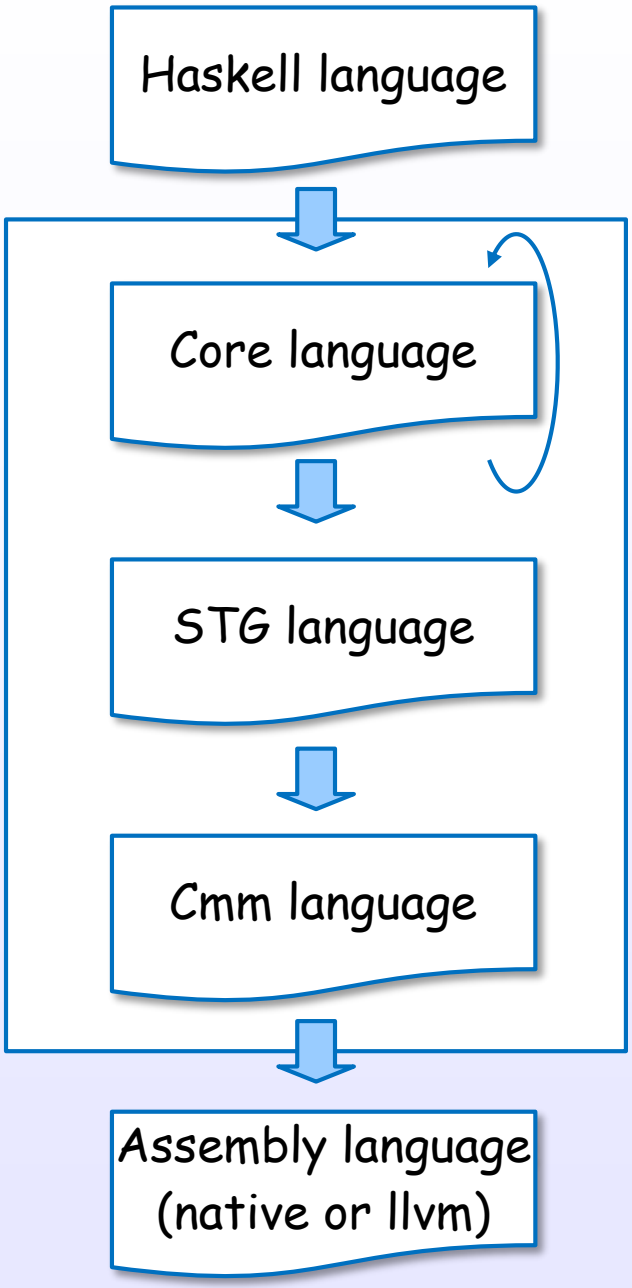



References : [1], [C1], [C3], [C10], [C19], [S7], [21], [22]

# Compile steps

# GHC transitions between five representations

GHC compile steps




*each intermediate code can be dumped by :*

```
$ ghc -ddump-parsed
$ ghc -ddump-rn
```

```
$ ghc -ddump-ds
$ ghc -ddump-simpl
$ ghc -ddump-prep
```

```
$ ghc -ddump-stg
```

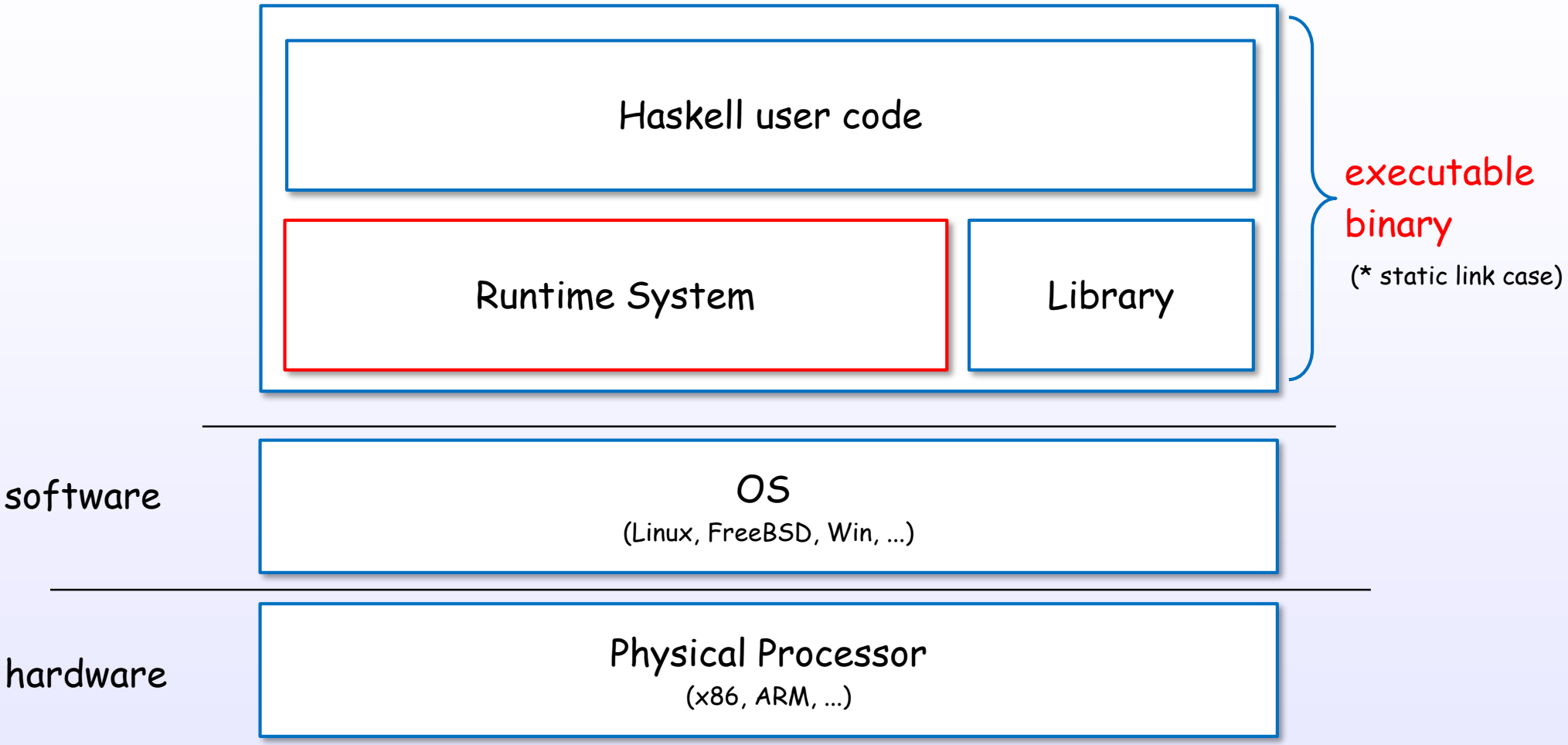
```
$ ghc -ddump-cmm
$ ghc -ddump-opt-cmm
```

```
$ ghc -ddump-llvm
$ ghc -ddump-asm
```

References : [1], [C3], [C4], [9], [C5], [C6], [C7], [C8], [S7], [S8], [21], [22]

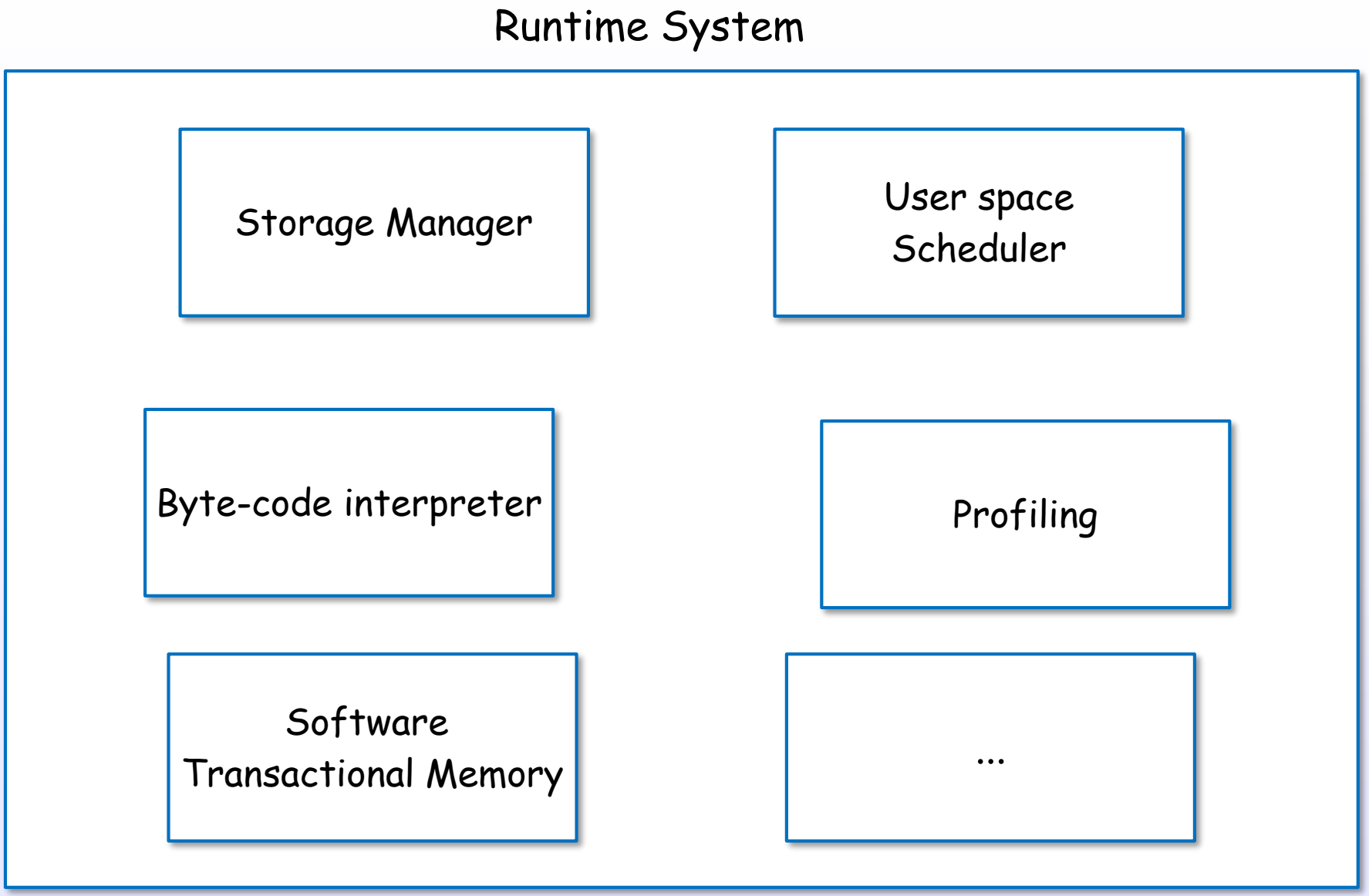
# Runtime System

# Generated binary includes the RTS




References : [C10], [9]

# Runtime System includes ...




References : [C10], [8], [9], [5], [17], [S13]

# Development languages

# The GHC is developed by some languages

compiler
( $(TOP)/compiler/*)

Haskell
+
Alex (lex)
Happy (yacc)
Cmm (C--)
Assembly

runtime system
( $(TOP)/rts/*)

C
+
Cmm
Assembly

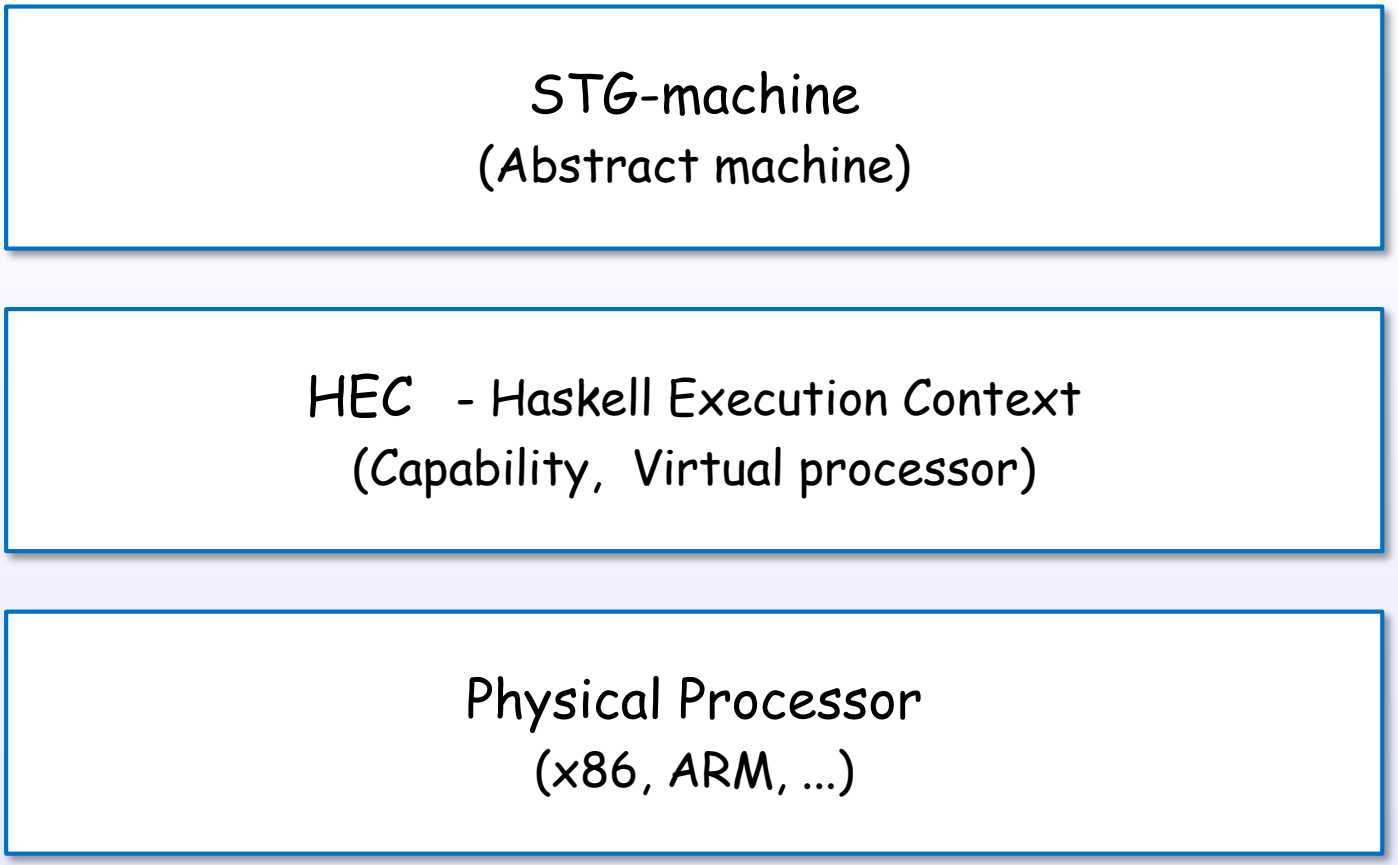
library
( $(TOP)/libraries/*)

Haskell
+
C

References : [C2], [22]

# Machine layer/models

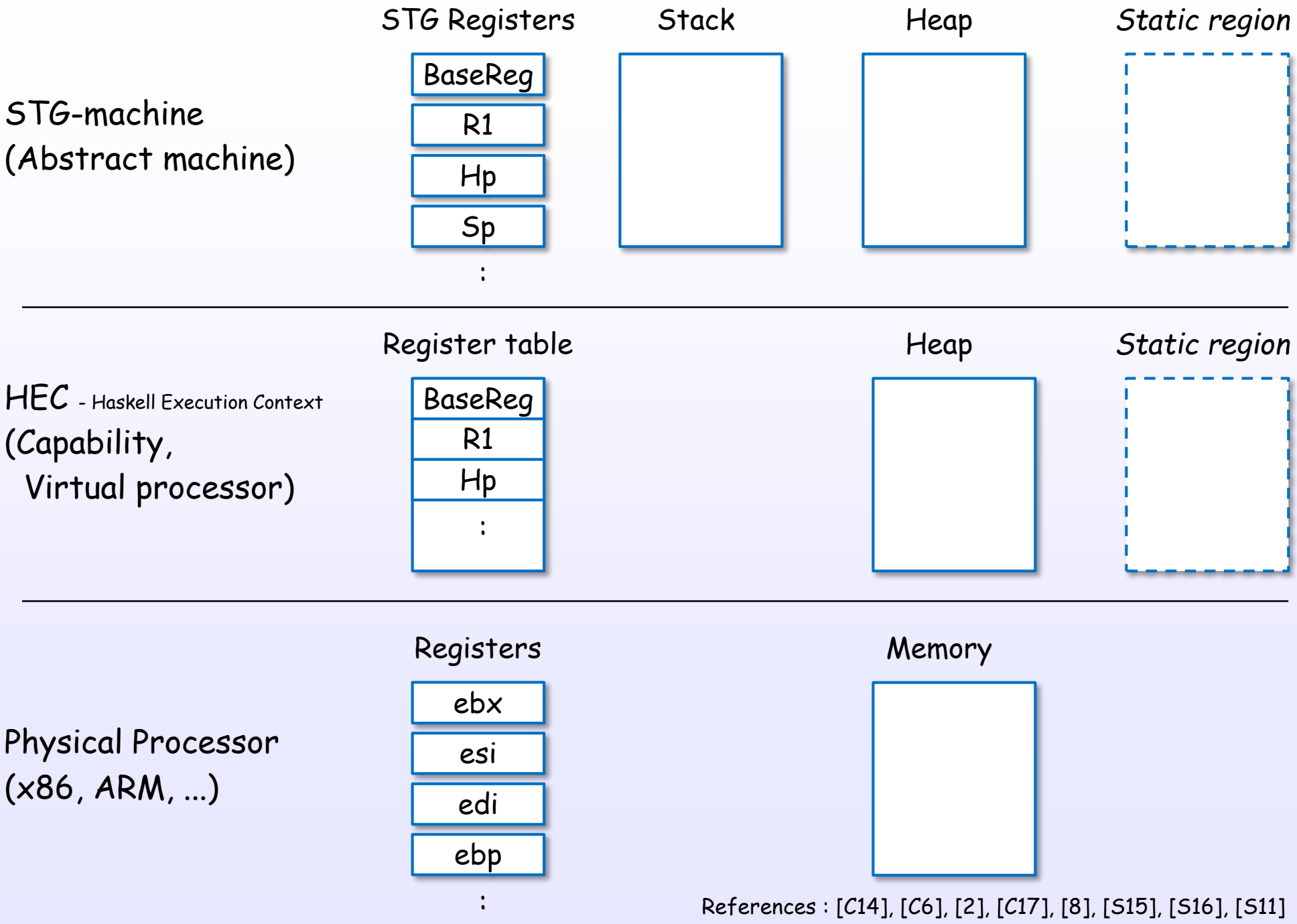
# Machine layer



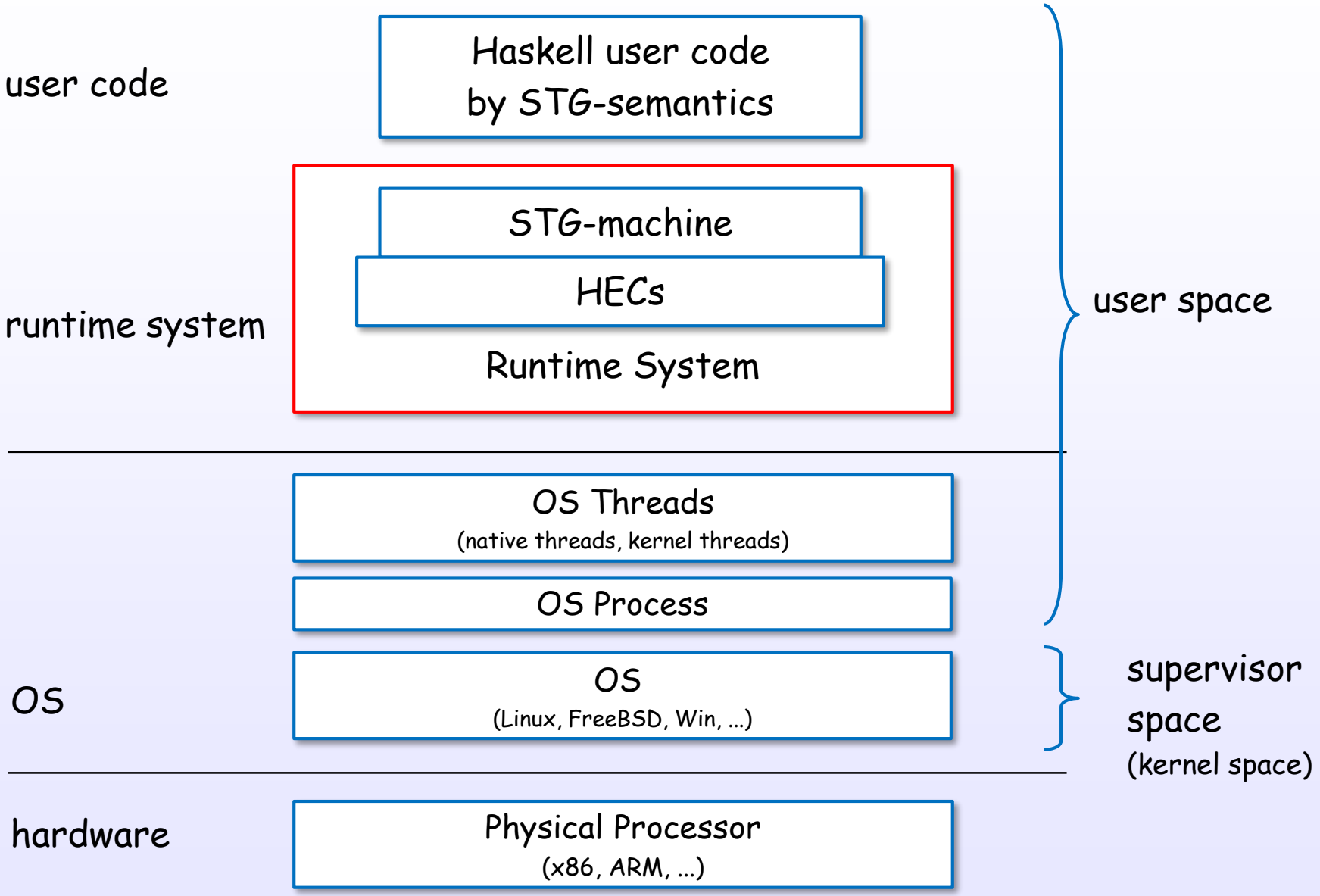

Each Haskell code is executed in STG semantics.

References : [C14], [C6], [2], [C17], [8], [S15], [S16], [S11]

# Machine layer



# Runtime system and HEC

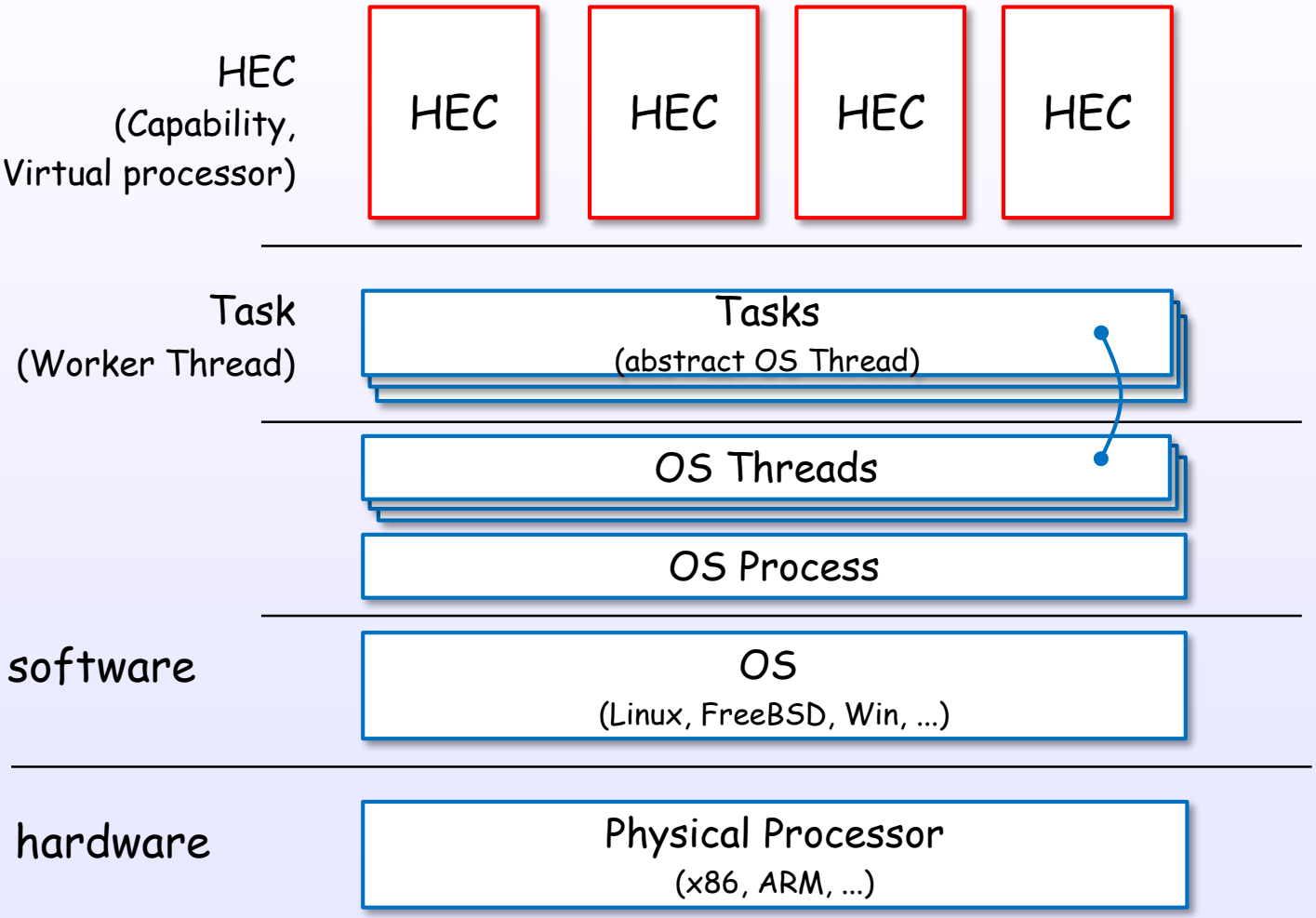



References : [C14], [C6], [2], [C17], [8], [S15], [S16], [S11]

# many HECs

Multi HECs can be generated by compile and runtime options :

```
$ ghc -rtsopts -threaded
$ ./xxx +RTS -N4
```




References : [1], [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

# HEC (Capability) data structure

[rts/Capability.h] (ghc 8.0)

```
struct Capability_ {
    StgFunTable f;
    StgRegTable r;
    nat no;
    Task *running_task;
    rtsBool in_haskell;
    nat idle;
    rtsBool disabled;
    StgTSO *run_queue_hd;
    StgTSO *run_queue_tl;
    InCall *suspended_ccalls;
    bdescr **mut_lists;
    bdescr **saved_mut_lists;
    bdescr *pinned_object_block;
    bdescr *pinned_object_blocks;
    StgWeak *weak_ptr_list_hd;
    StgWeak *weak_ptr_list_tl;
    int context_switch;
    int interrupt;
    W_ total_allocated;

#if defined(THREADED_RTS)
    Task *spare_workers;
    nat n_spare_workers;
    Mutex lock;
    Task *returning_tasks_hd;
    Task *returning_tasks_tl;
    Message *inbox;
    SparkPool *sparks;
#endif

    StgTVarWatchQueue *free_tvar_watch_queues;
    StgInvariantCheckQueue *free_invariant_check_queues;
    StgTRecChunk *free_trec_chunks;
    StgTRecHeader *free_trec_headers;
    nat transaction_tokens;
}
```

*register table*

*run queue*

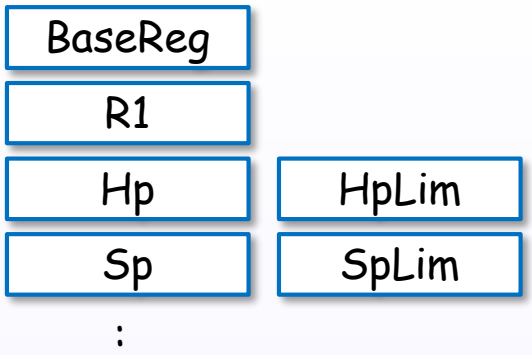
Each HEC (Capability) has a register table and a run queue and ...
Each HEC (Capability) is initialized at initCapabilities [rts/Capability.c]

References : [S15], [S16], [C11], [C17]

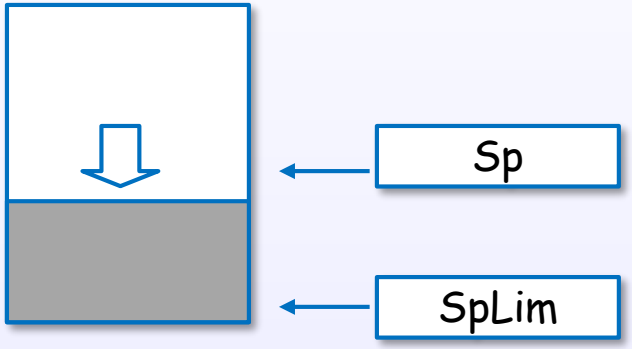
# STG-machine

# The STG-machine consists of three parts

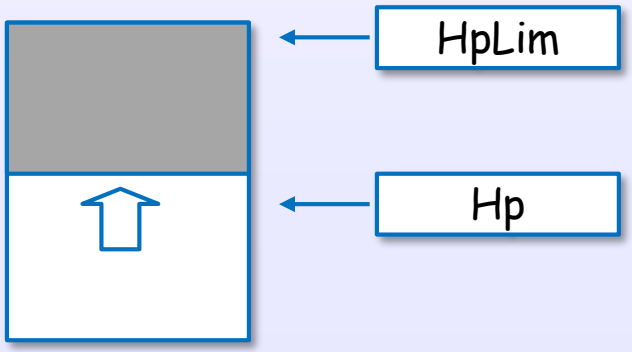
STG Registers




Stack

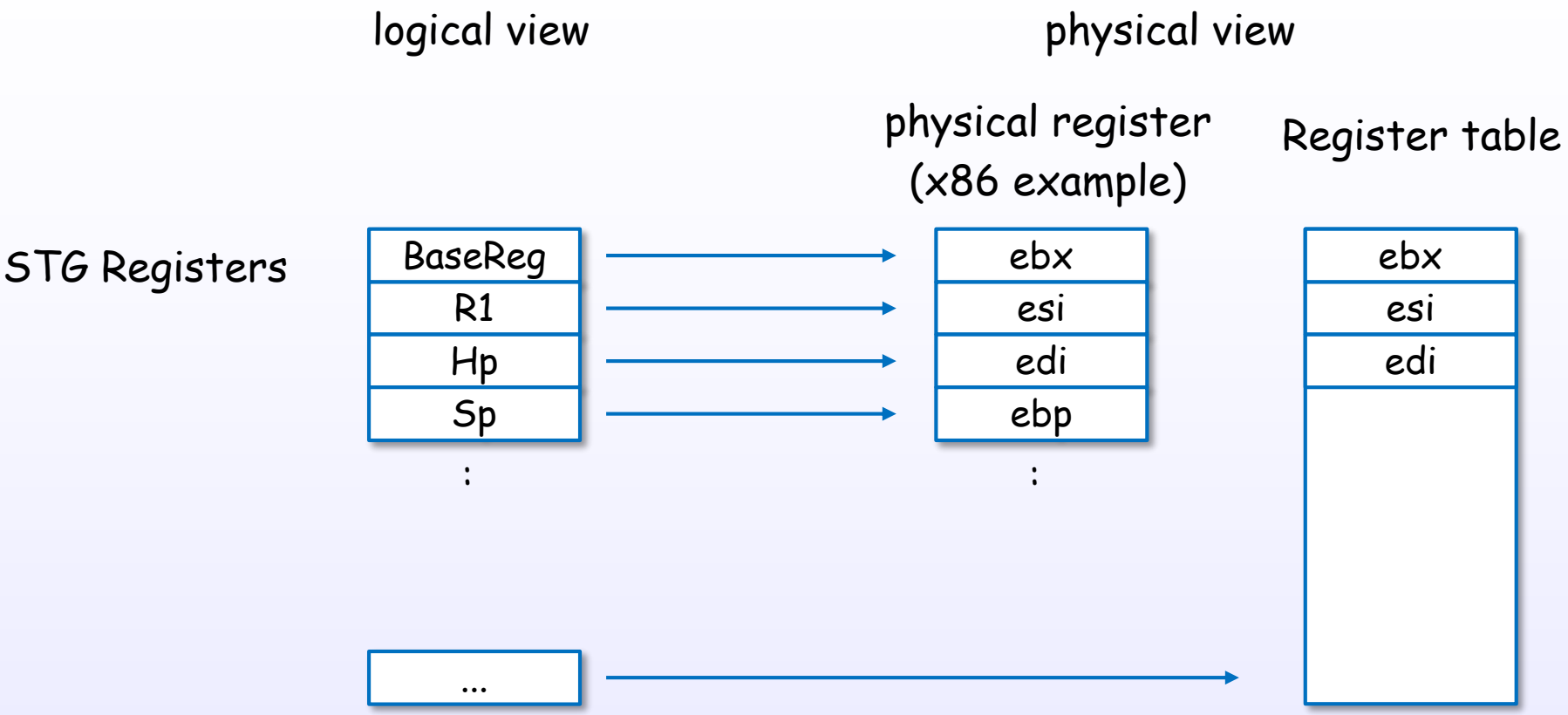



Heap



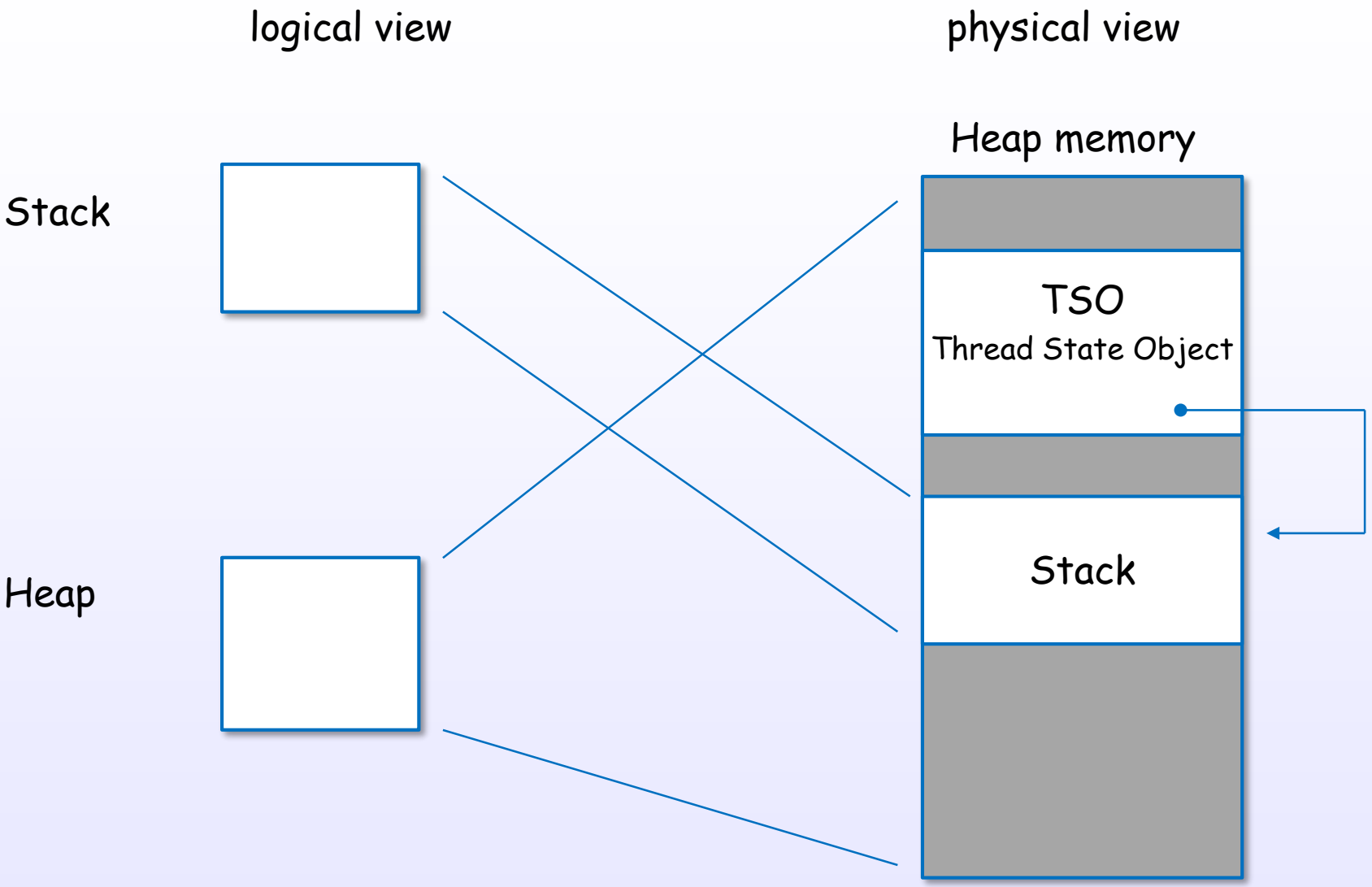

References : [2], [C15], [C11], [C12]

# STG-machine is mapped to physical processor




References : [C15], [S1], [S2]

# STG-machine is mapped to physical processor




A stack and a TSO object are in the heap.
The stack is stored separately from the TSO for size extension and GC.

References : [C11], [C12], [S16], [S5]

# TSO data structure

[includes/rts/storage/TSO.h] (ghc 8.0)

```
typedef struct StgTSO_ {
   StgHeader            header;
   struct StgTSO_*      _link;
   struct StgTSO_*      global_link;
   struct StgStack_     *stackobj;
   StgWord16            what_next;
   StgWord16            why_blocked;
   StgWord32            flags;
   StgTSOBlockInfo      block_info;
   StgThreadID          id;
   StgWord32            saved_errno;
   StgWord32            dirty;
   struct InCall_*      bound;
   struct Capability_*  cap;
   struct StgTRecHeader_ * trec;
   struct MessageThrowTo_ * blocked_exceptions;
   struct StgBlockingQueue_ *bq;
   StgInt64  alloc_limit;
   StgWord32  tot_stack_size;
} *StgTSOPtr;
```



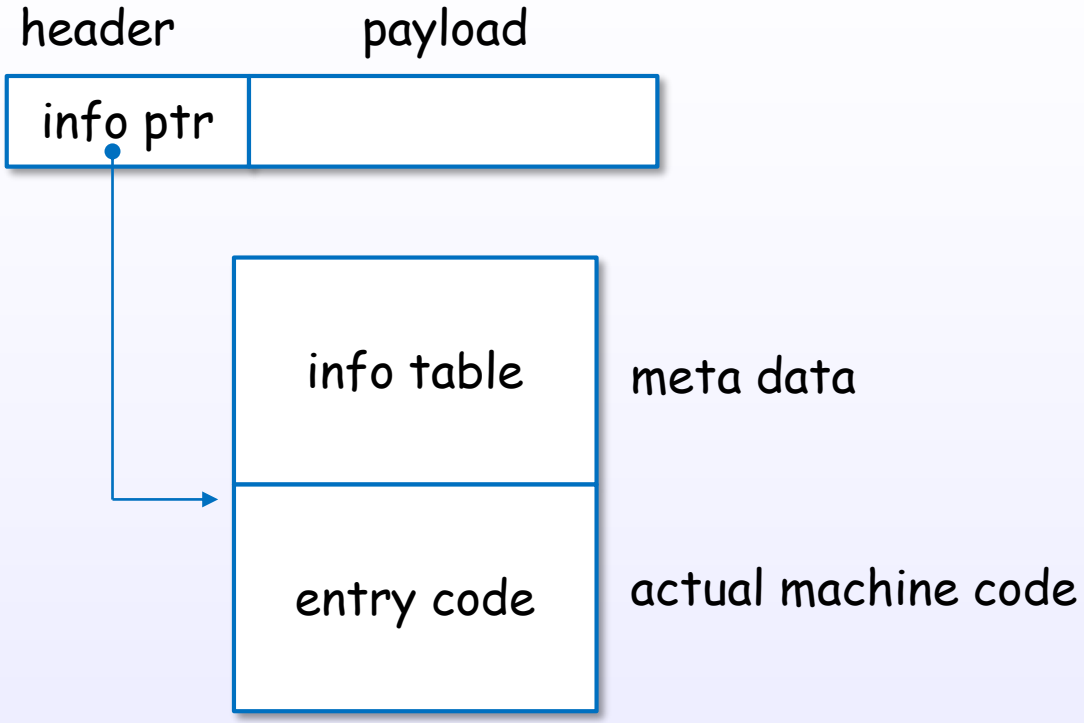
link to stack object

A TSO object is only ~18words + stack. Lightweight!

References : [S5]

# Heap objects in STG-machine

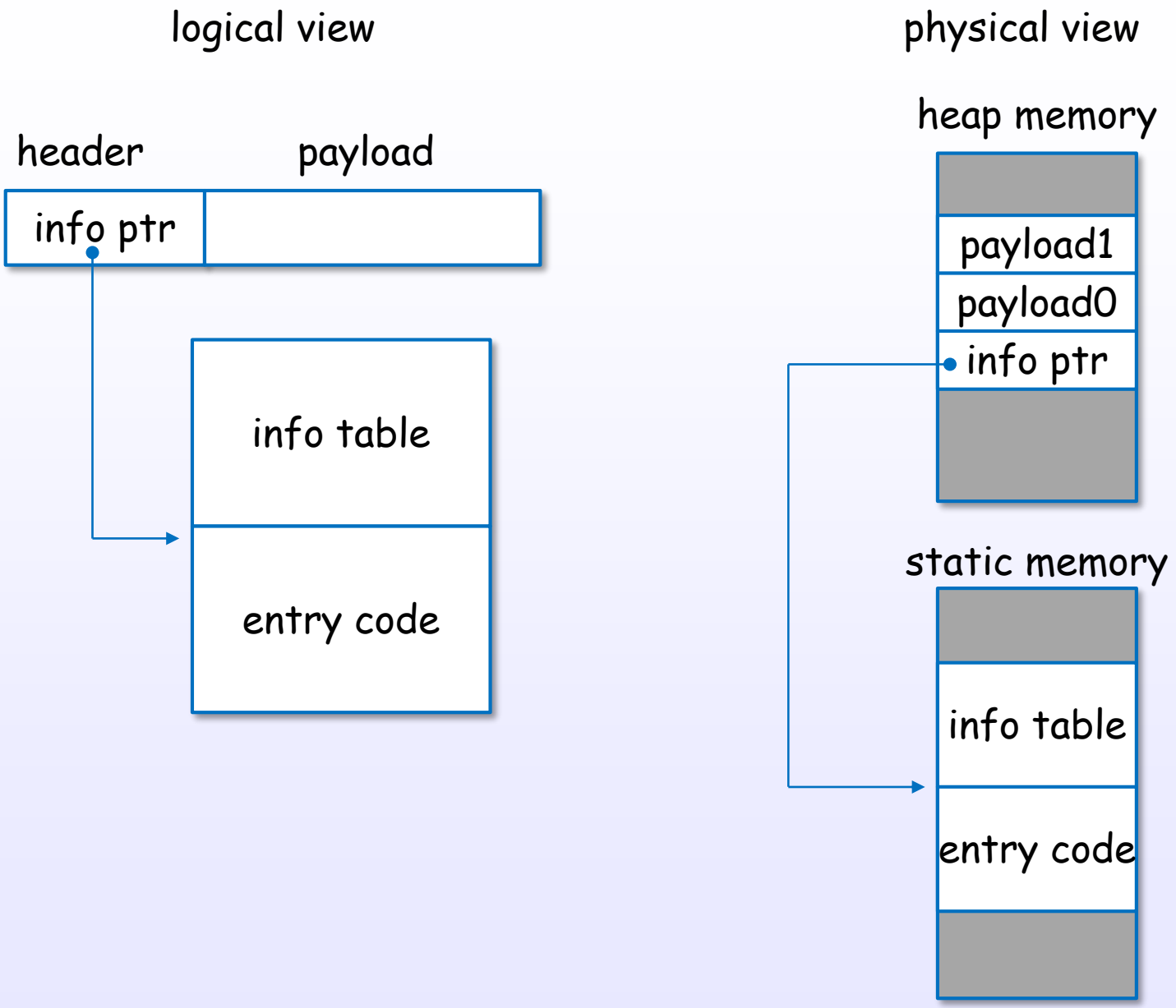
# Every heap object is represented uniformly




Closure (header + payload) + Info Table + Entry Code

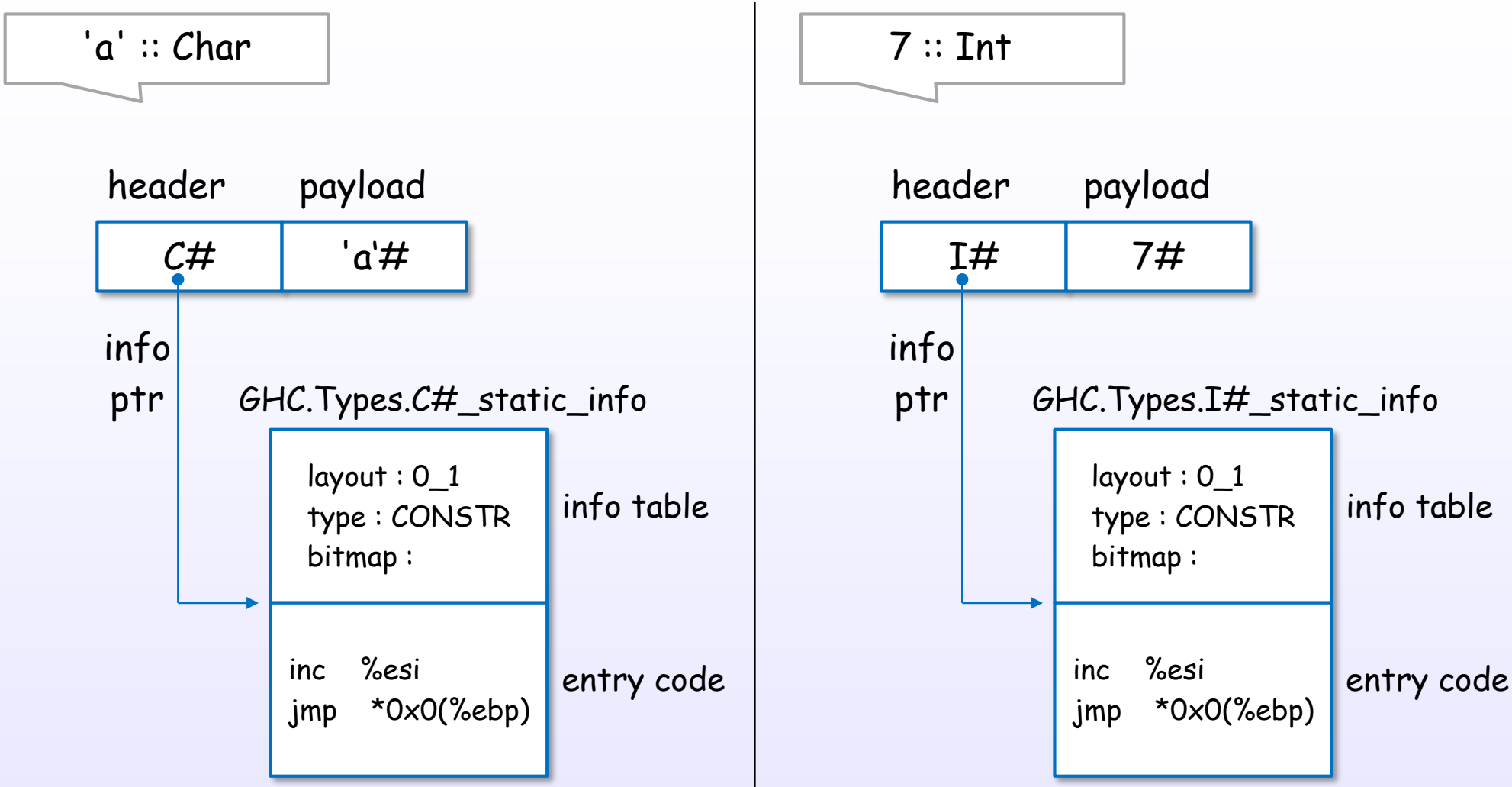
References : [C11], [S3], [S4], [S6], [2]

# Heap object (closure)




References : [C11], [S3], [C9], [C8], [2], [12], [13]

# Closure examples : Char, Int




References : [C11], [S3], [C9], [C8], [2], [S20], [13]

# Closure example (code)

[Example.hs]

```
module Example where
value1 :: Int
value1 = 7
```

STG

[ghc -O -ddump-stg Example.hs]

```
Example.value1 :: GHC.Types.Int
[GblId, Caf=NoCafRefs, Str=DmdType m, Unf=OtherCon []] =
    NO_CCS GHC.Types.I#! [7#];
```

Cmm

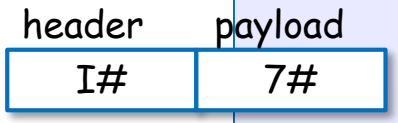
[ghc -O -ddump-opt-cmm Example.hs]

```
section ""data" .
__stginit_main@main:Example" {
    __stginit_main@main:Example:
}

section ""data" . Example.value1_closure" {
    Example.value1_closure:
        const GHC.Types.I#_static_info;
        const 7;
}

section ""readonly" . cHc_str" {
    cHc_str:
        I8[] [109,97,105,110]
}
```

asm

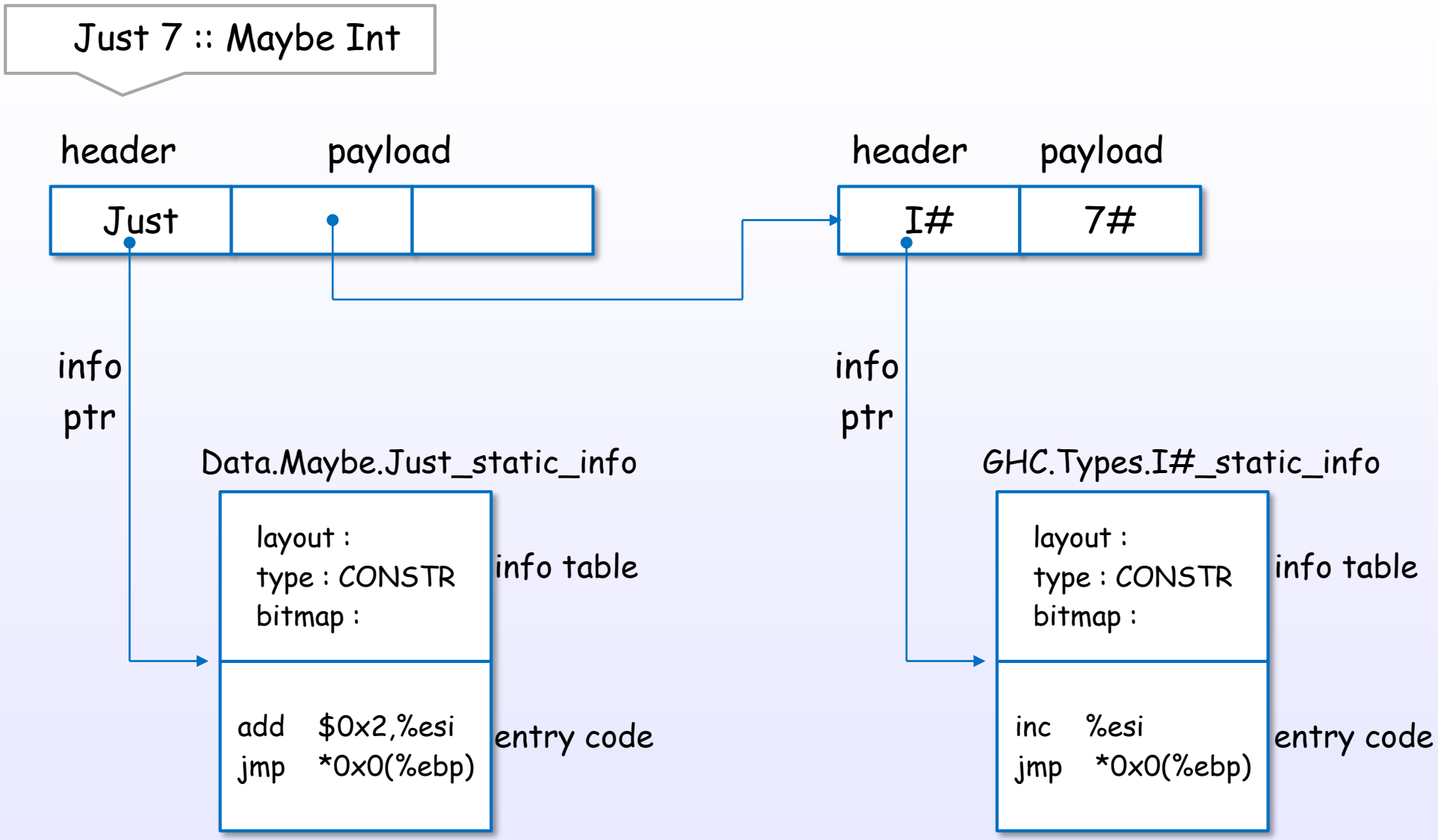
[ghc -O -ddump-asm Example.hs]

```
.section .data
.align 8
.align 1
.globl __stginit_main@main:Example
__stginit_main@main:Example:

.section .data
.align 8
.align 1
.globl Example.value1_closure
Example.value1_closure:
        .quad   GHC.Types.I#_static_info
        .quad   7

.section .rodata
.align 8
.align 1
```



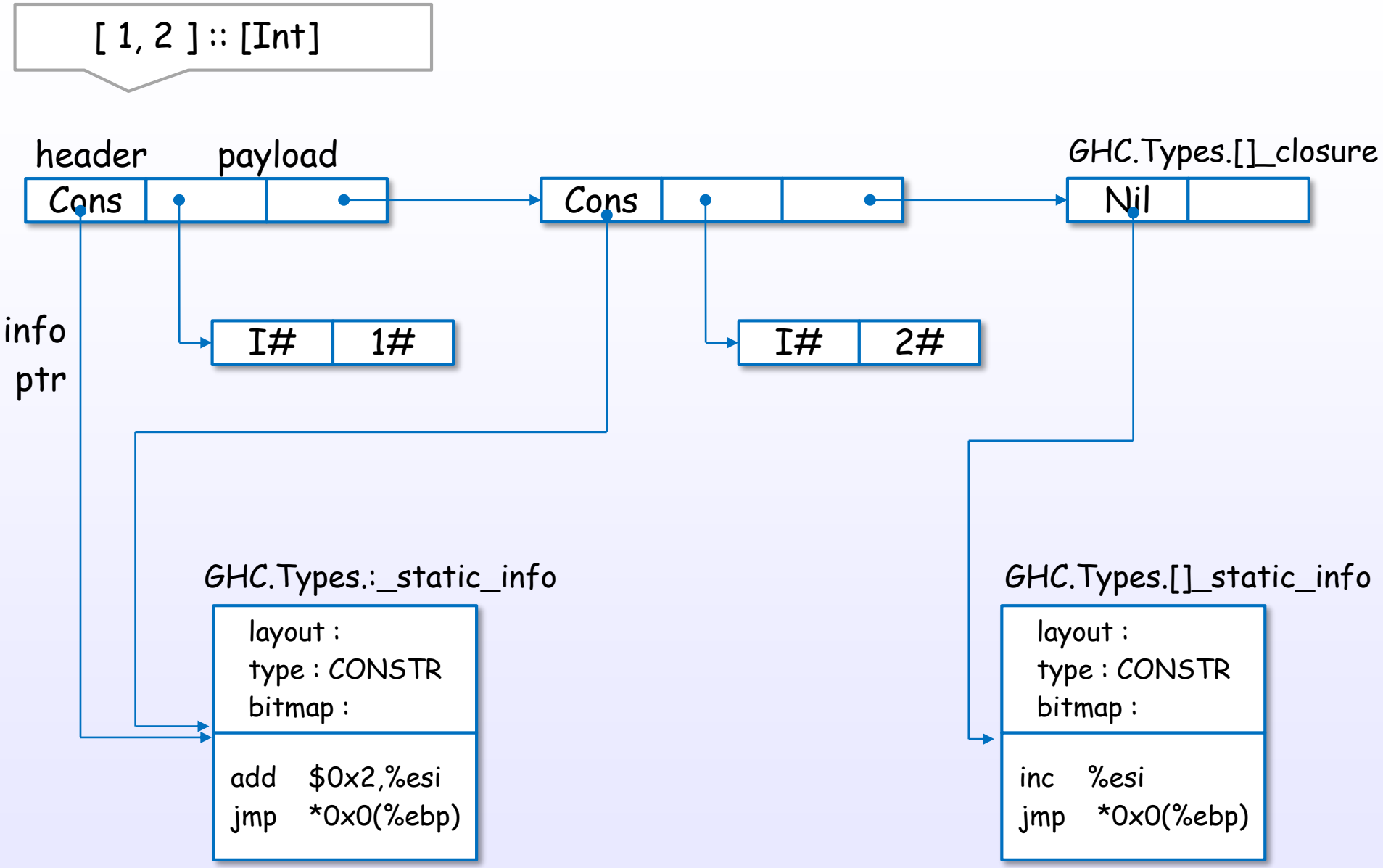

References : [C11], [S3], [C9], [C8], [2], [S20]

# Closure examples : Maybe



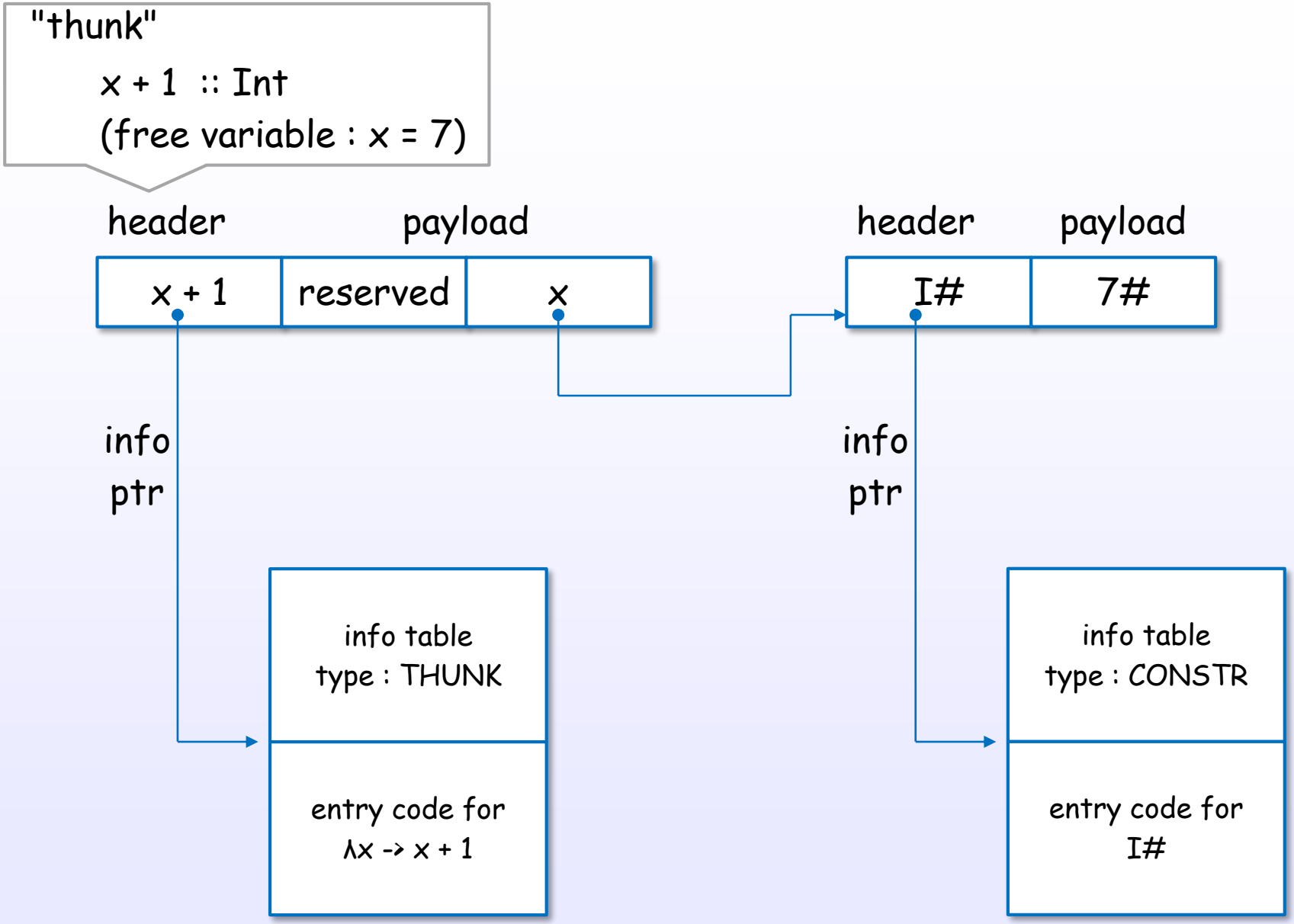

References : [C11], [S3], [C9], [C8], [2], [S20]

# Closure examples : List




References : [C11], [S3], [C9], [C8], [2], [S20]

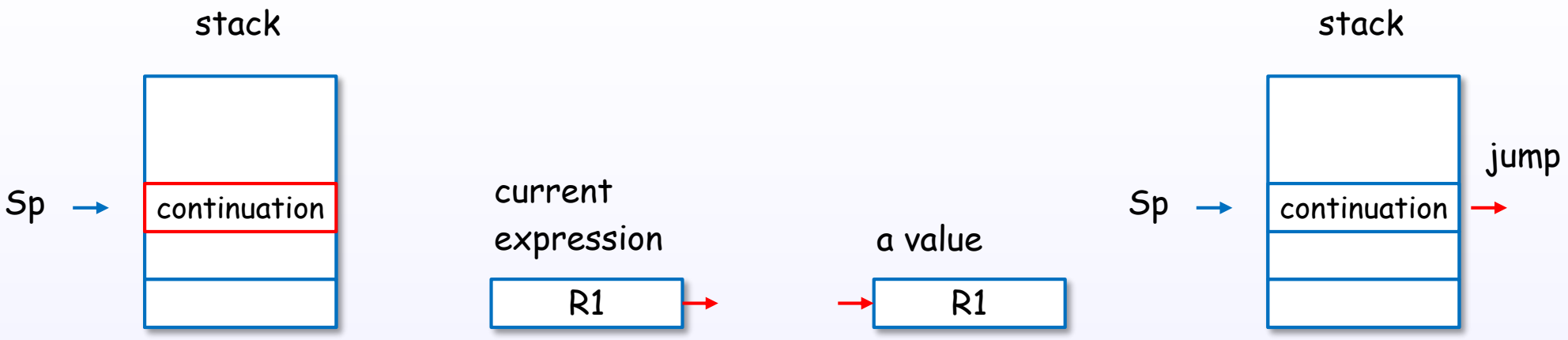
# Closure examples : Thunk




References : [C11], [S3], [C9], [C8], [2], [S20]

# STG-machine evaluation

# STG evaluation flow




(1)
push a continuation code (next code) to the stack top

(2)
enter to R1 closure

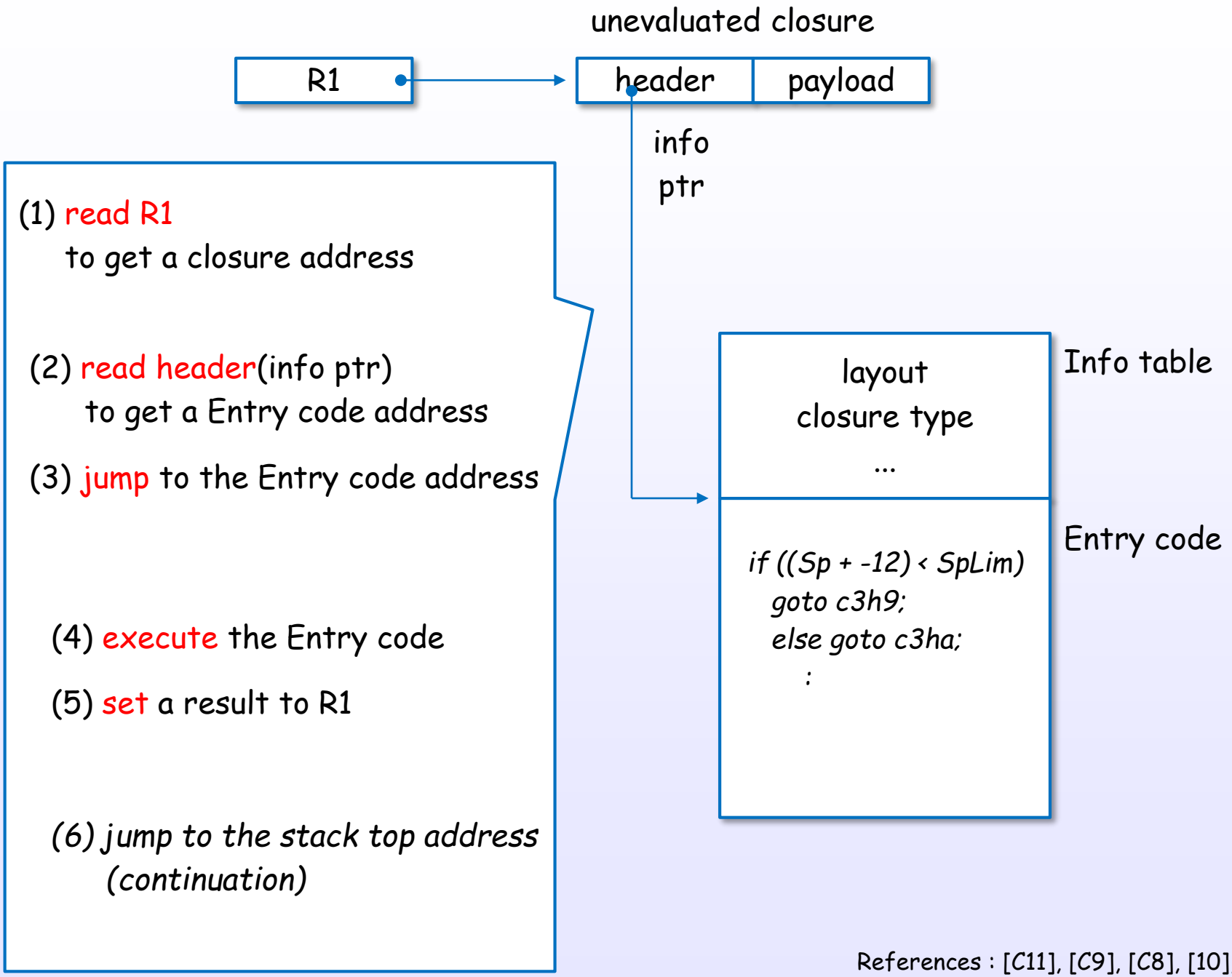
(3)
set a result to R1

(4)
jump (return) to the stack top code

(5)
repeat from (1)

References : [C8], [3], [12], [13]

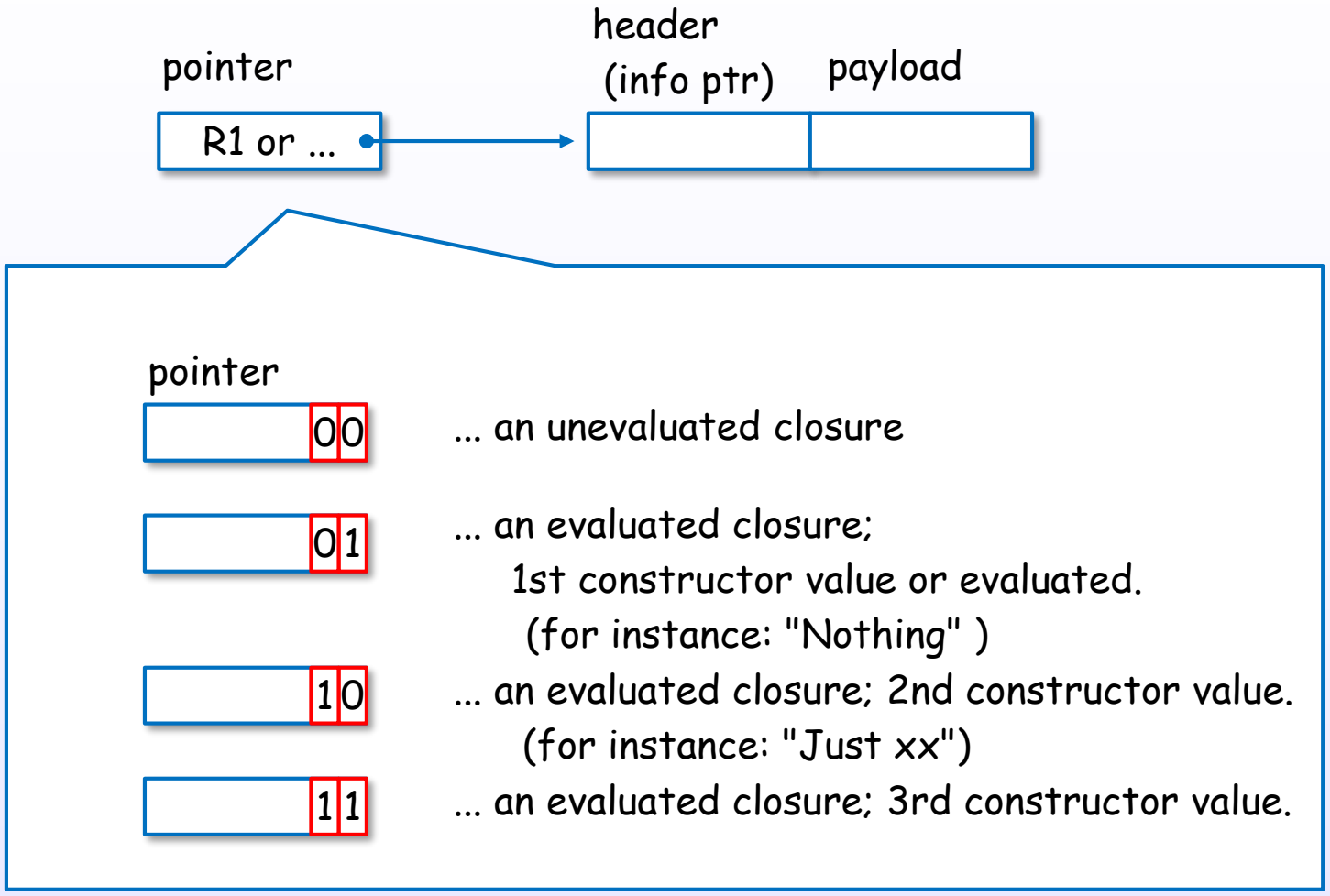
# Enter to a closure




References : [C11], [C9], [C8], [10], [3], [2], [12], [13]

# Pointer tagging

# Pointer tagging




* 32bit machine case

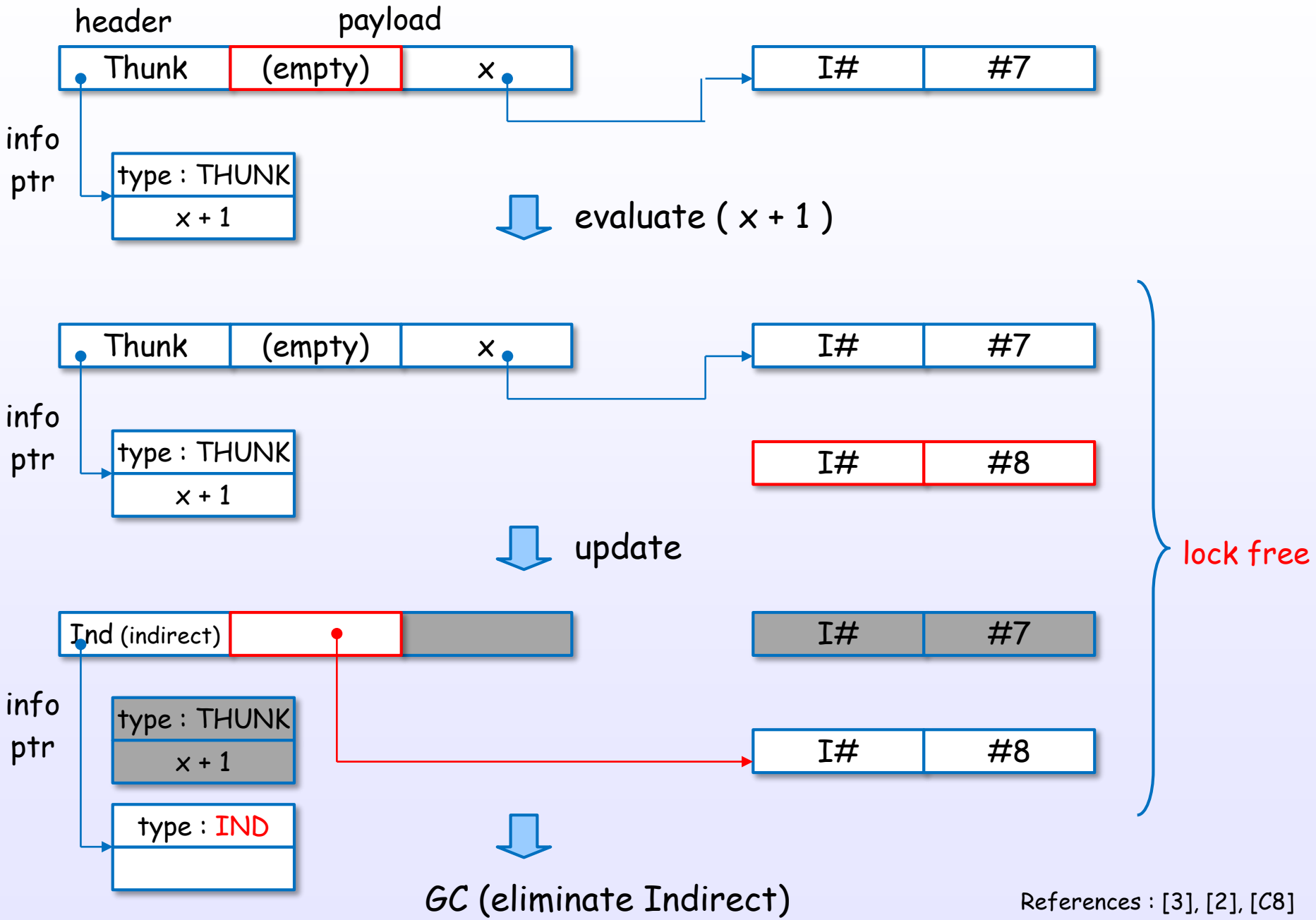
fast judgment!
check only pointer's lower bits without evaluating the closure.

References : [4], [2], [C16], [12], [13]

# Thunk and update

# Thunk and update

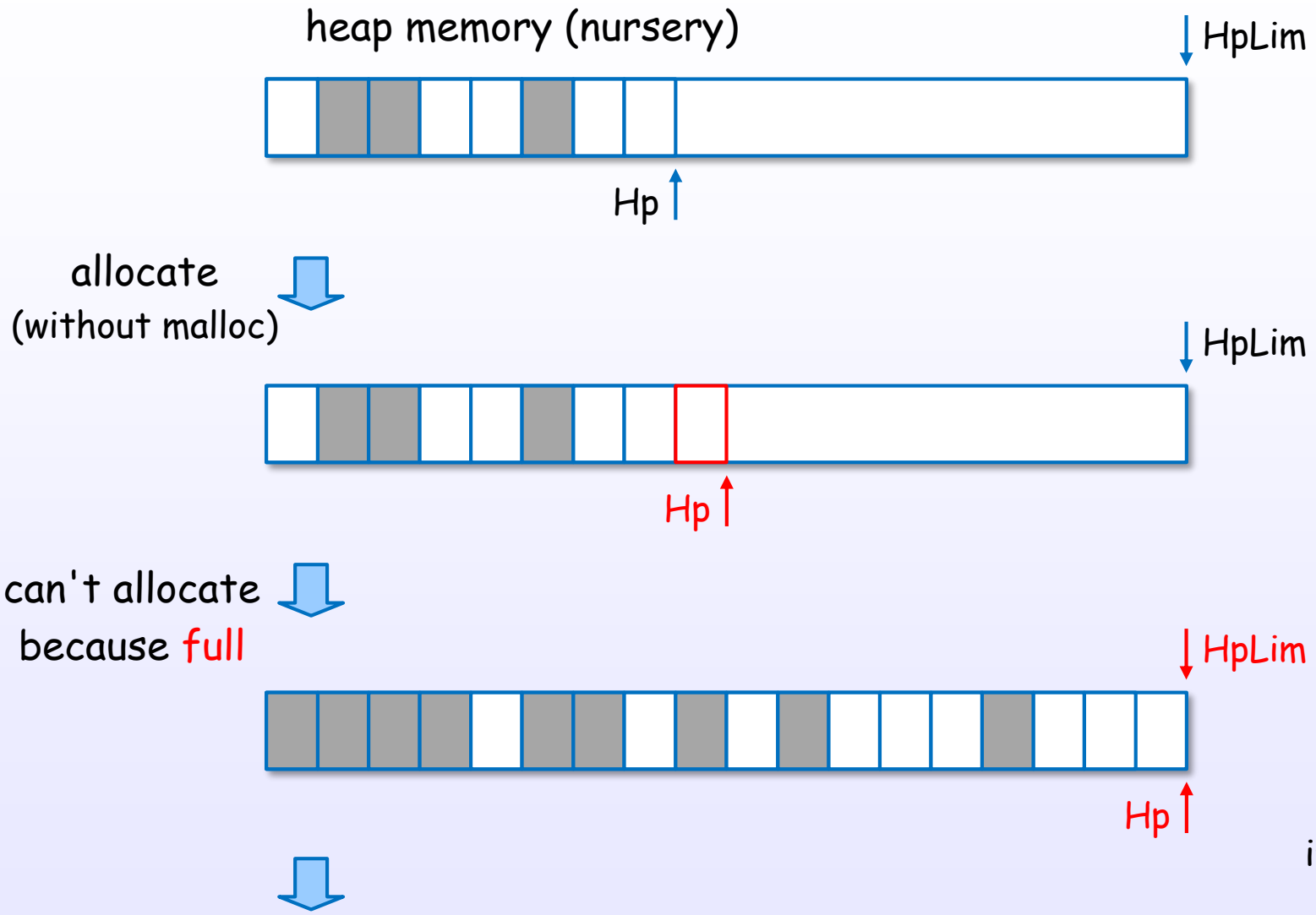
"thunk"  x + 1 :: Int  (free variable : x = 7)




References : [3], [2], [C8]

# Allocate and free heap objects

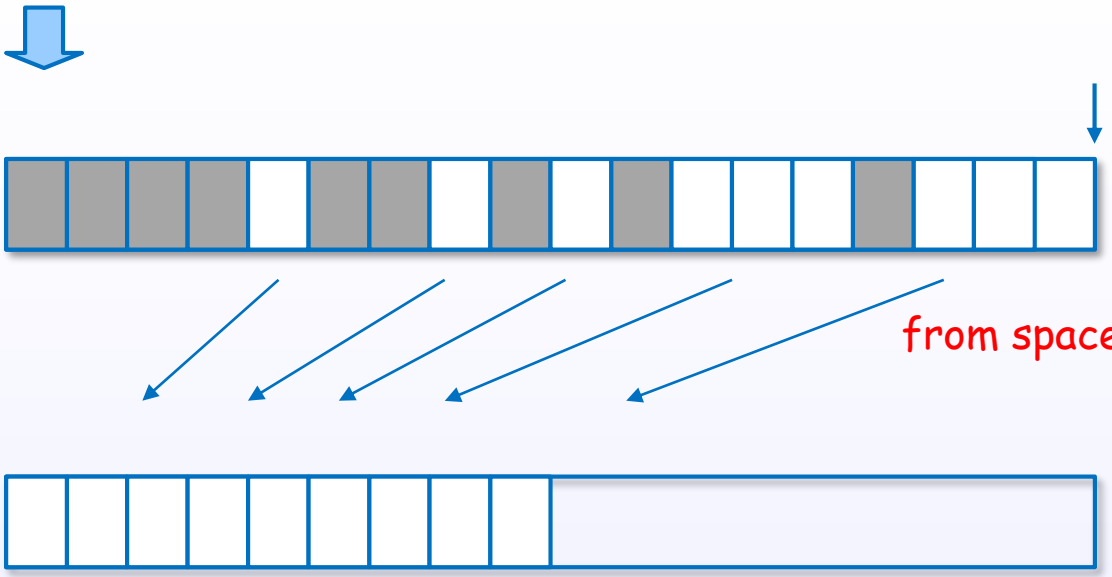
# Allocate heap objects




if (Hp > HpLim ) goto ...
call stg_gc_...

References : [C11], [C13], [8], [9], [5], [15], [12], [13], [19], [S25]

# free and collect heap objects



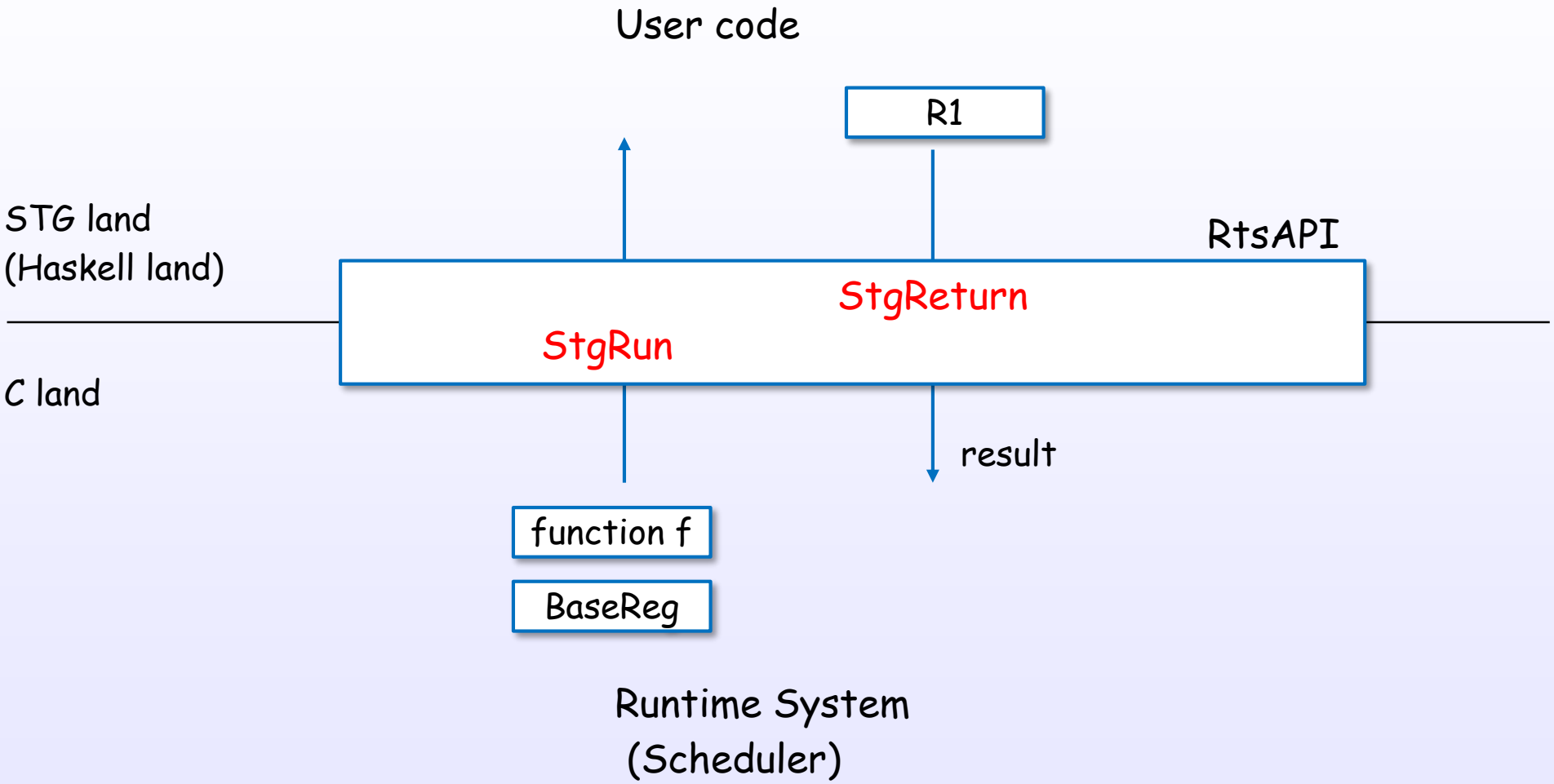

copying collection (minor GC)

if (Hp > HpLim ) goto ...
call stg_gc_...

References : [C11], [C13], [8], [9], [5], [15], [12], [13], [19], [S25]

# STG - C land interface

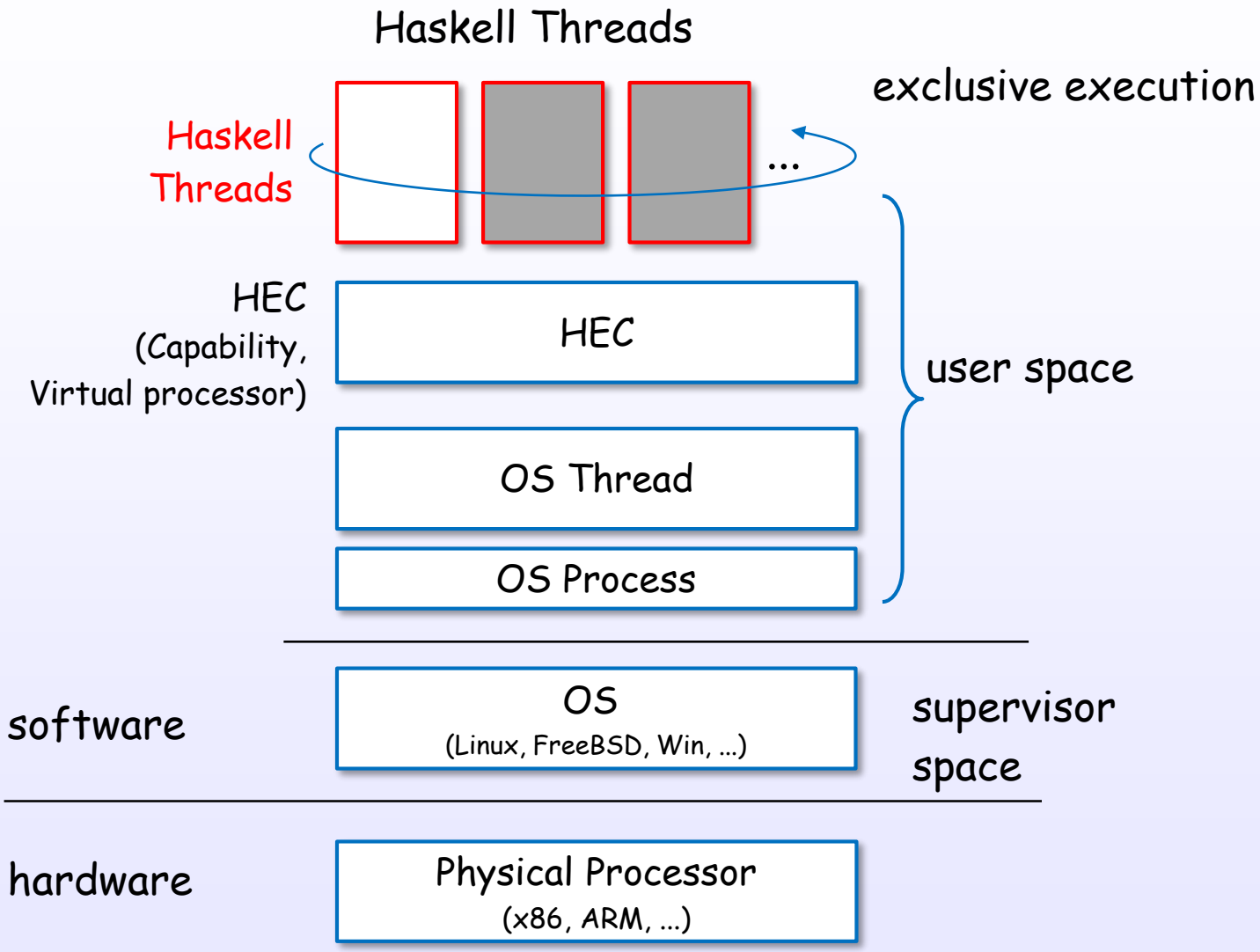
# STG (Haskell) land - C land interface




References : [S18], [S17], [S19], [S21]

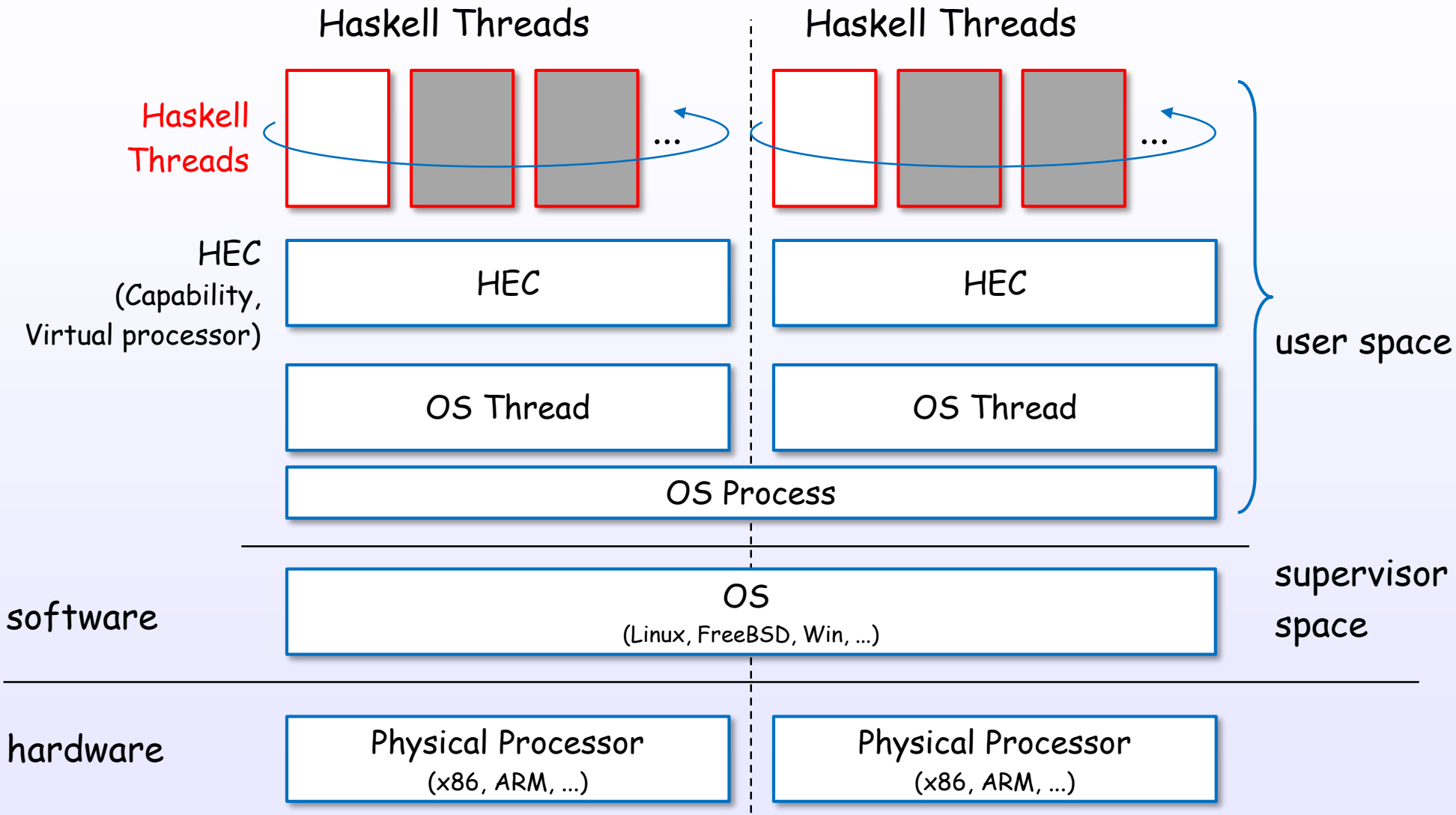
# Thread

# Thread layer (single core)




References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

# Thread layer (multi core)

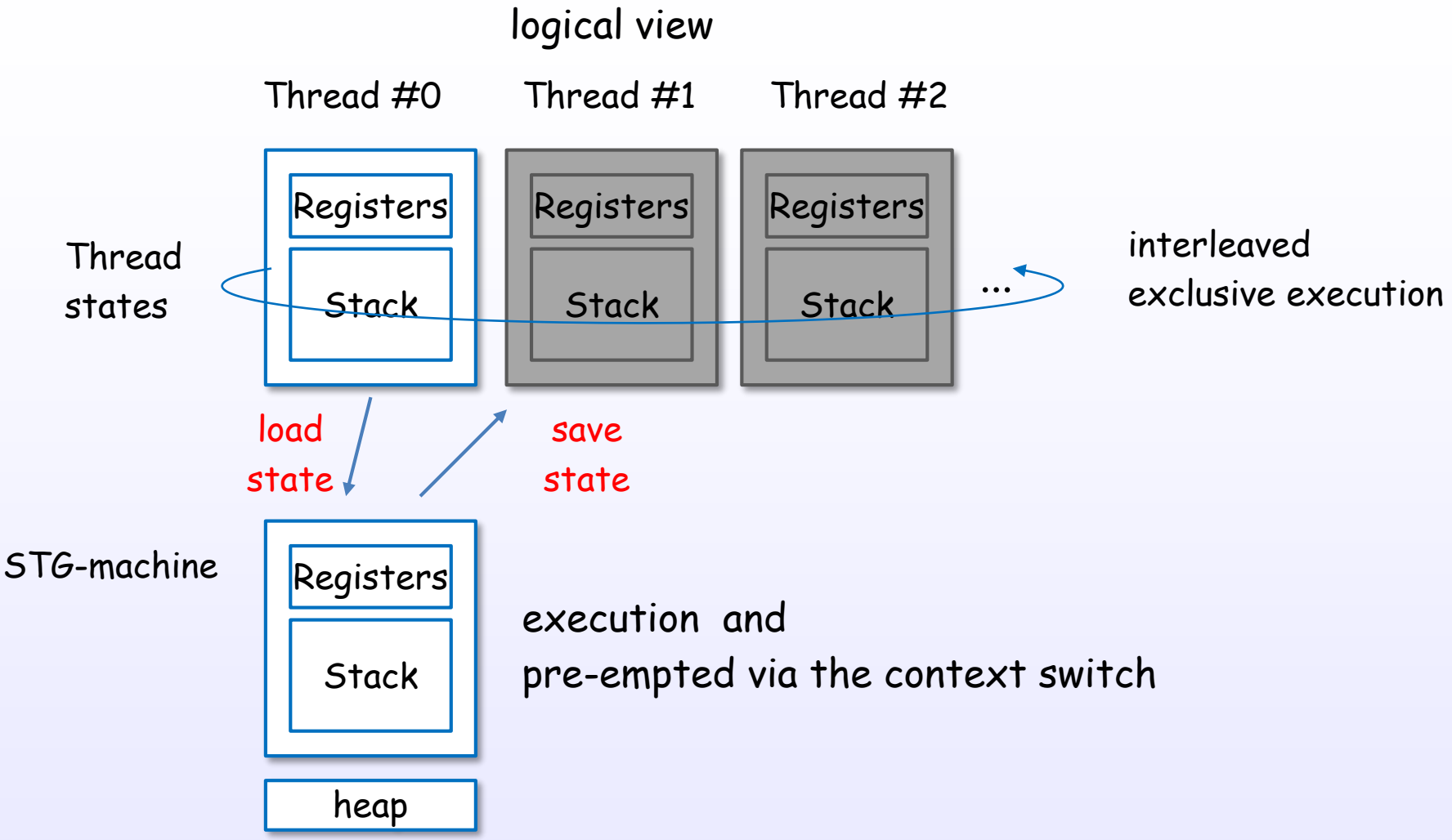



*Threaded option case (ghc -threaded)

References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

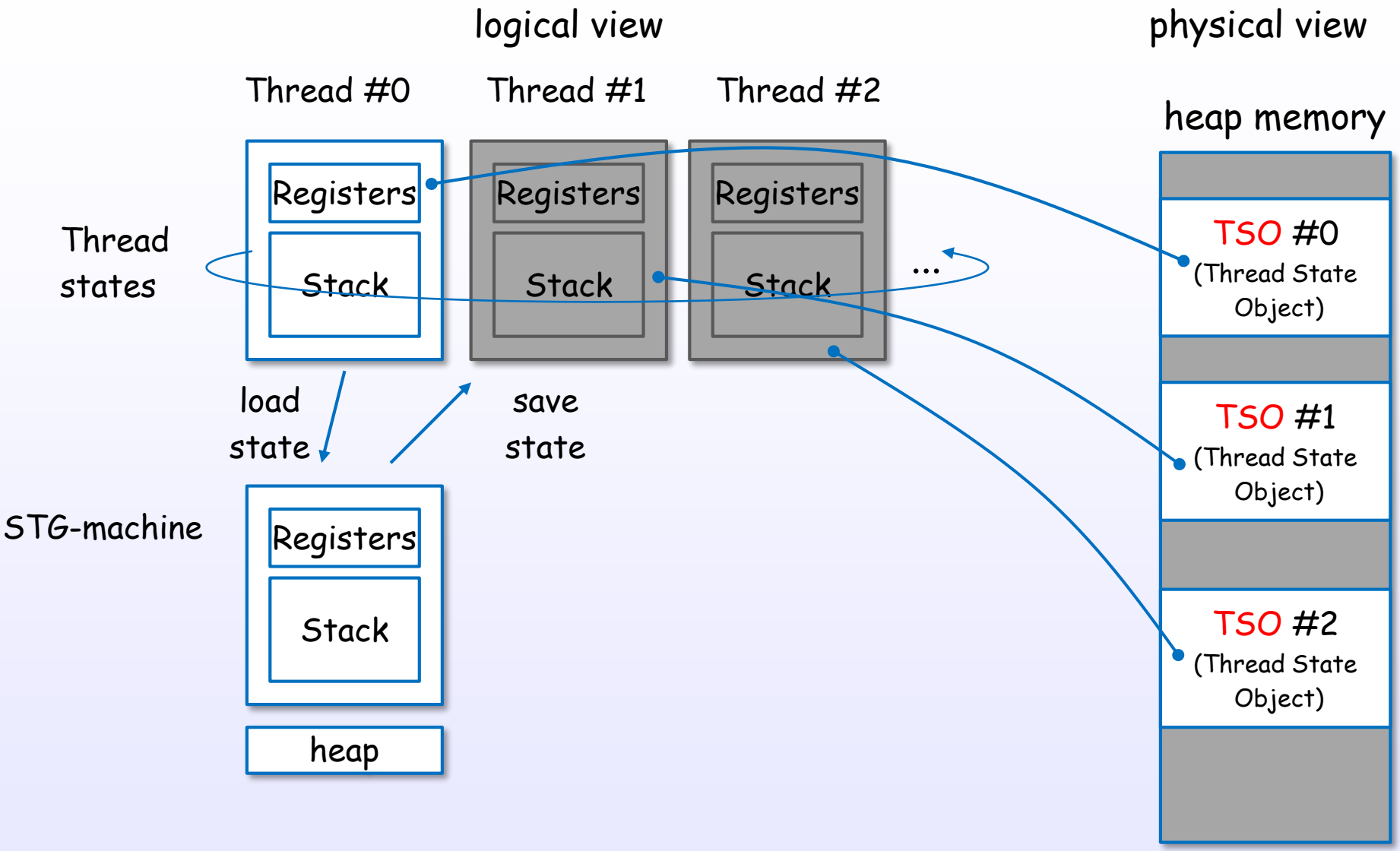
# Thread context switch

# Threads and context switch



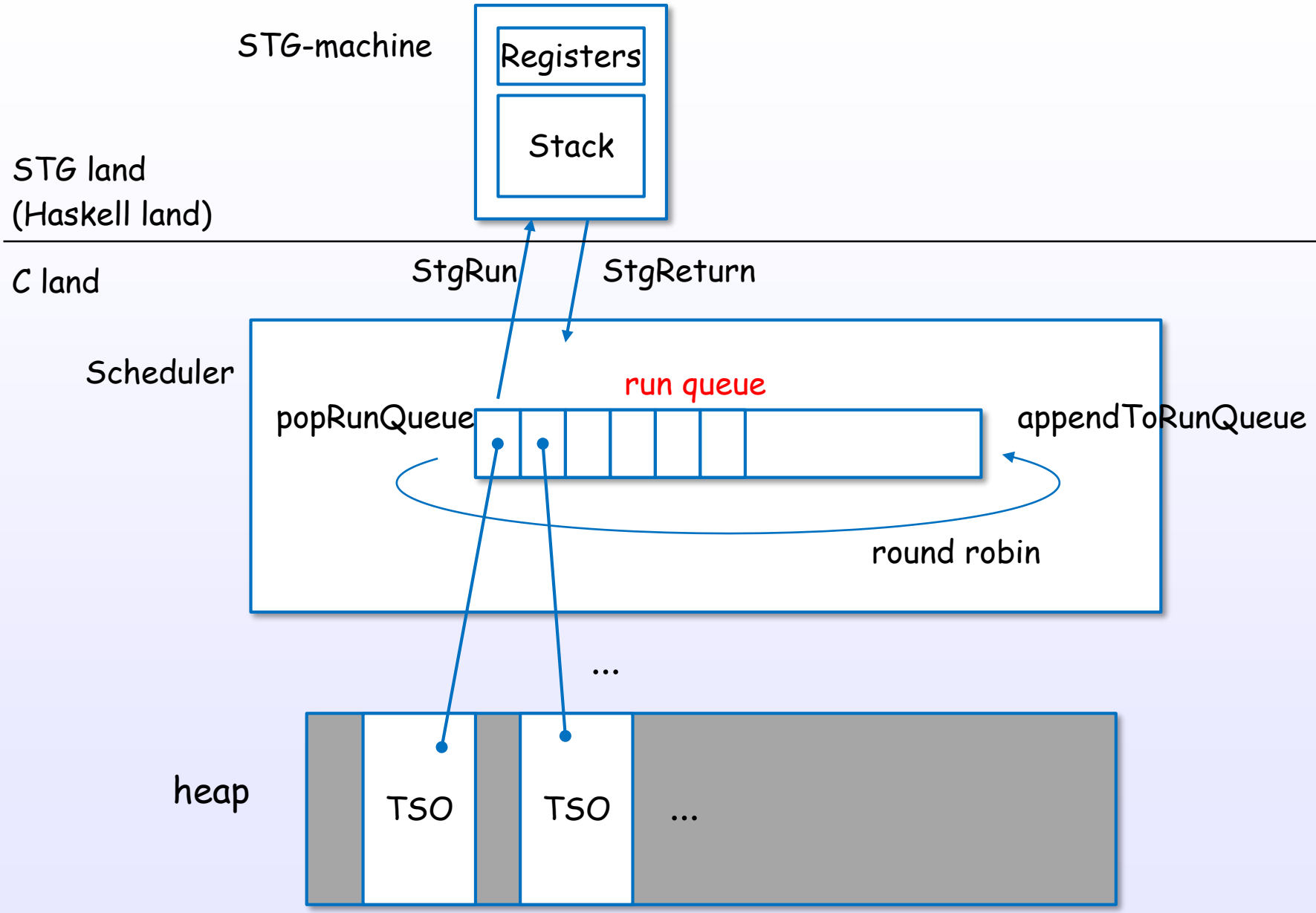

References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

# Threads and TSOs



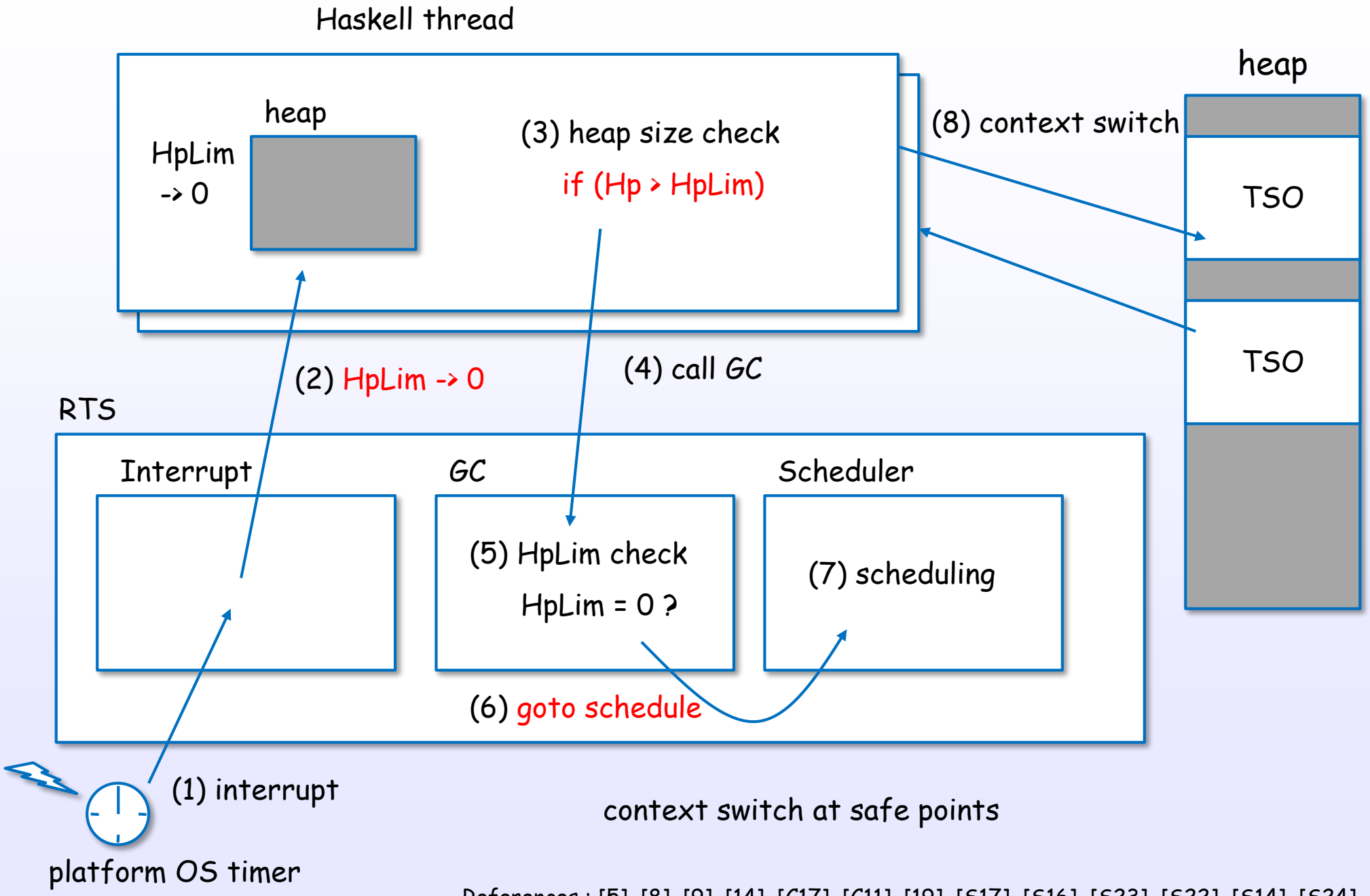

References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

# Scheduling by run queue



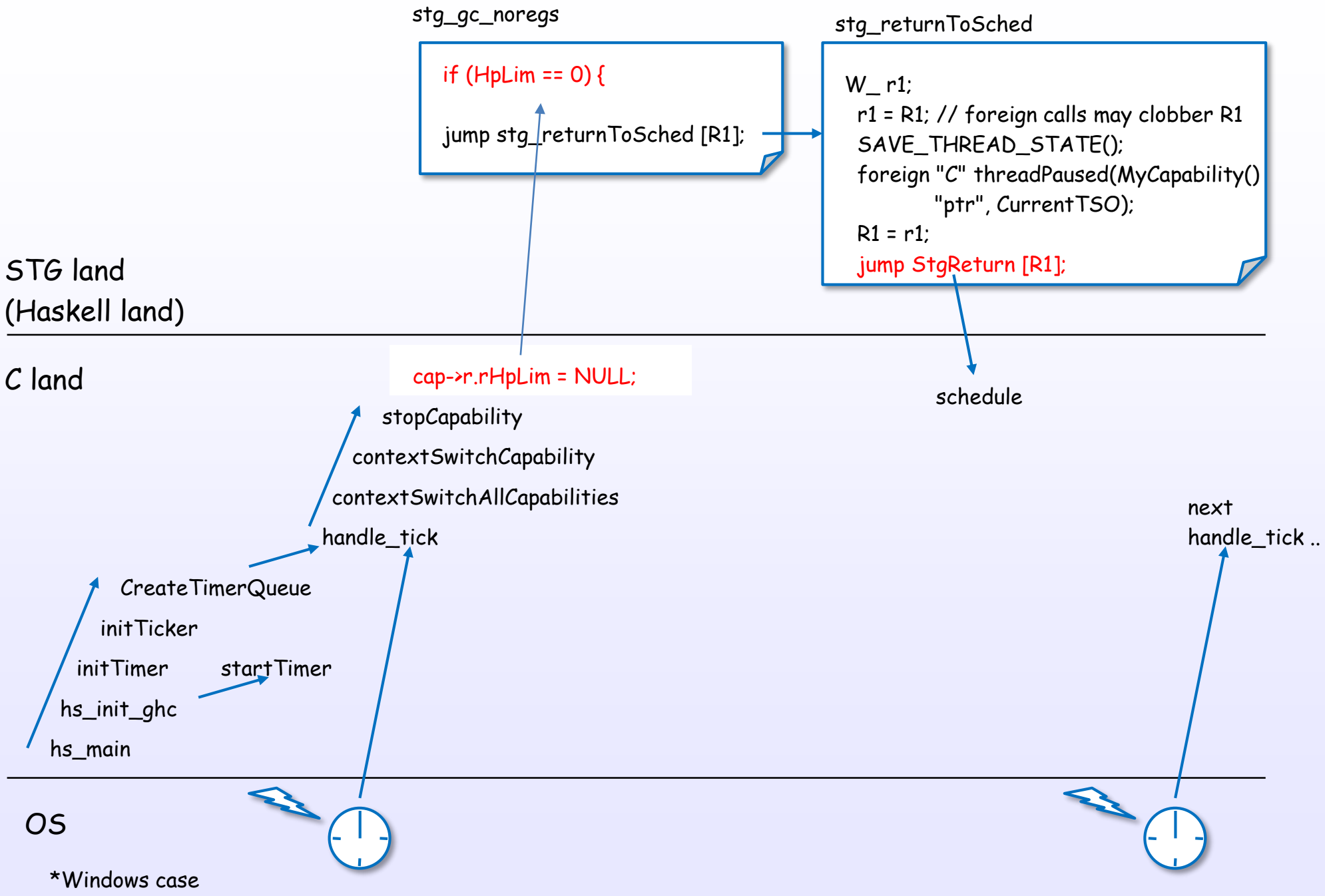

References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

# Context switch flow




References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14], [S24]

# Context switch flow (code)




References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S21], [S23], [S22], [S14], [S24]

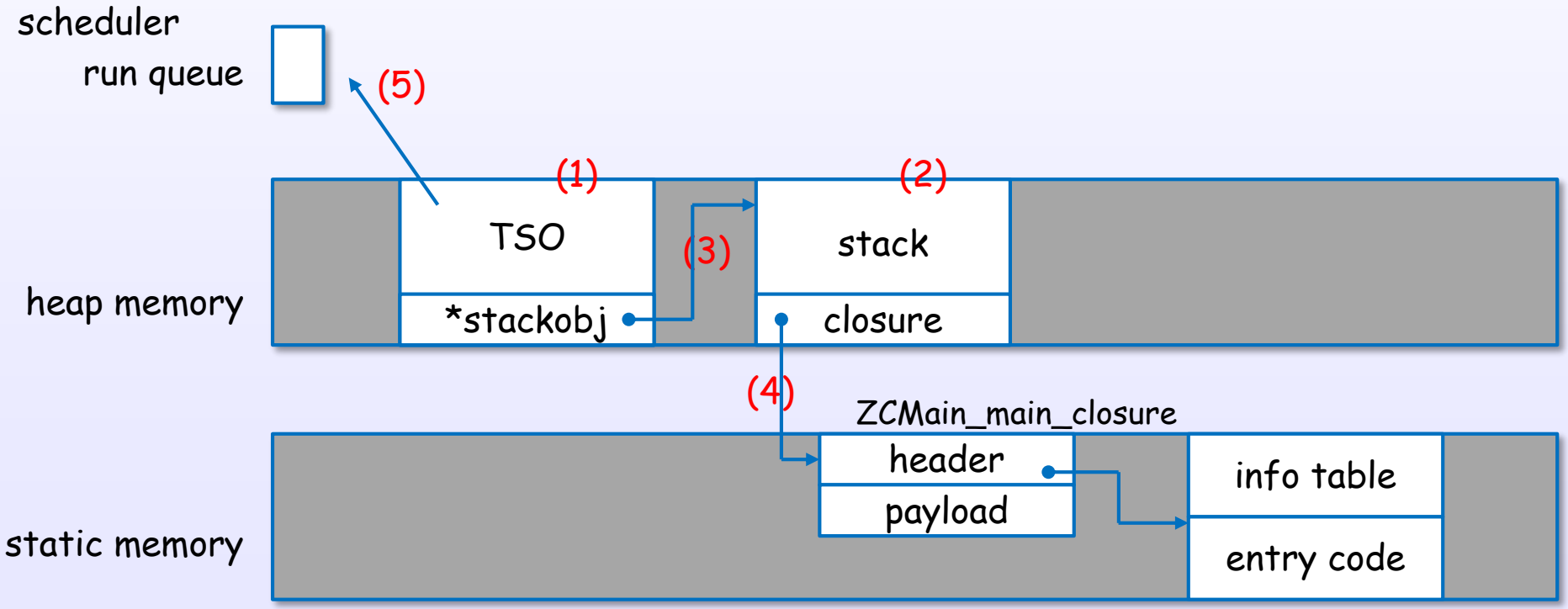
# Creating main and sub threads

# Create a main thread

Runtime System

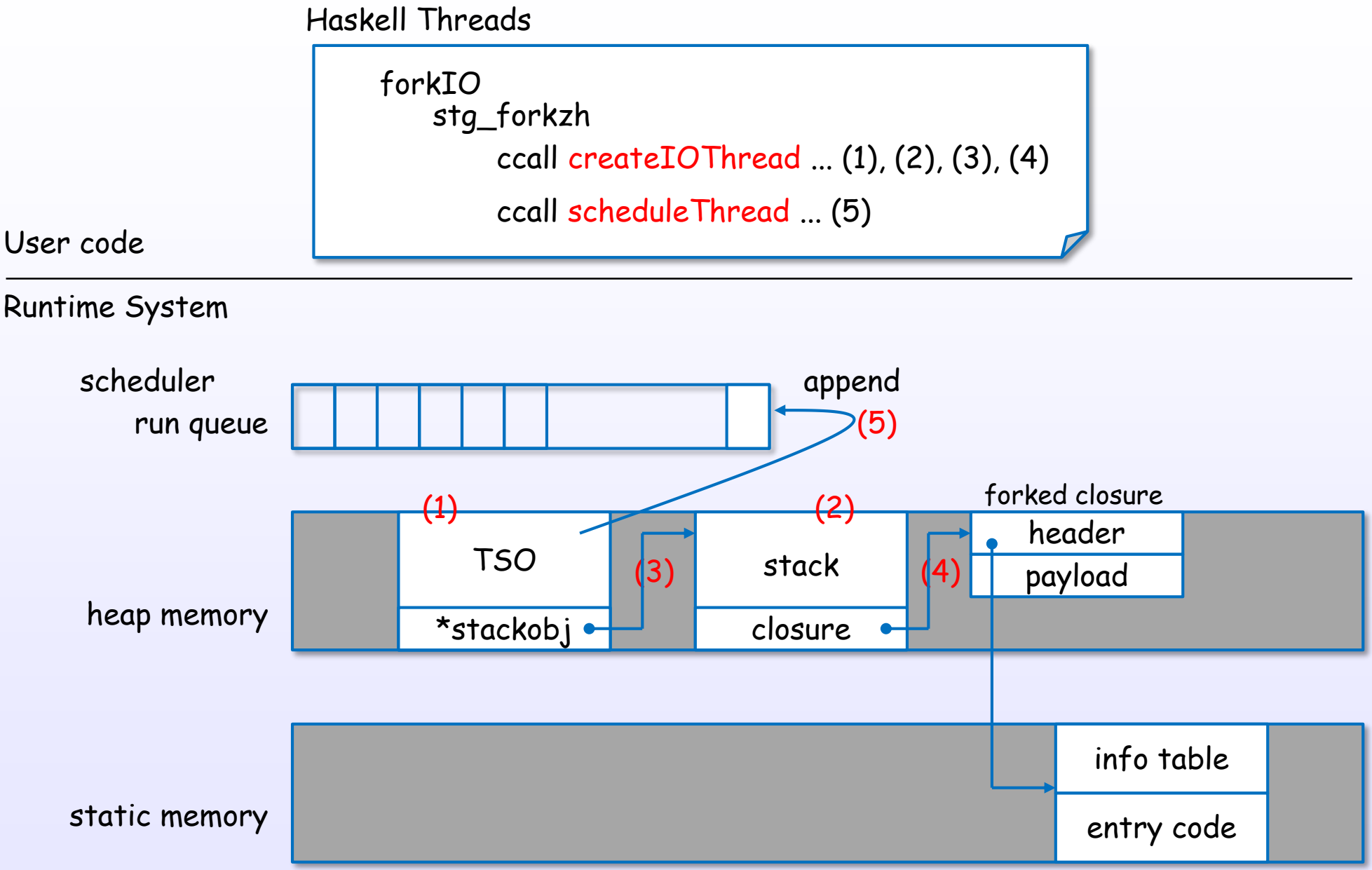
Runtime system bootstrap code [rts/RtsAPI.c]

```
rts_evalLazyIO
    createIOThread
        createThread ... (1), (2), (3)
        pushClosure    ... (4)
    scheduleWaitThread
        appendToRunQueue ... (5)
```




References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14], [S24]

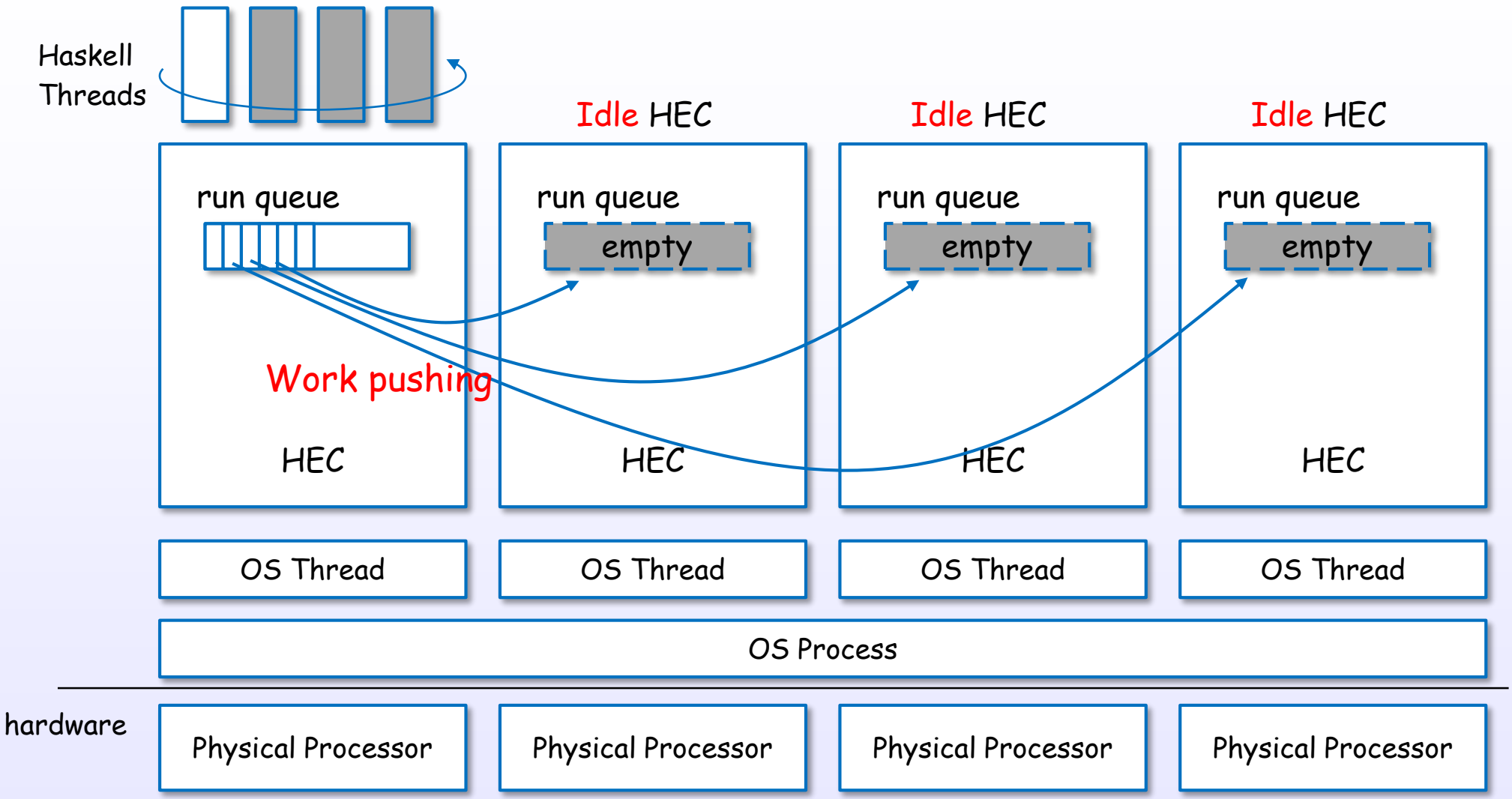
# Create a sub thread using forkIO




References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14], [S24]

# Thread migration

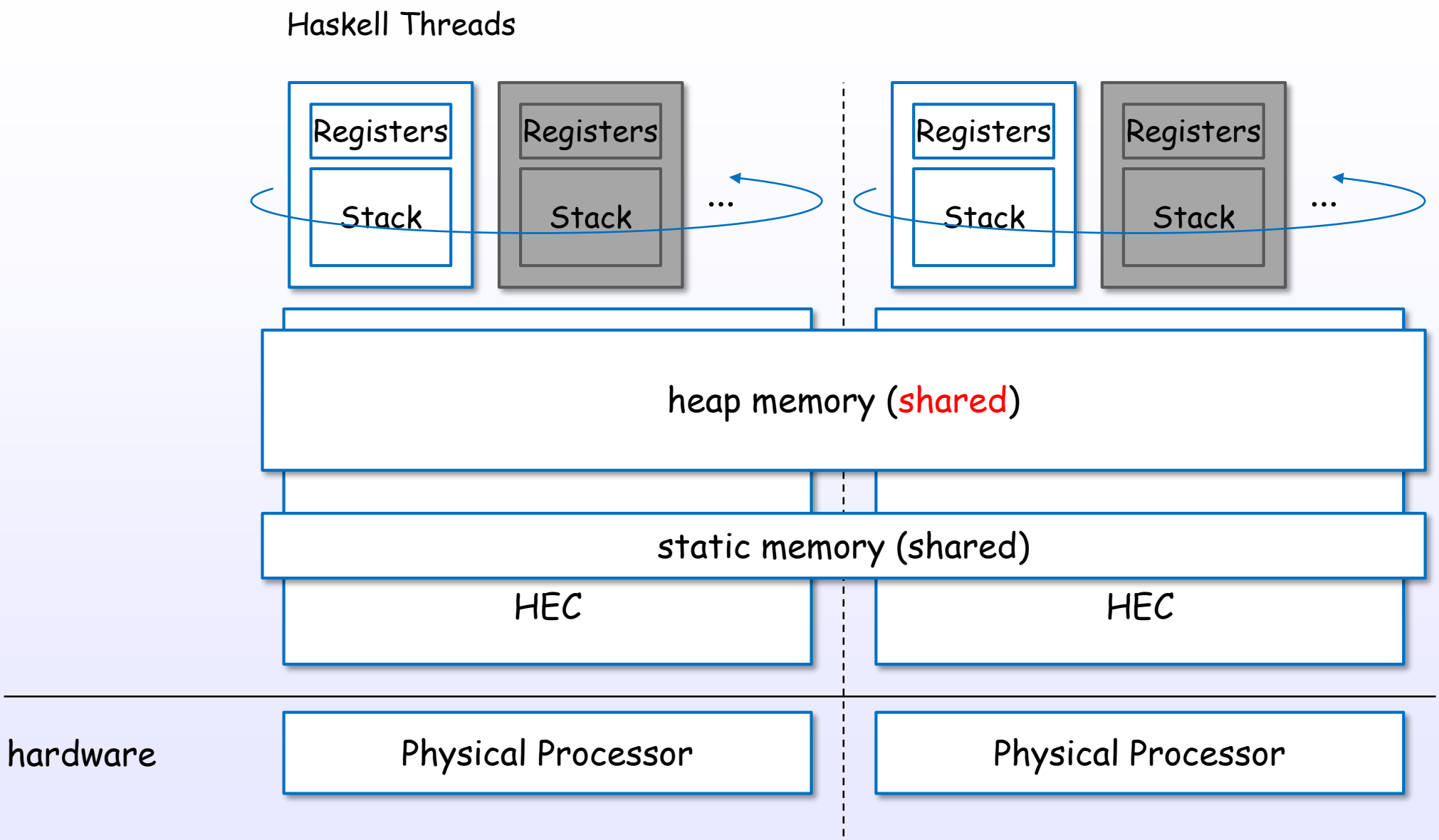
# Threads are migrated to idle HECs




References : [5], [8], [9], [14], [C17], [C18], [S17], [S16], [S23], [S24]

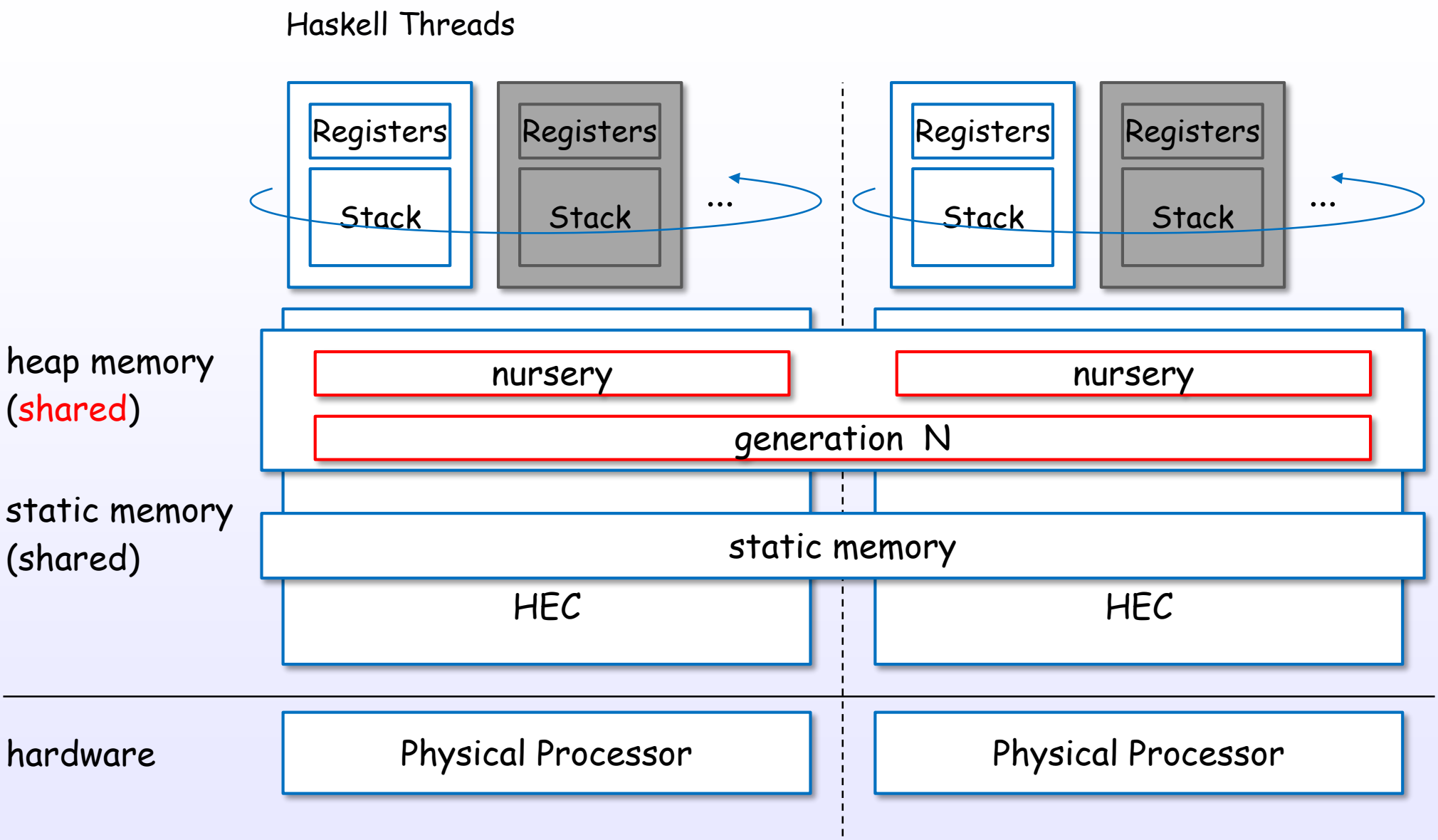
# Heap and Threads

# Threads share a heap




References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14], [S17], [S16], [S25]

# Local allocation area (nursery)

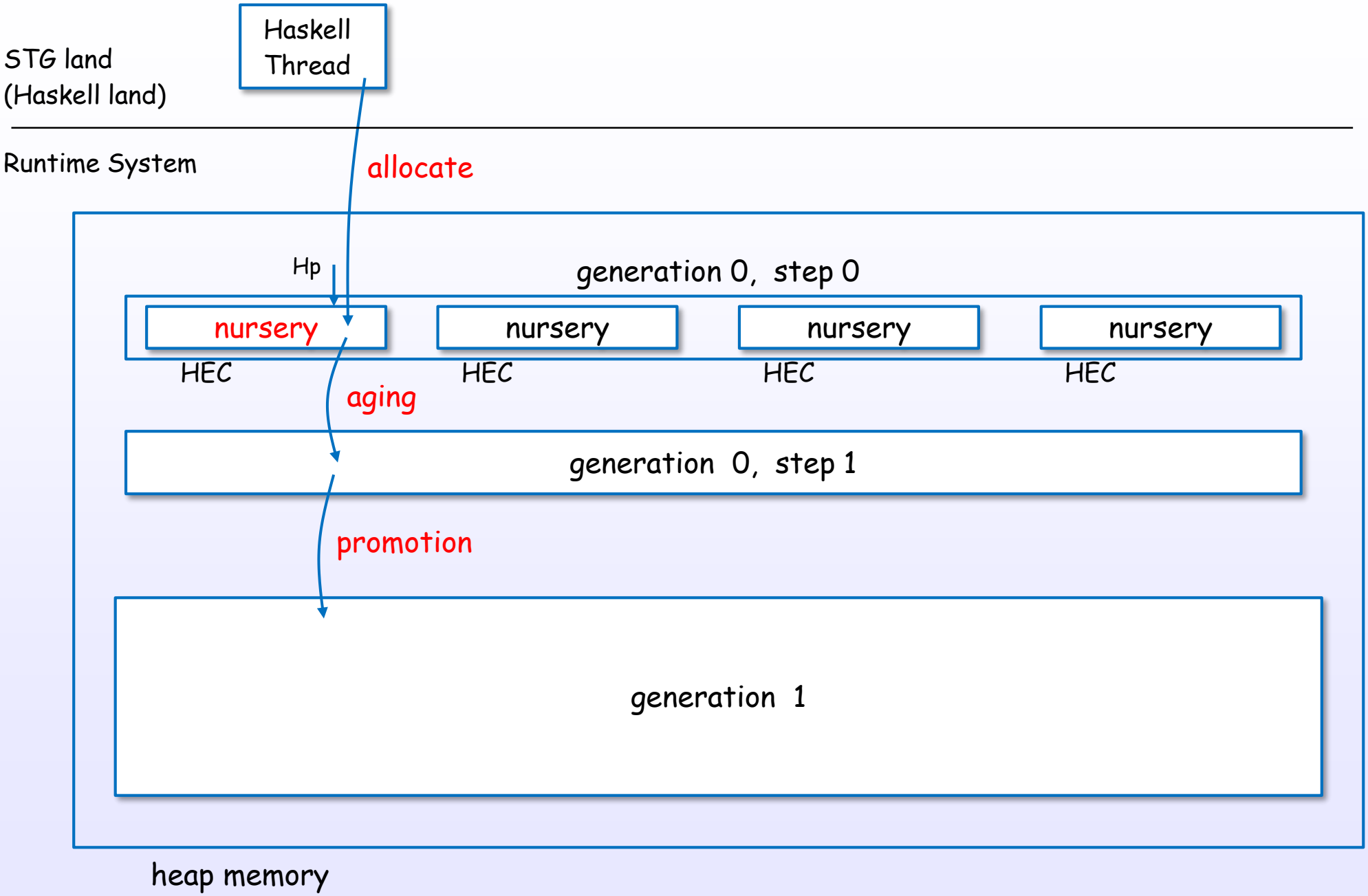



fast access using nursery for each processors

References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14], [S17], [S16], [S25]

# Threads and GC

# GC, nursery, generation, aging, promotion

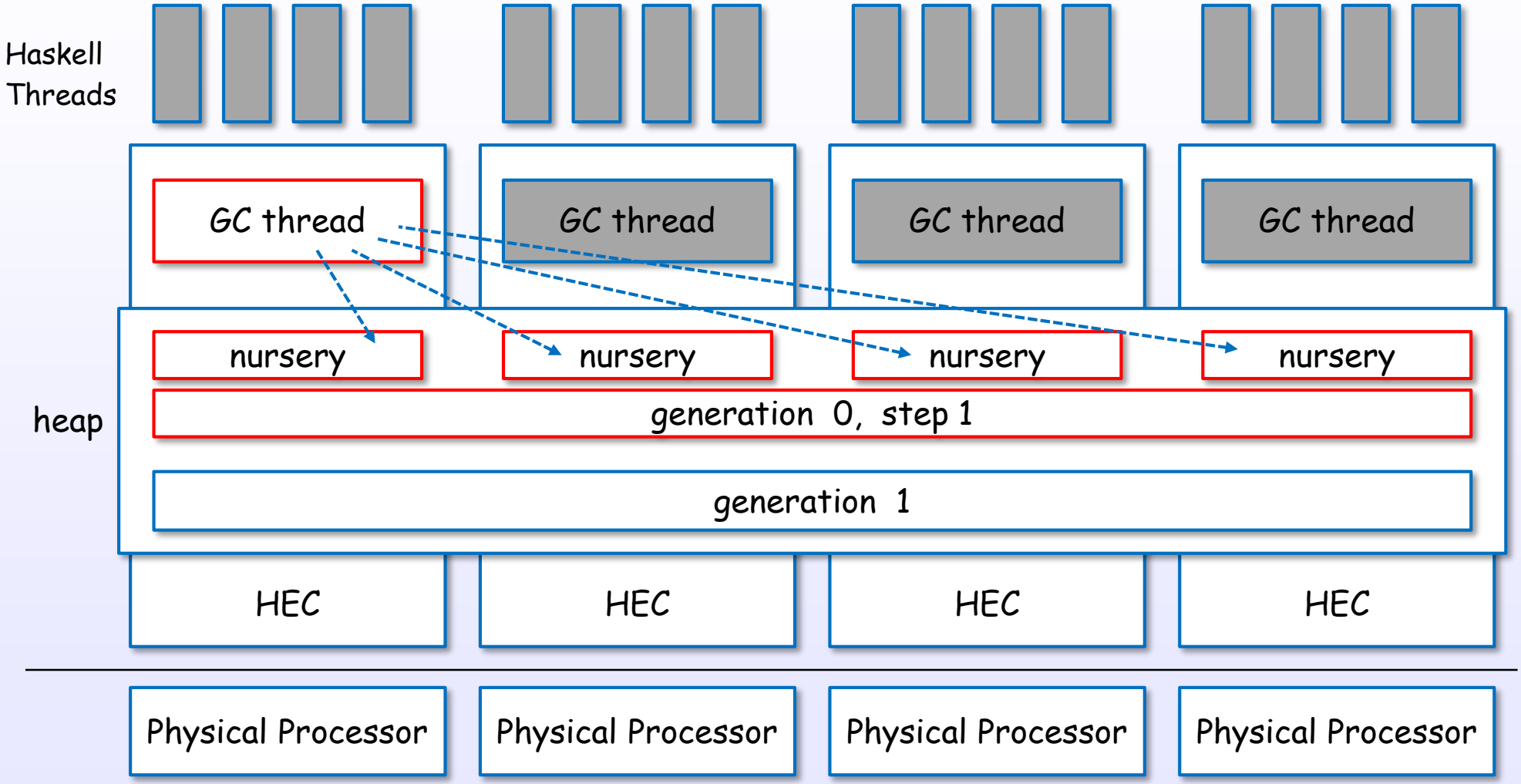



References : [8], [9], [15], [C13], [C11], [S25]

# Threads and minor GC

sequential GC for young generation (minor GC)

"stop-the-world" GC

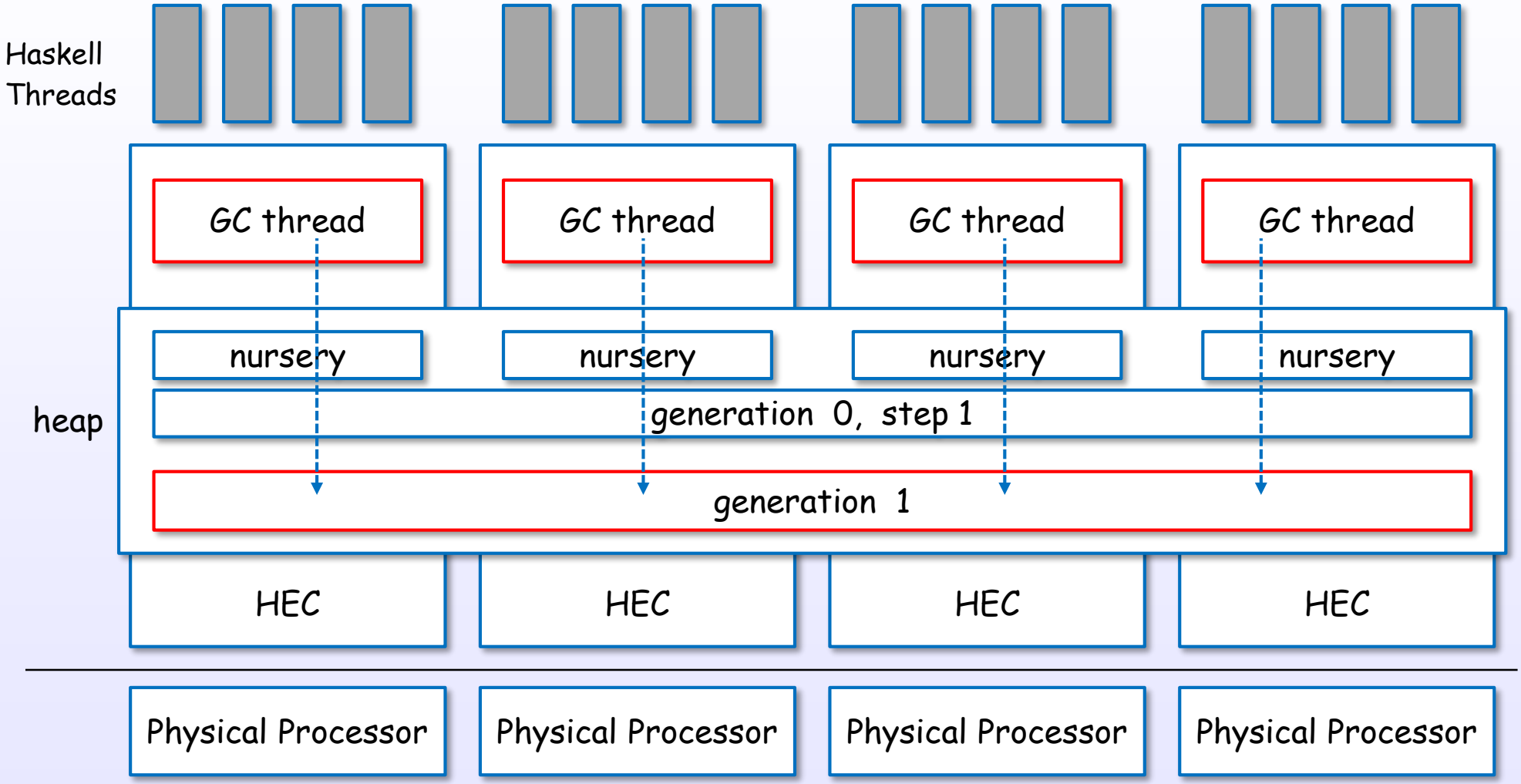



References : [8], [9], [15], [C13], [C11], [S25]

# Threads and major GC

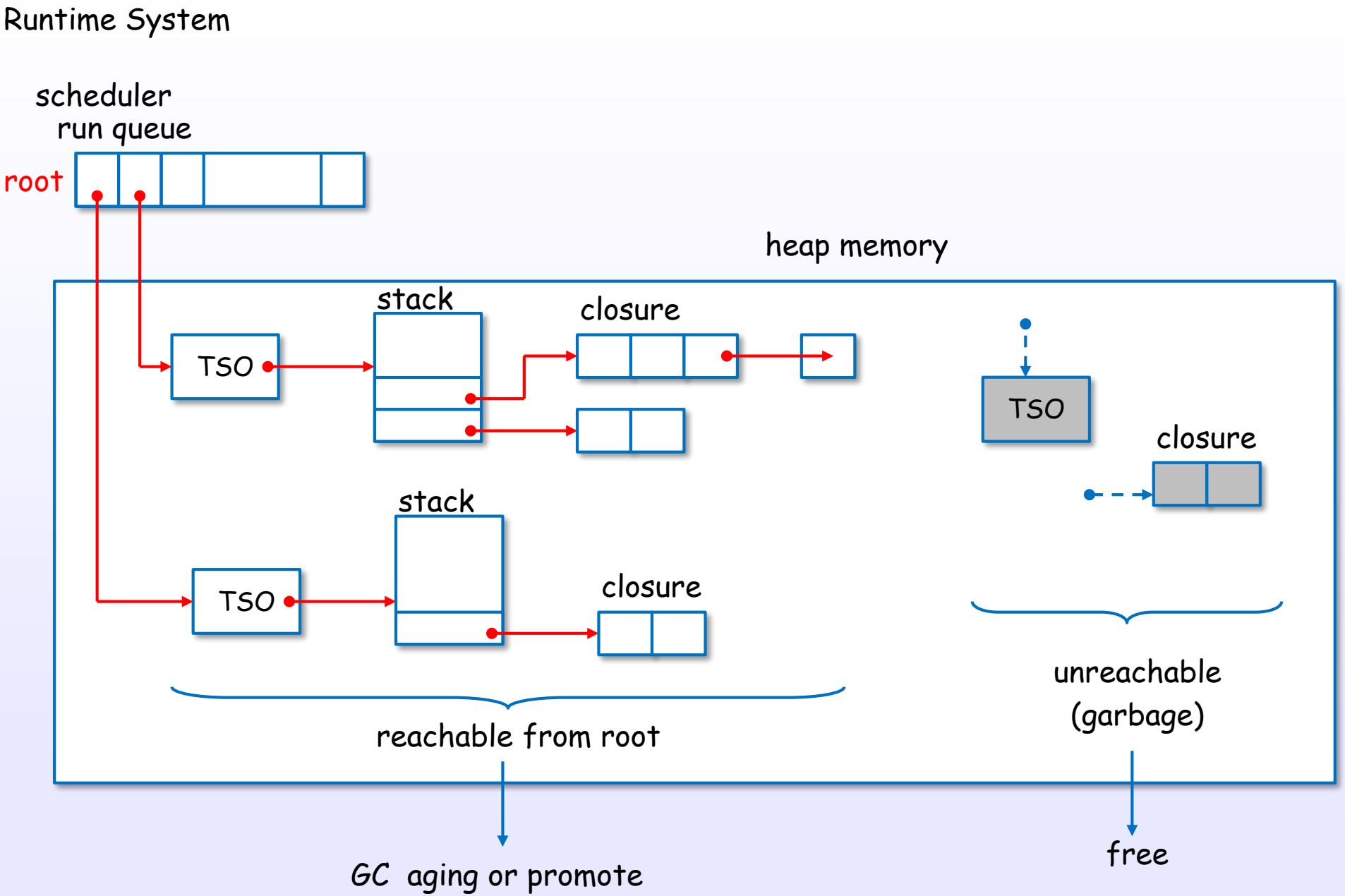
parallel GC for oldest generation (major GC)

"stop-the-world" GC




References : [8], [9], [15], [C13], [C11], [S25]

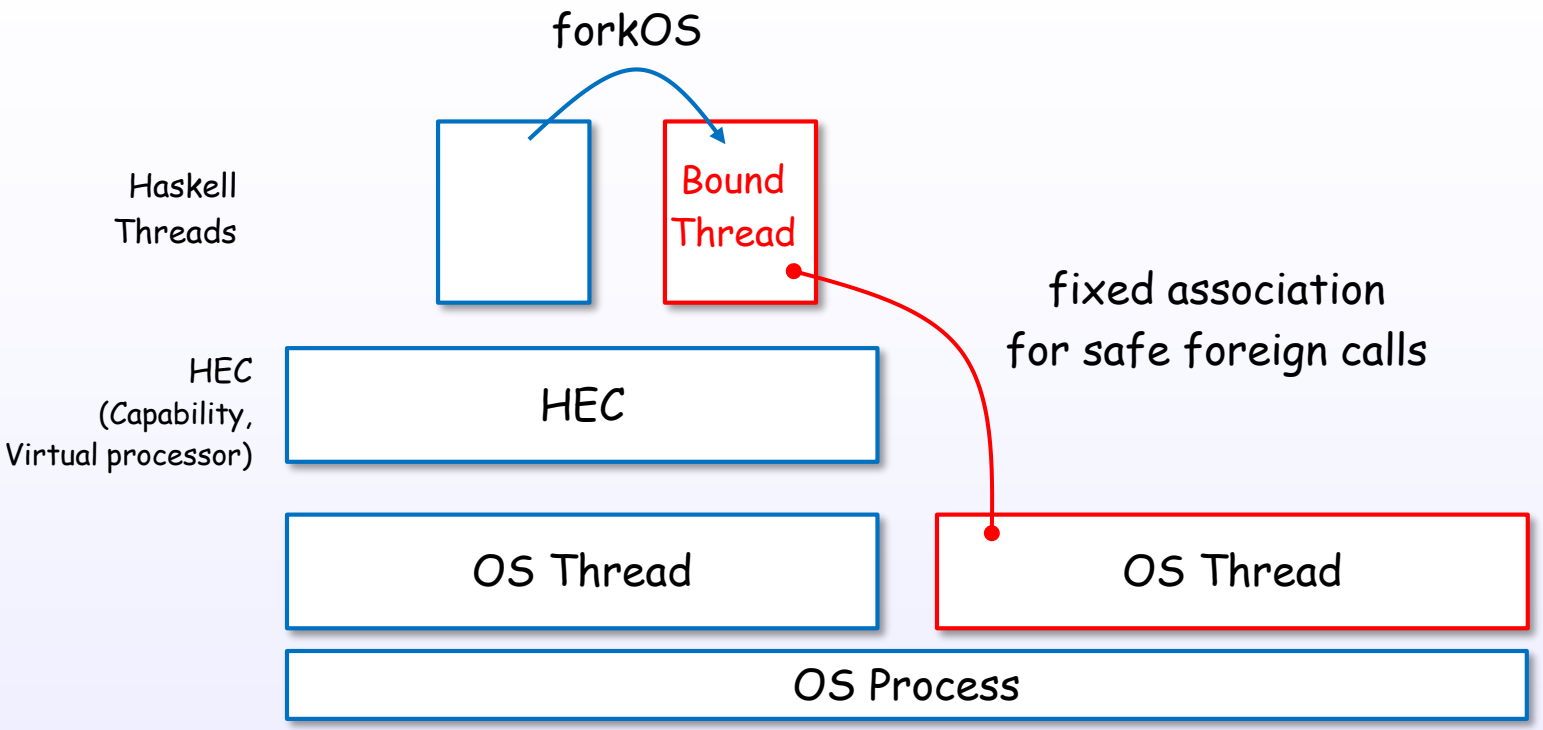
# GC discover live objects from the root




References : [8], [9], [15], [C13], [C11], [S25]

# Bound thread

# A bound thread has a fixed associated OS Thread

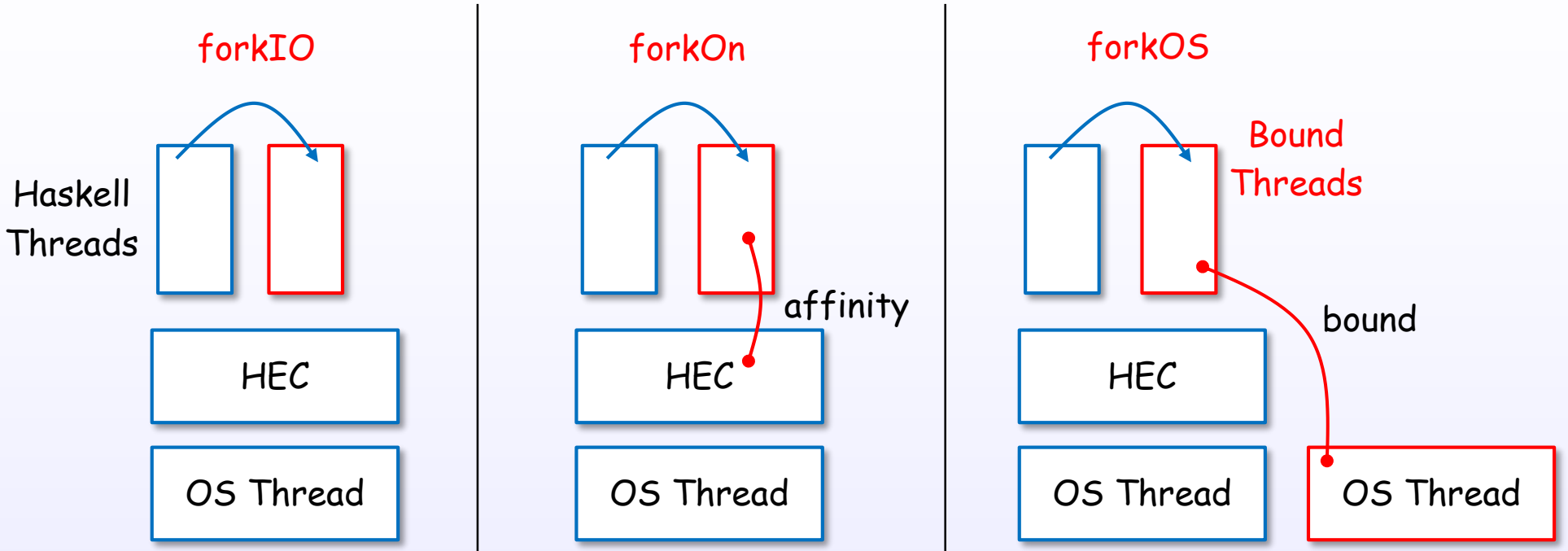



Foreign calls from a bound thread are all made by the same OS thread.
A bound thread is created using forkOS.

The main thread is bound thread.

References : [6], [5], [8], [9], [14], [C17], [19], [S17], [S16], [S23], [S22]

# forkIO, forkOn, forkOS




create a haskell unbound thread

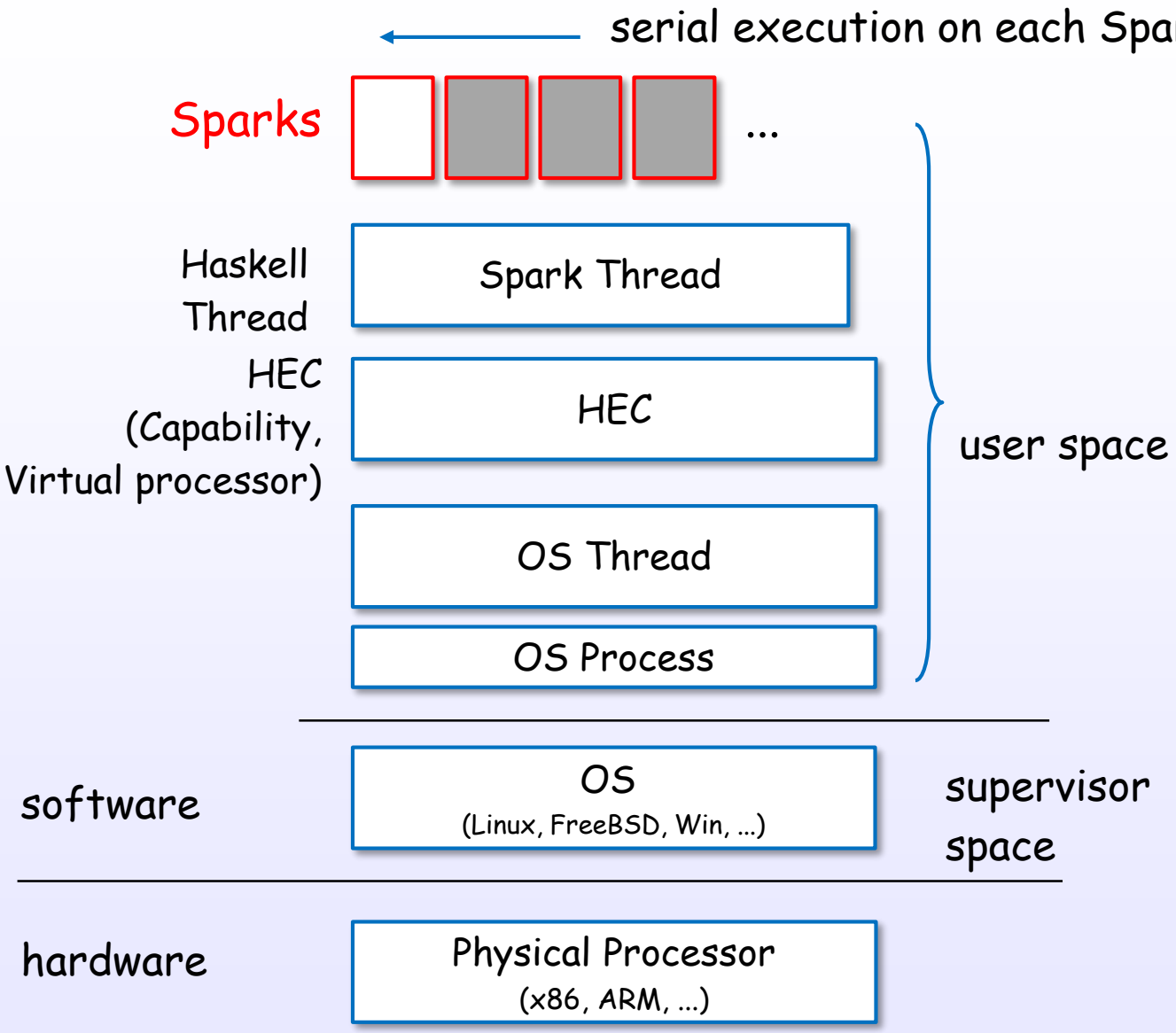
create a haskell unbound thread
on the specified HEC

create a haskell bound thread
and an OS thread

References : [6], [5], [8], [9], [14], [C17], [19], [S17], [S16], [S23], [S22]

# Spark

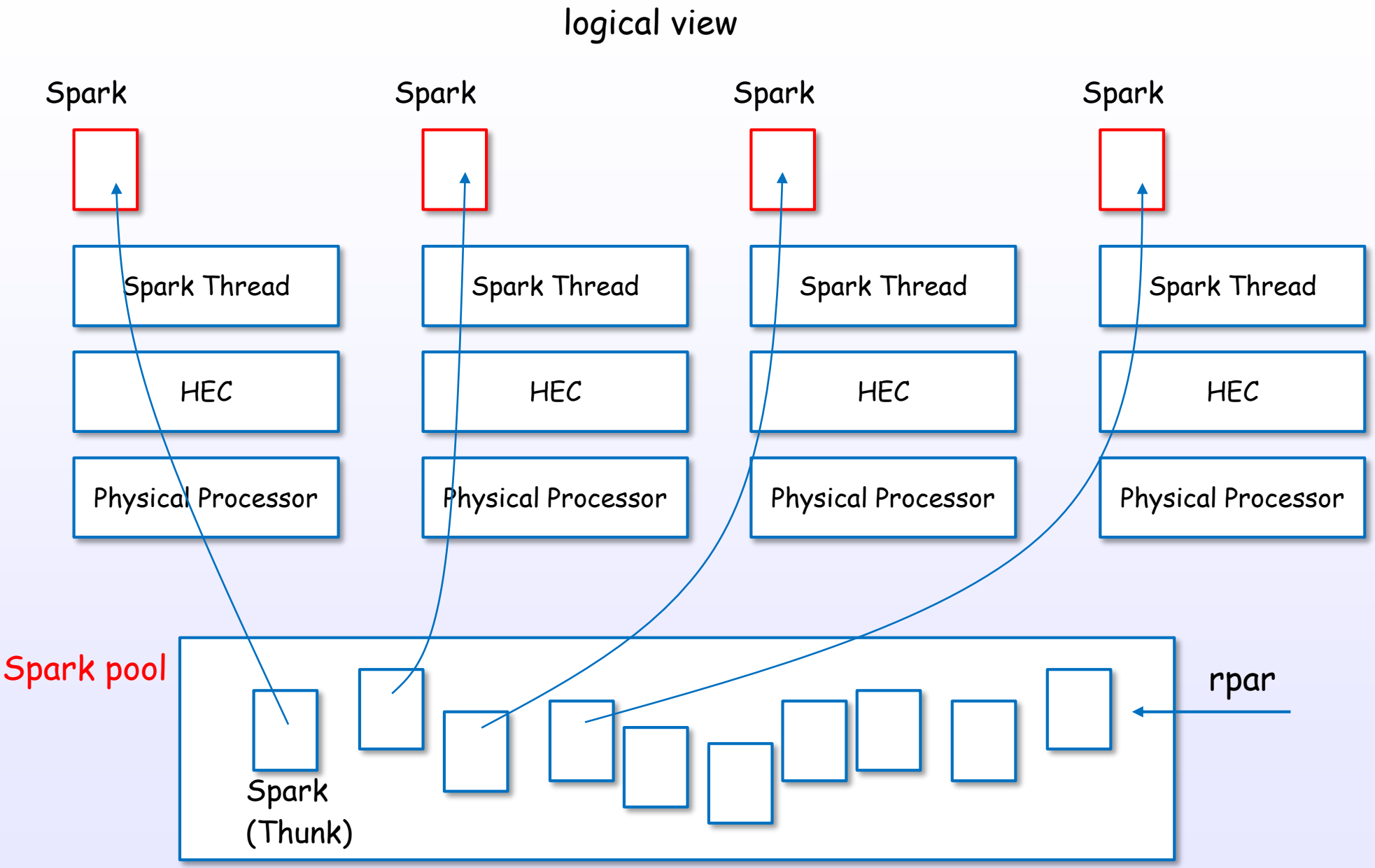
# Spark layer




Spark Threads are generated on idle HECs.

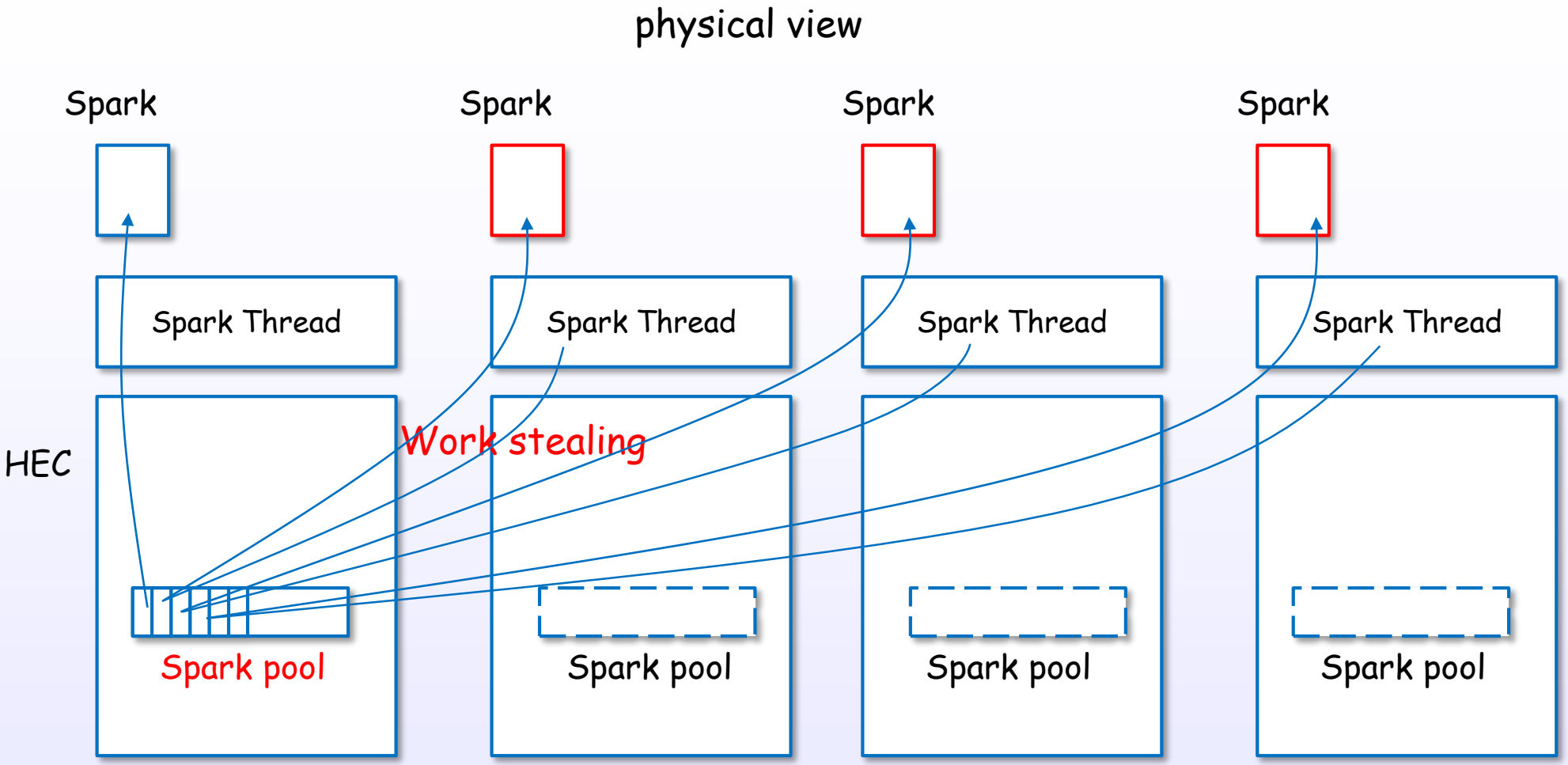
References : [C17], [19], [S17], [S26], [S27], [S33], [S12]

# Sparks and Spark pool



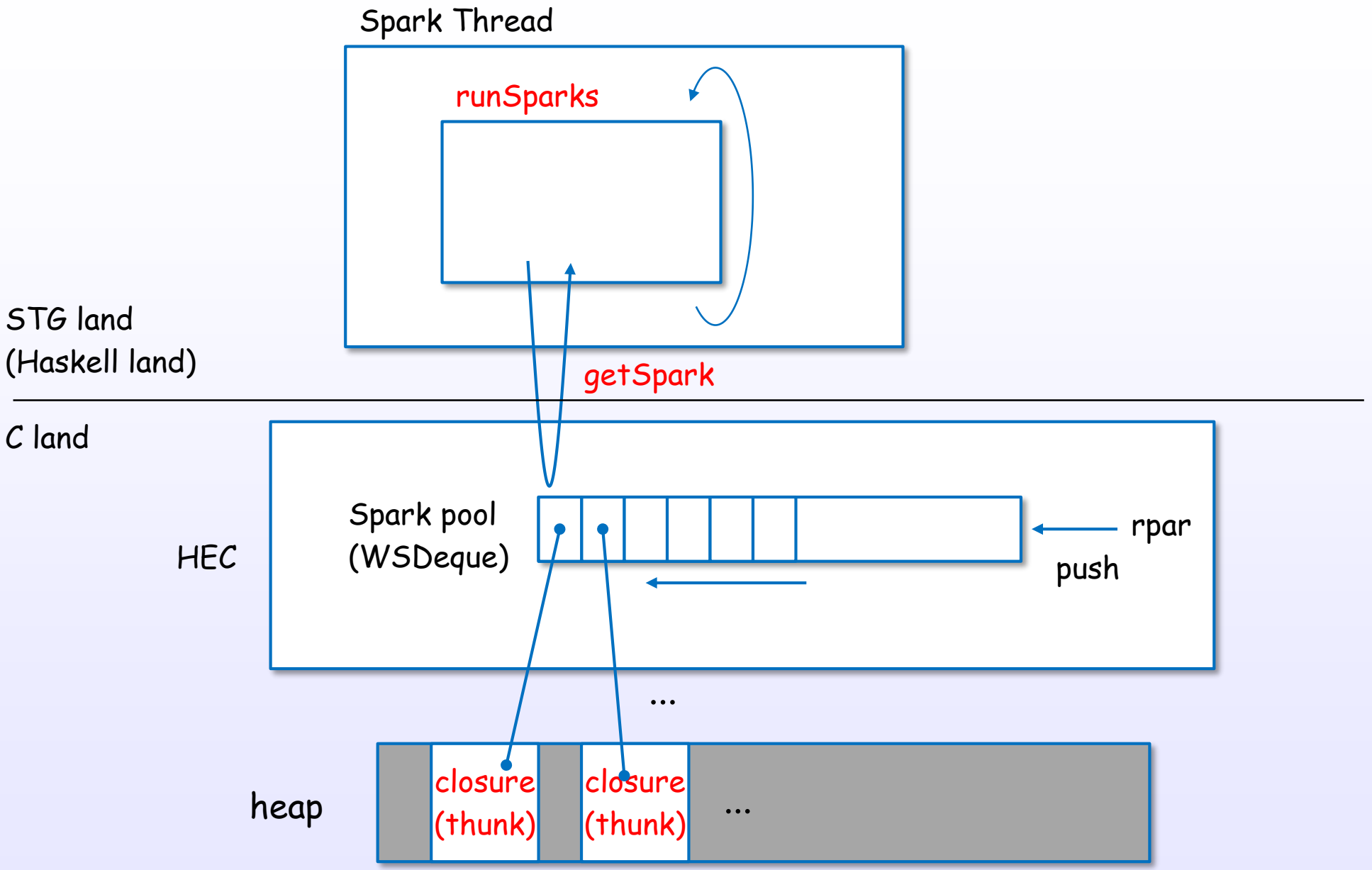

References : [C17], [19], [S17], [S26], [S27], [S33], [S12]

# Spark pool and work stealing




References : [C17], [19], [S17], [S26], [S27], [S33], [S12]

# Sparks and closures

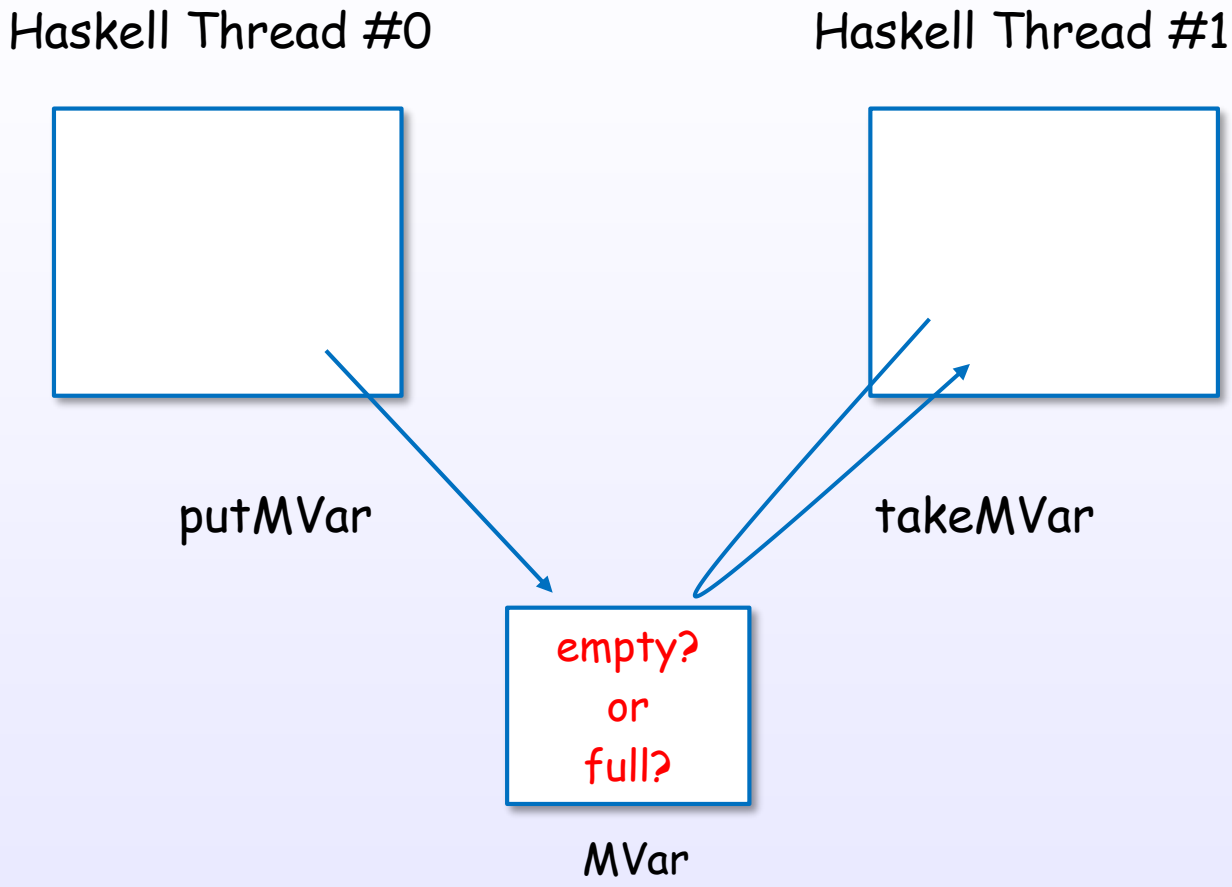



(not TSO objects, but closures. therefore very lightweight)

References : [C17], [19], [S17], [S26], [S27], [S33], [S12]

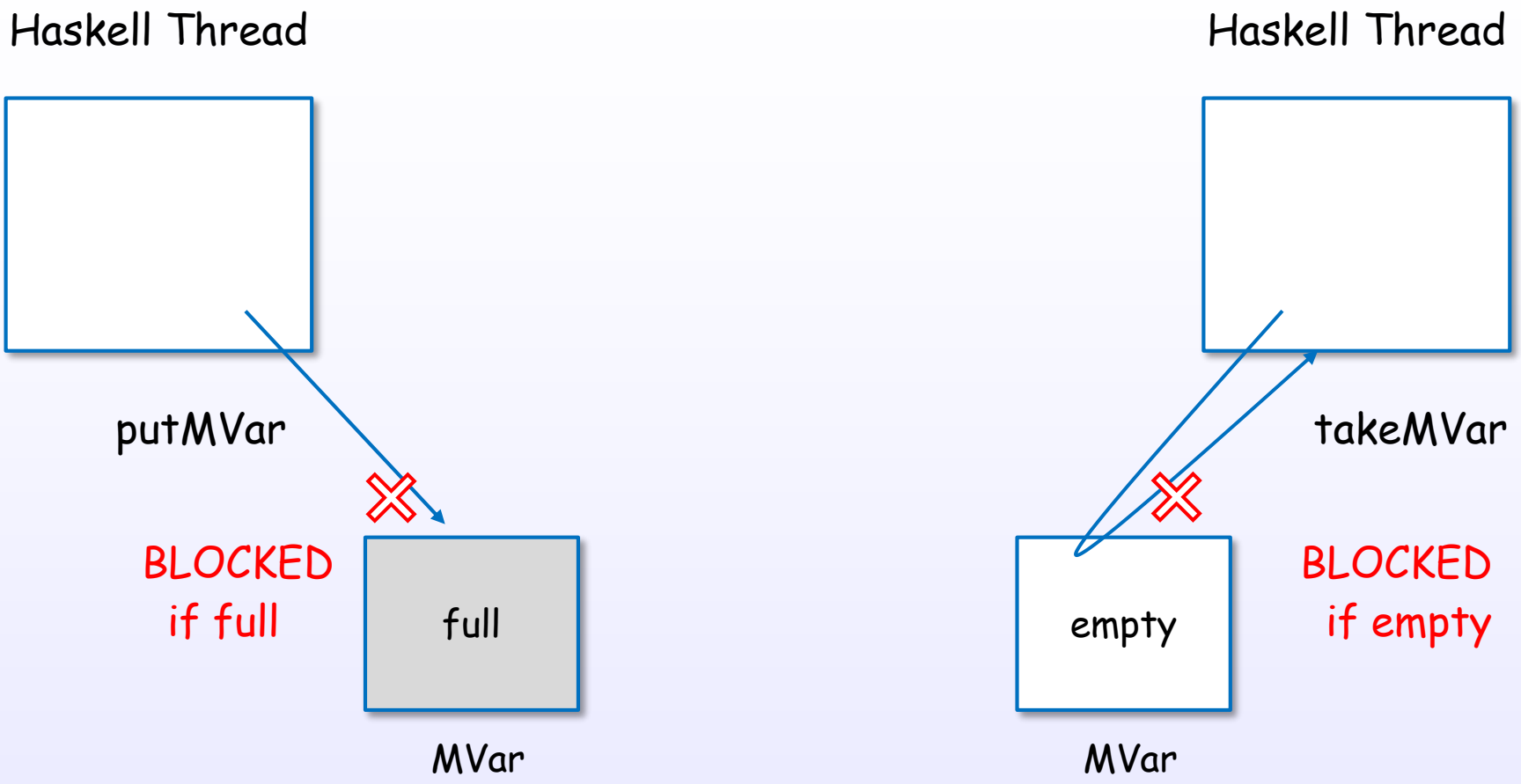
# MVar

# MVar



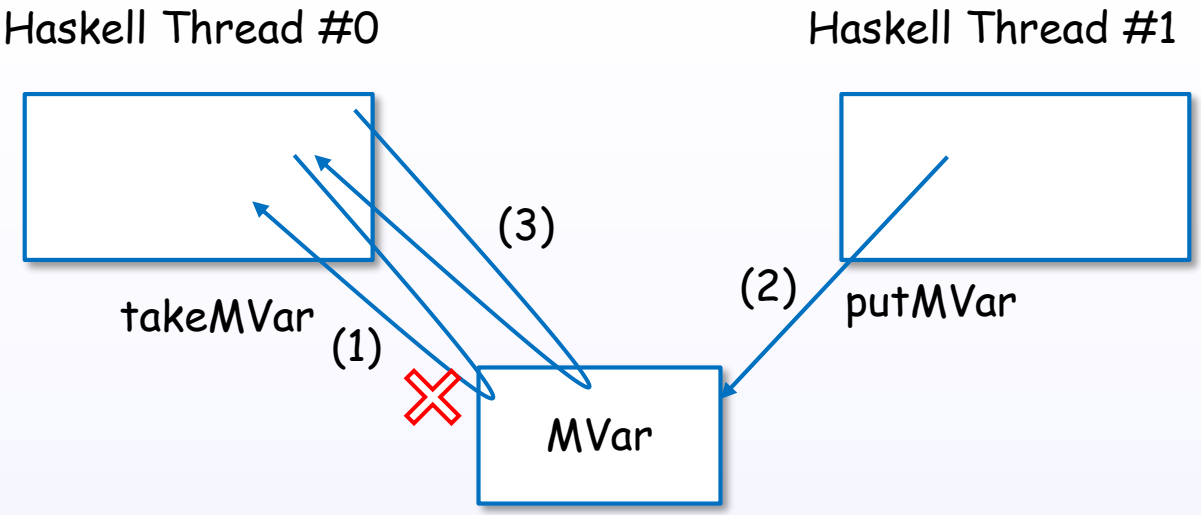

References : [16], [18], [19], [S31], [S12]

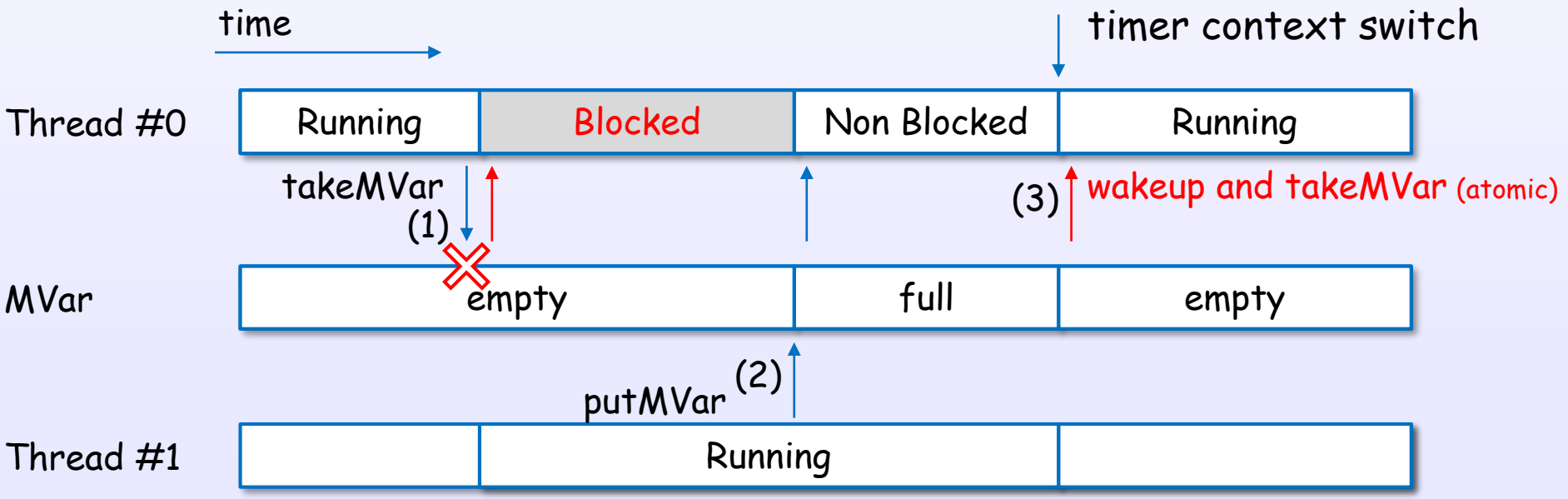
# MVar and blocking




References : [16], [18], [19], [S31], [S12]

# MVar example




* single core case

References : [16], [18], [19], [S31], [S12]

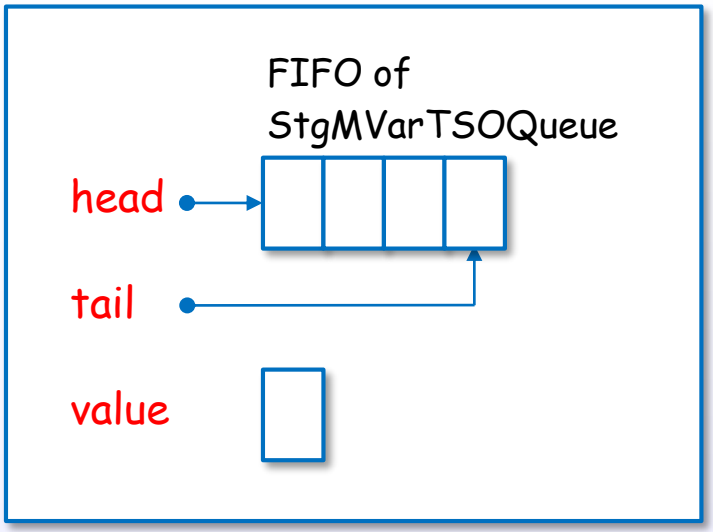
# MVar object view

User view

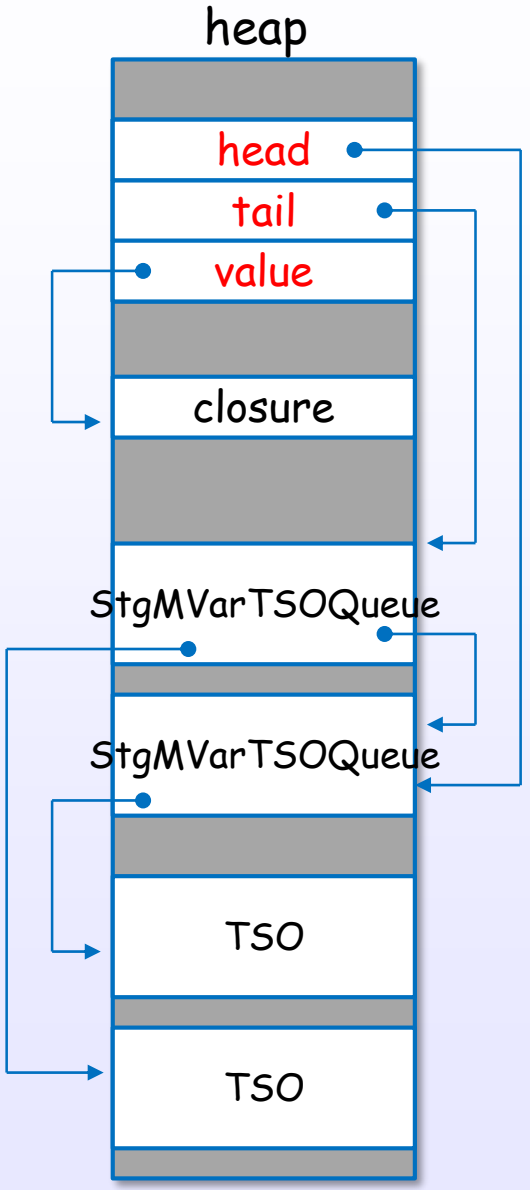
MVar

empty?
or
full?

logical MVar object

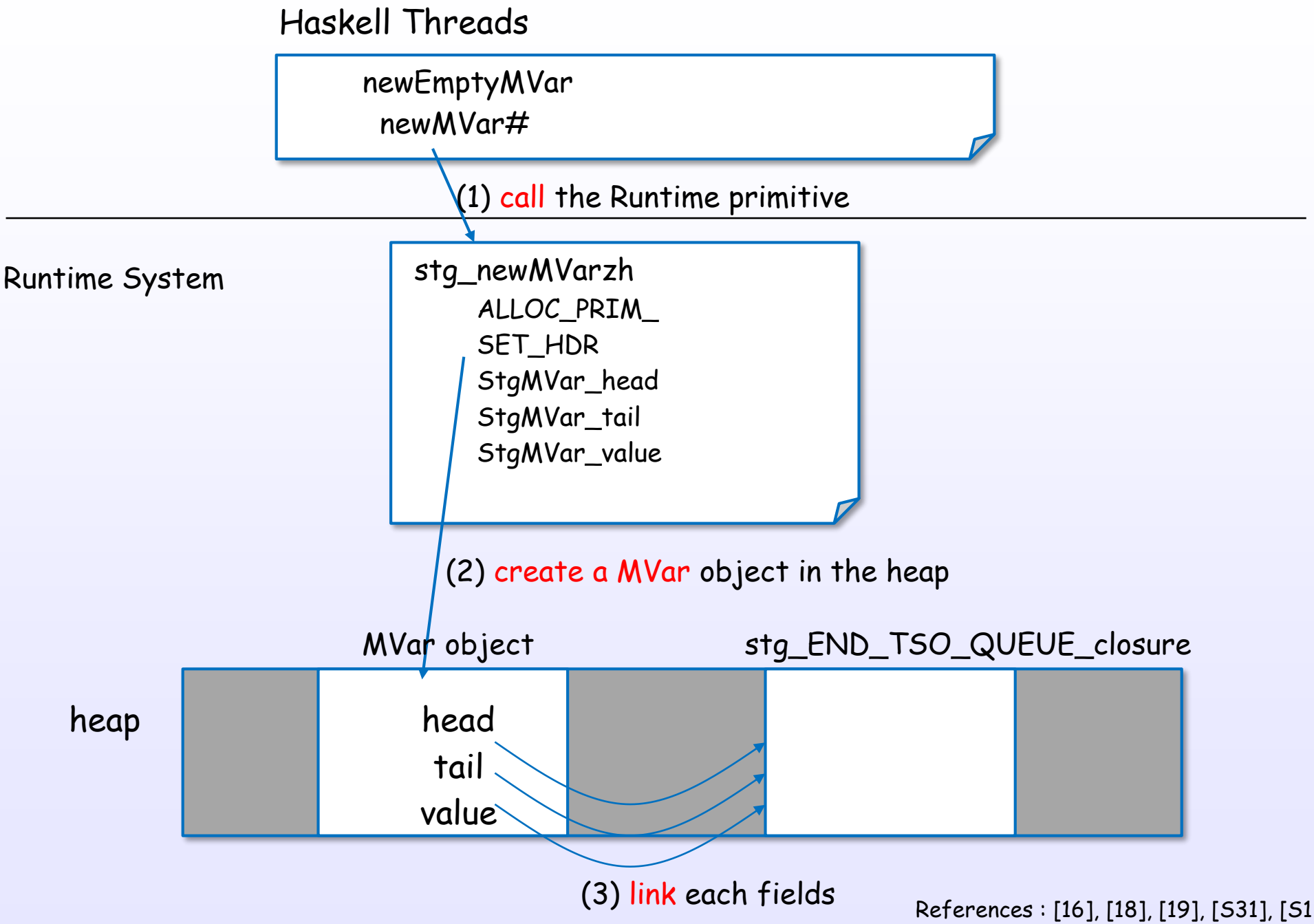



physical MVar object



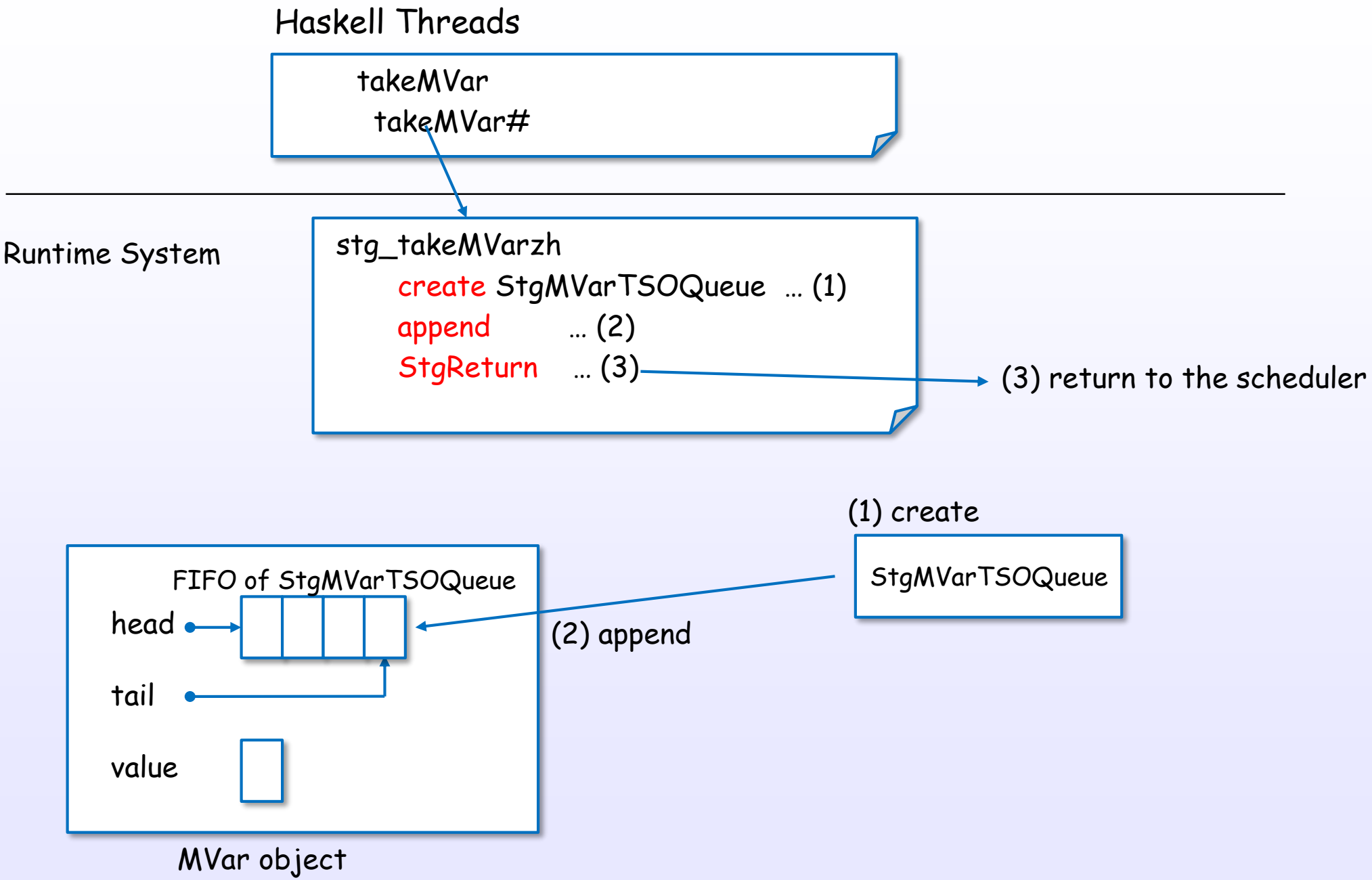

References : [16], [18], [19], [S31], [S12]

# newEmptyMVar




References : [16], [18], [19], [S31], [S12]

# takeMVar (empty case)




References : [16], [18], [19], [S31], [S12]

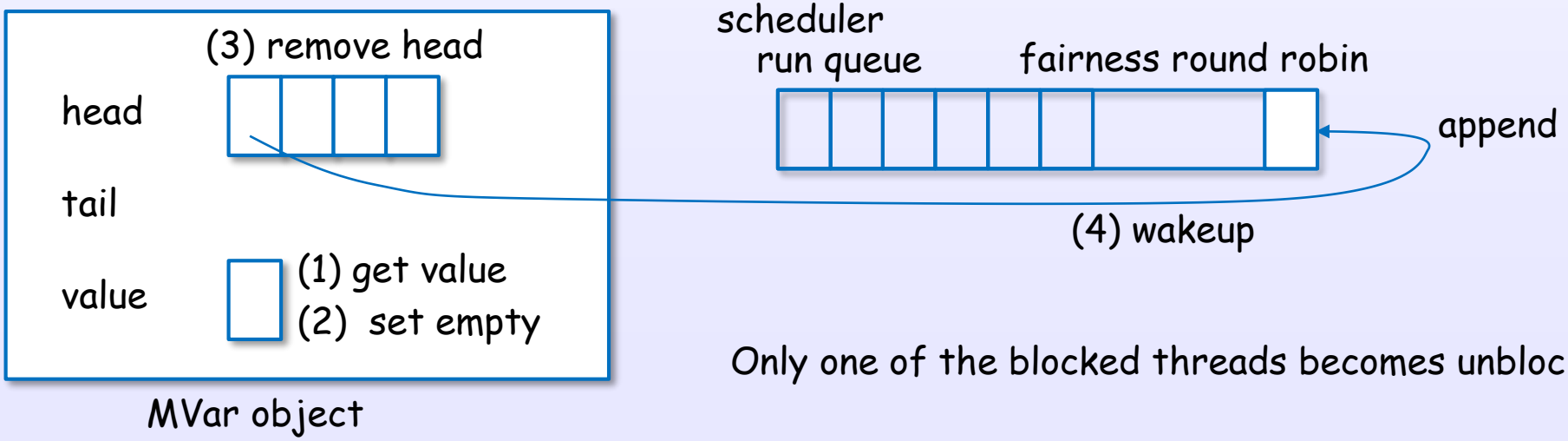
# takeMVar (full case)

Haskell Threads

takeMVar
takeMVar#

Runtime System

stg_takeMVarzh
(1) get value
(2) set empty
(3) remove head
(4) tryWakeupThread



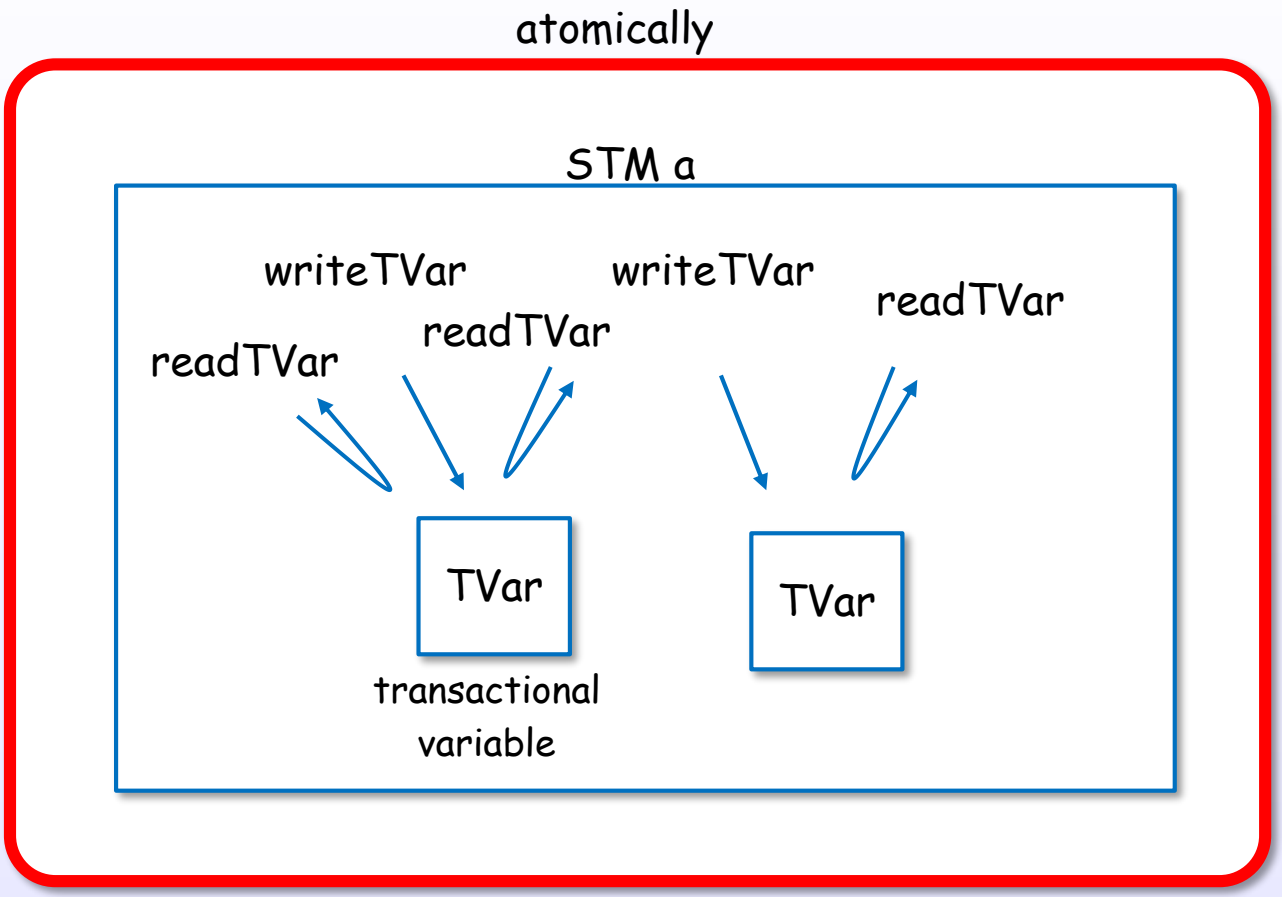

Only one of the blocked threads becomes unblocked.

References : [16], [18], [19], [S31], [S12]

# Software transactional memory

# Create a atomic block using atomically

```
atomically :: STM a -> IO a
```

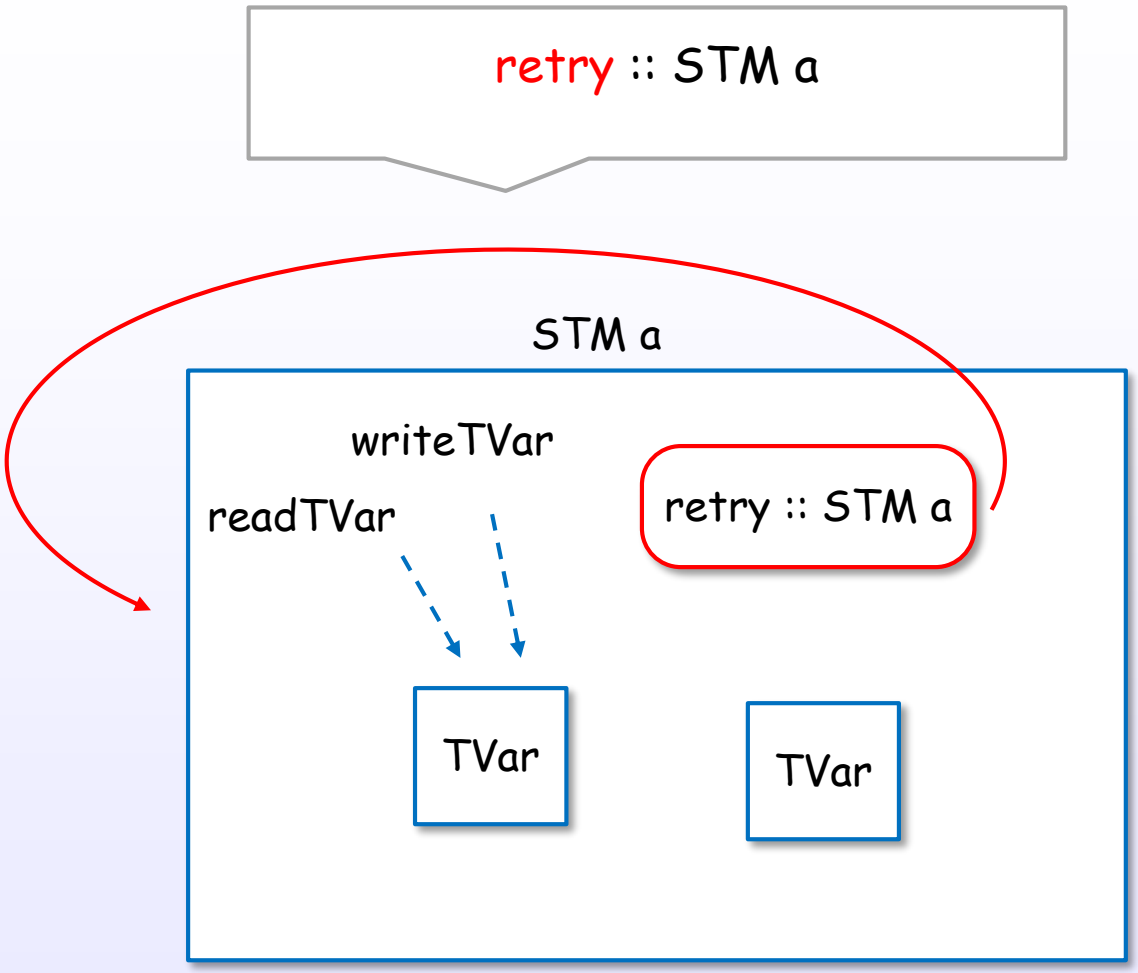



Create and evaluate a composable "atomic block"

Atomic block = All or Nothing

References : [17], [19], [20], [C18], [S12], [S28]

# Rollback and blocking control using retry

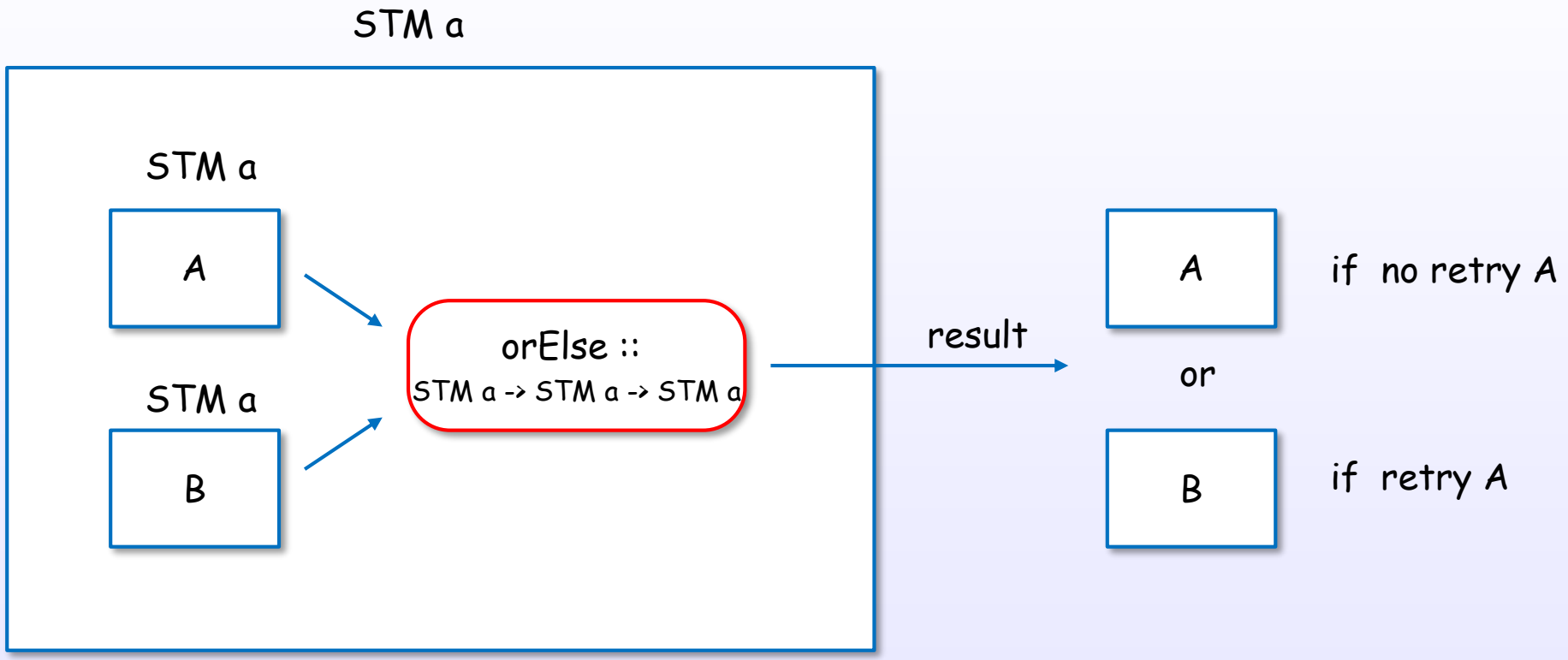



Discard, blocking and try again

References : [17], [19], [20], [C18], [S12], [S28]

# Compose OR case using orElse

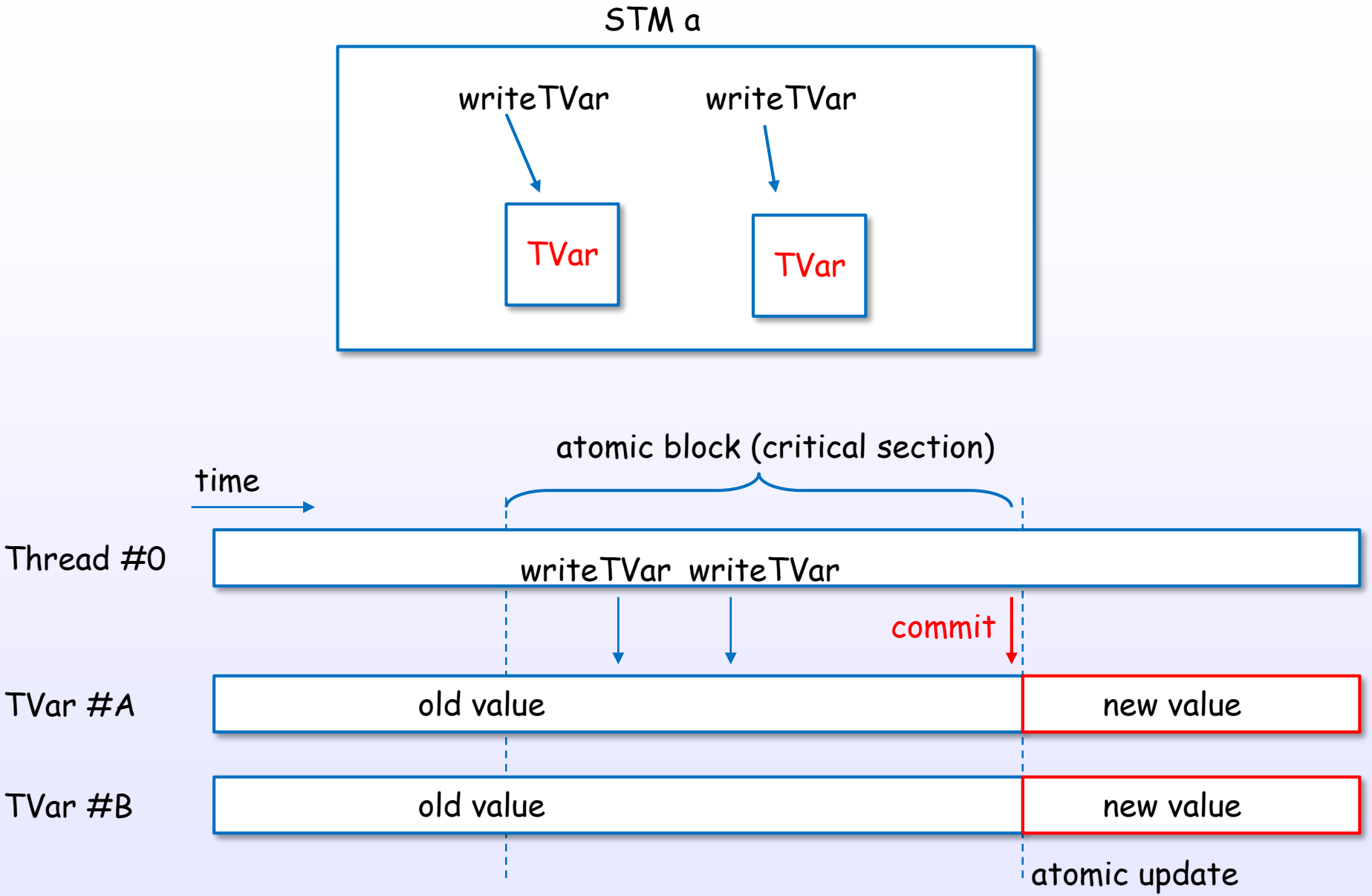
```
orElse :: STM a -> STM a -> STM a
```




A or B or Nothing

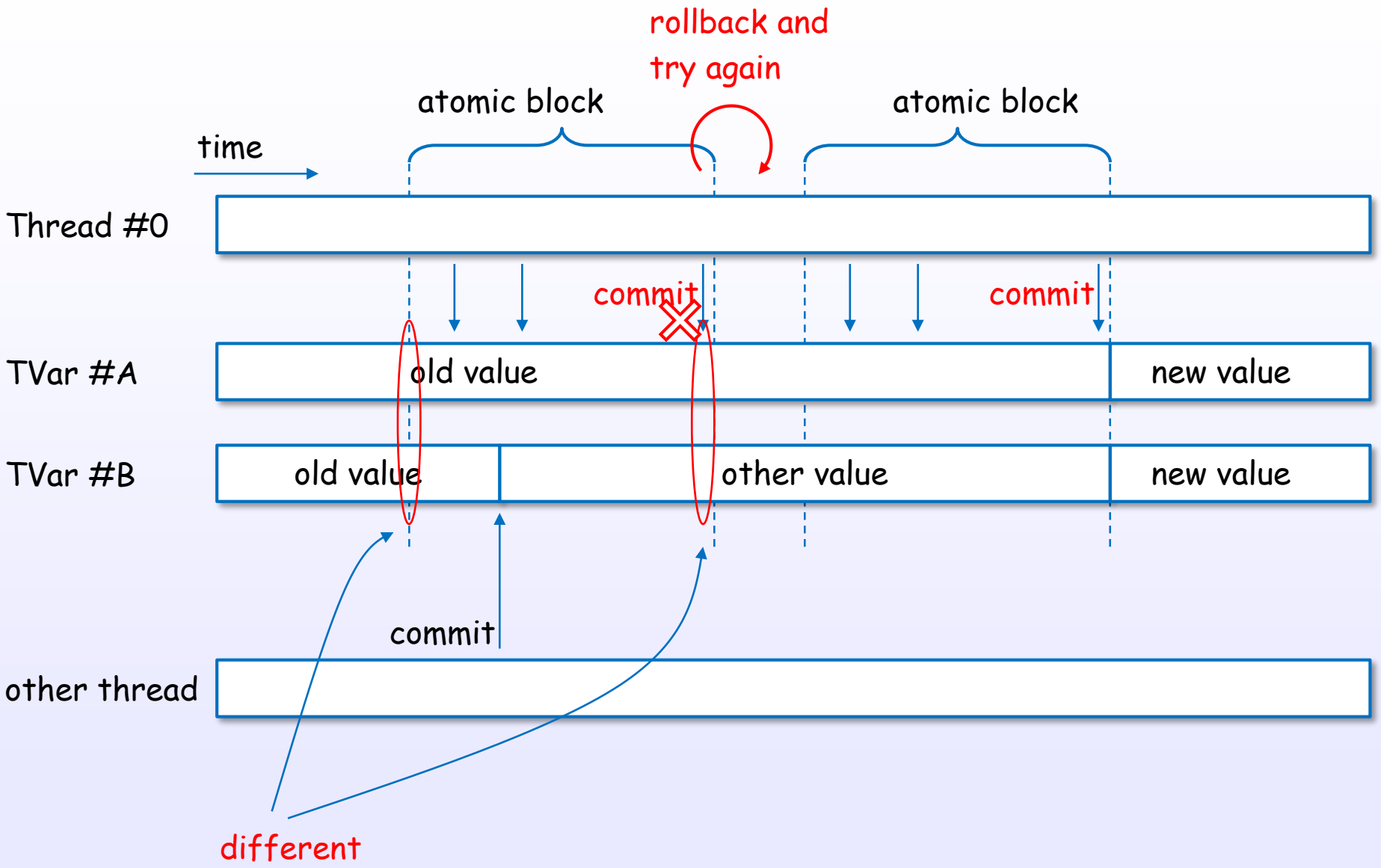
References : [17], [19], [20], [C18], [S12], [S28]

# STM, TVar example (normal case)



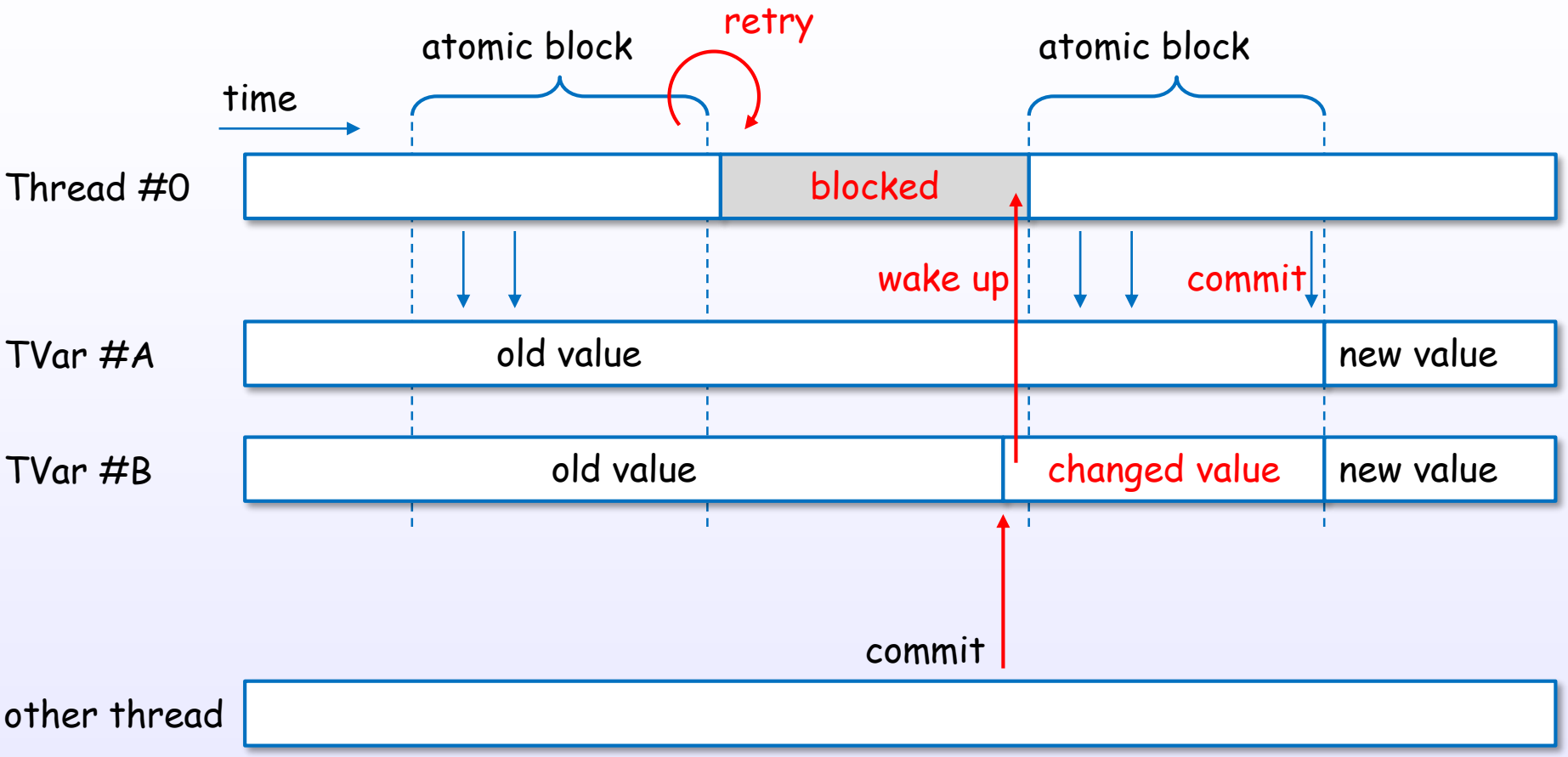

References : [17], [19], [20], [C18], [S12], [S28]

# STM, TVar example (conflict case)



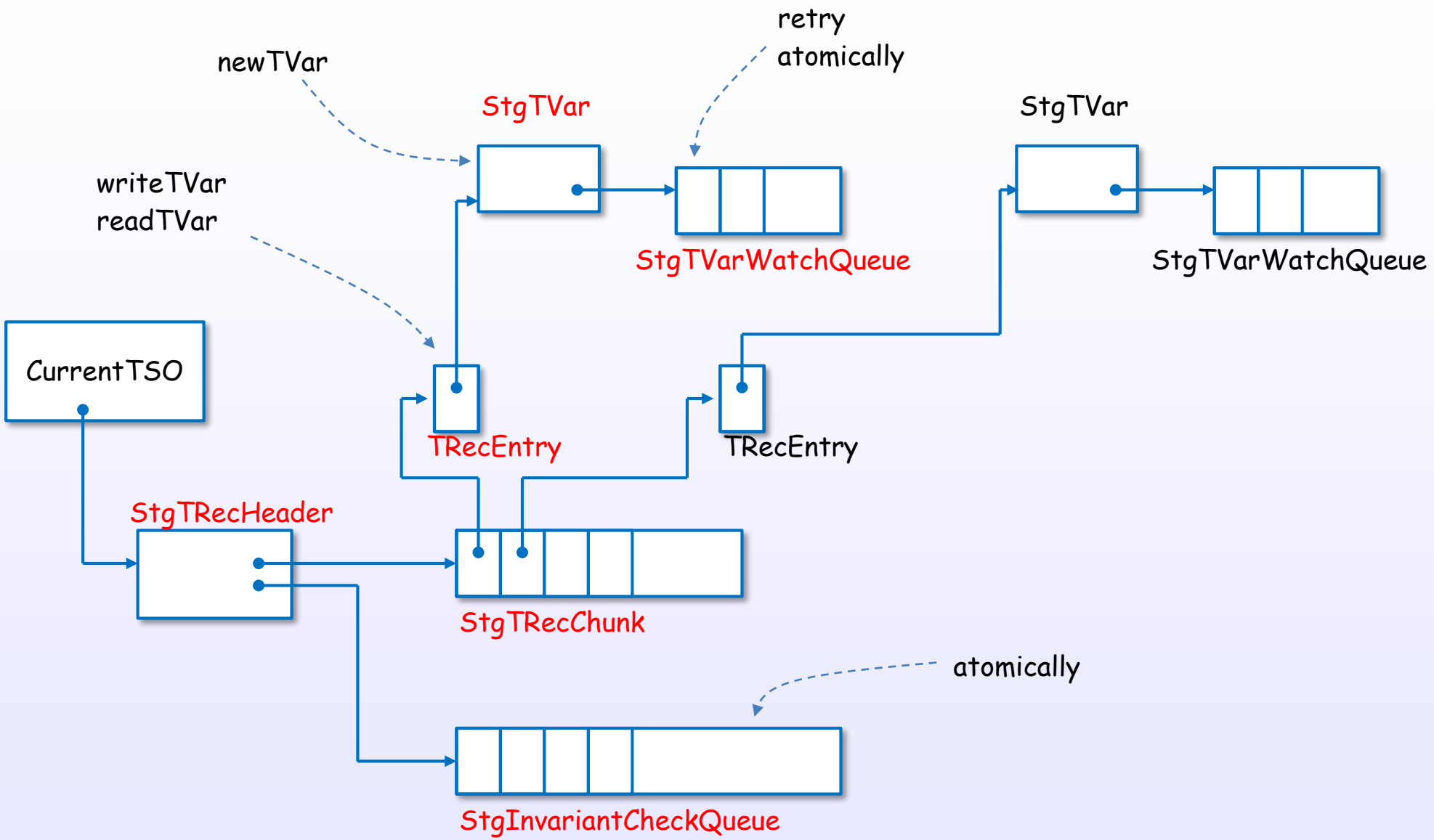

References : [17], [19], [20], [C18], [S12], [S28]

# retry example



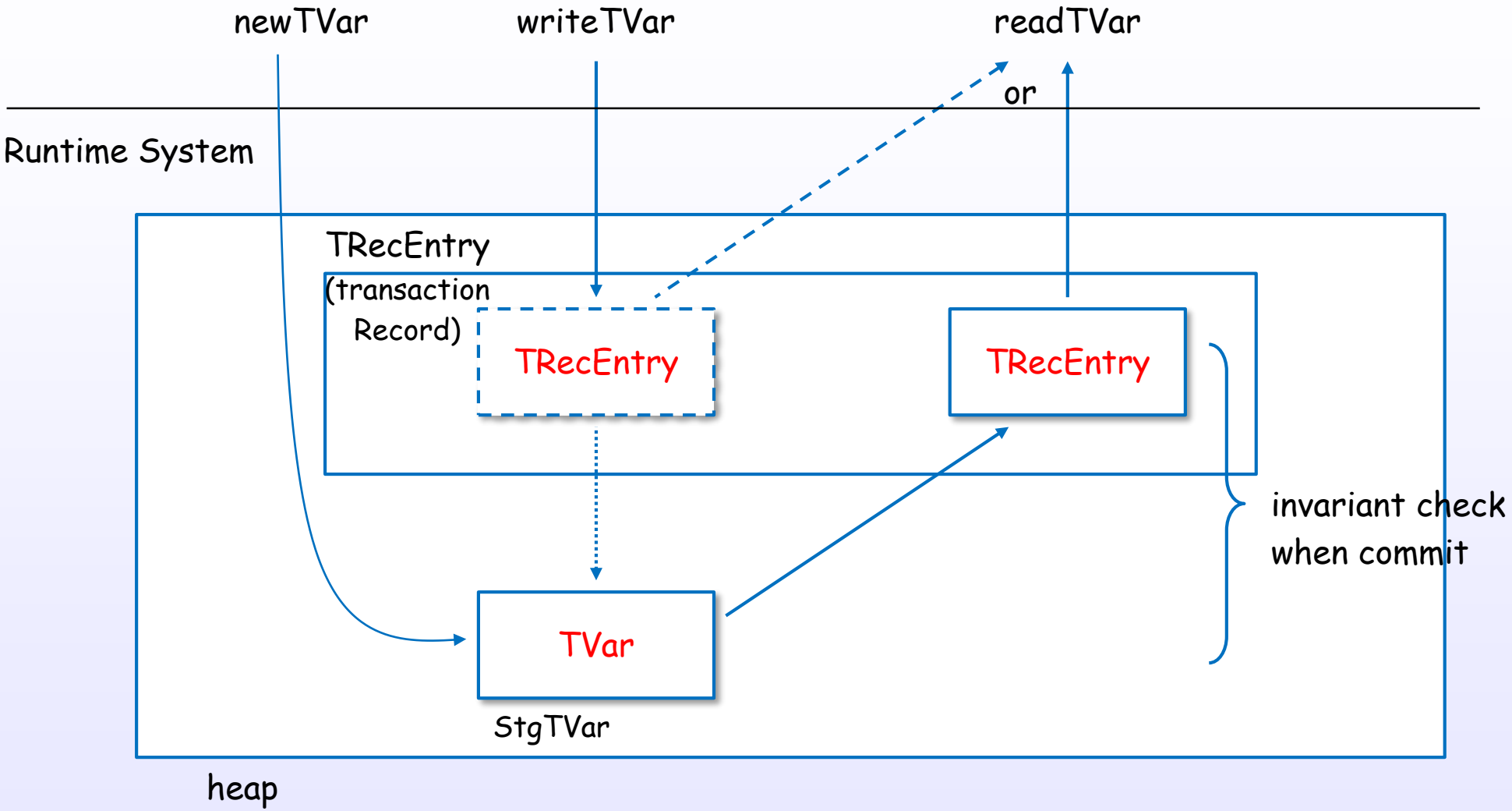

References : [17], [19], [20], [C18], [S12], [S28]

# STM, TVar data structure



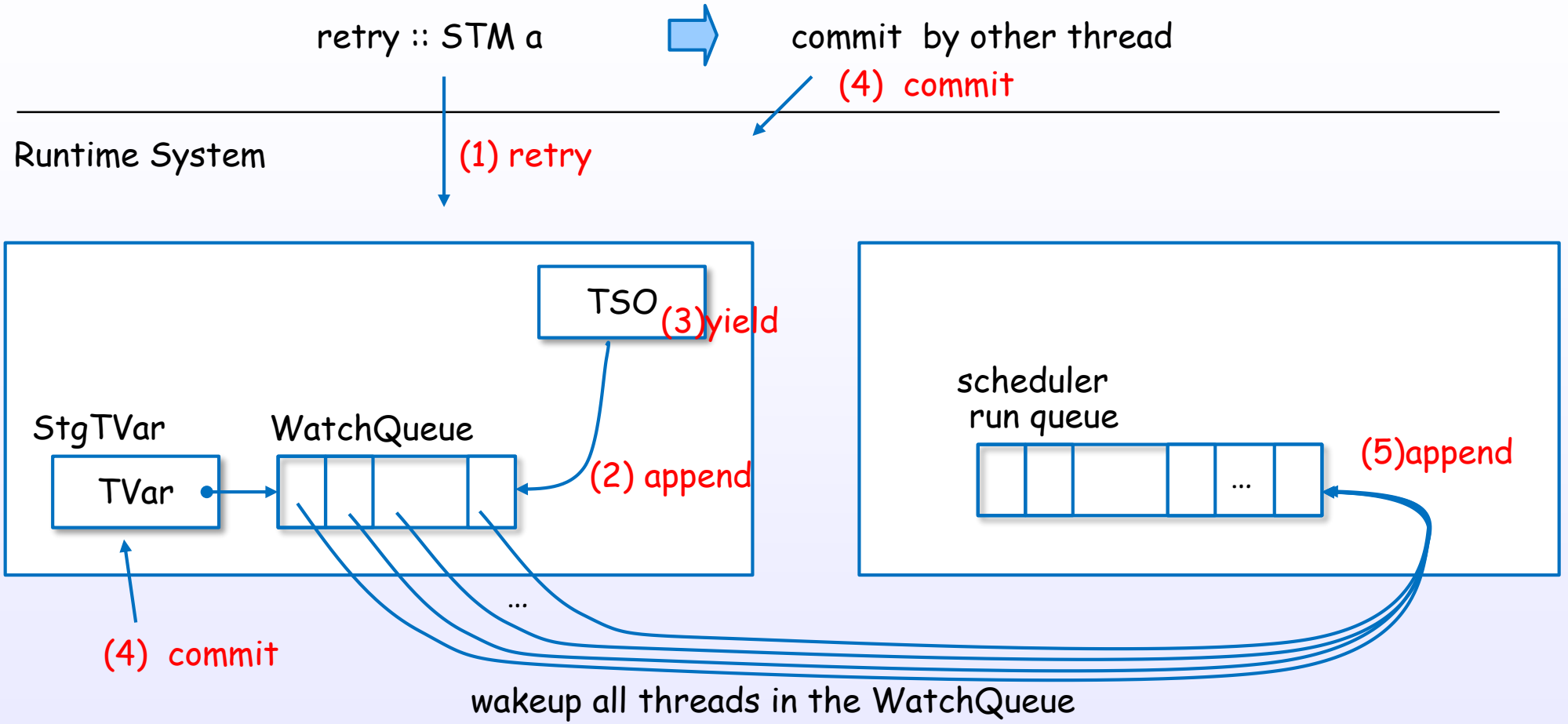

References : [17], [19], [20], [C18], [S12], [S28]

# newTVar, writeTVar, readTVar




References : [17], [19], [20], [C18], [S12], [S28]

# block by retry, wake up by commit

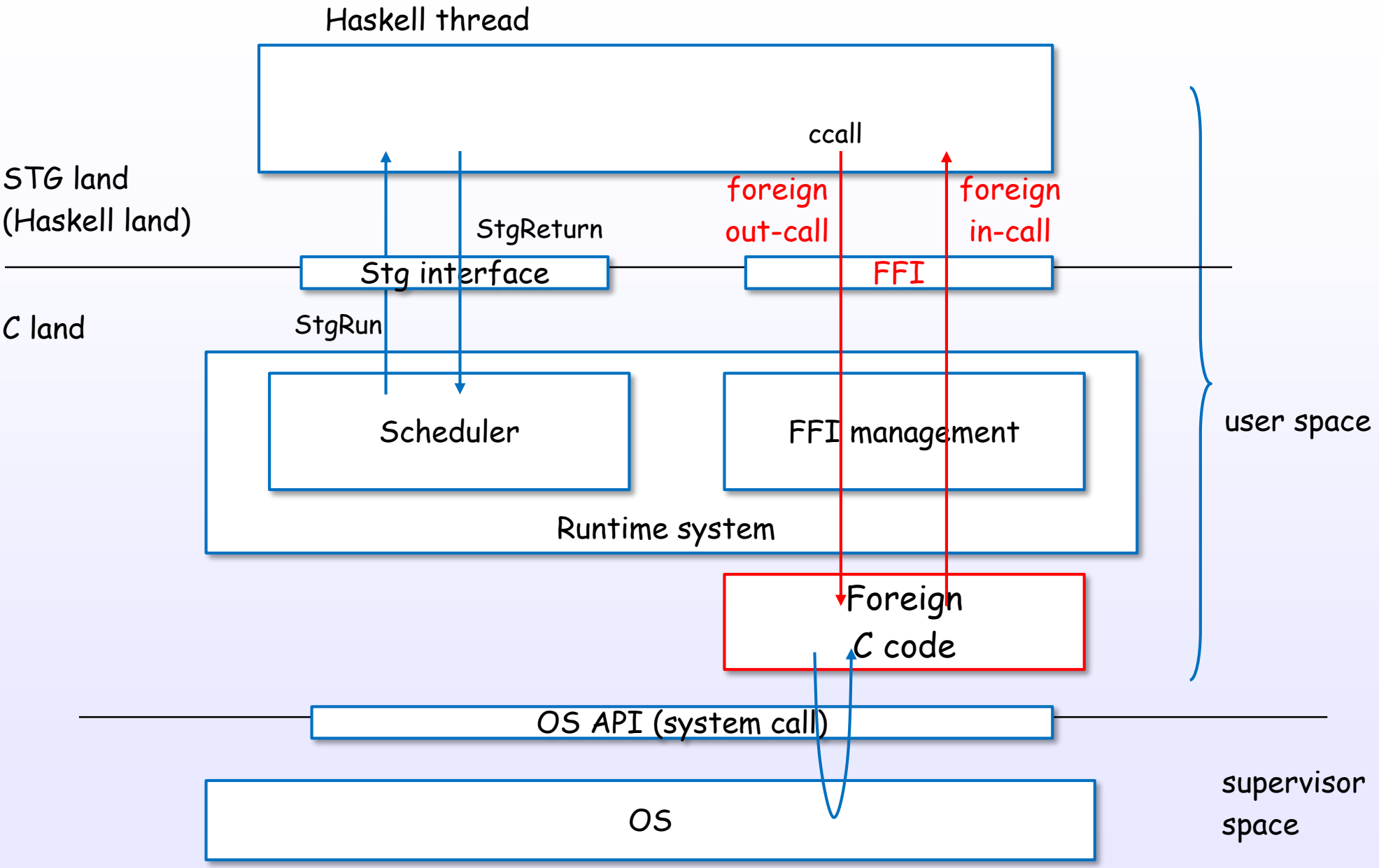



no guarantee of fairness,
because the RTS has to run all the blocked transaction.

References : [17], [19], [20], [C18], [S12], [S28]

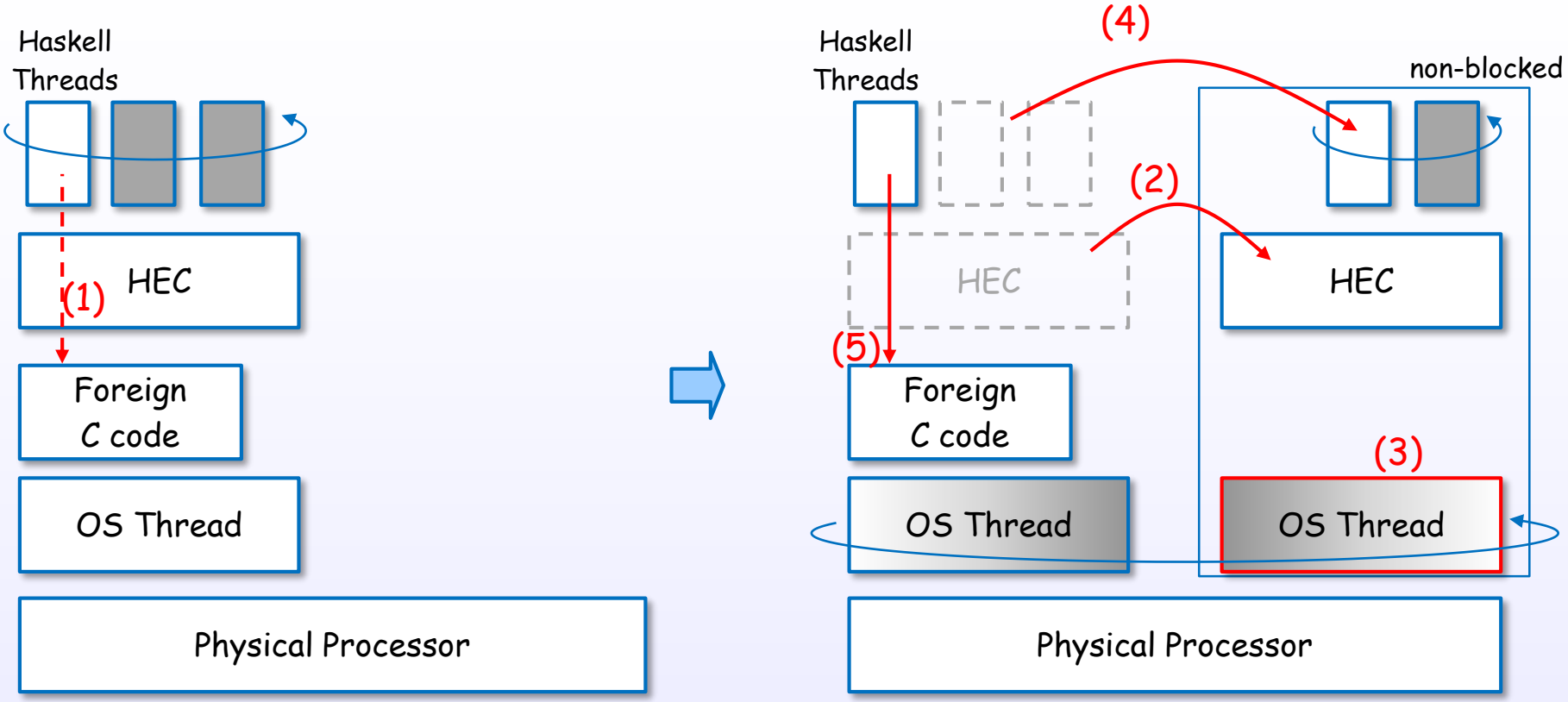
# FFI

# FFI (Foreign Function Interface)




References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

# FFI and OS Threads




(1) a safe foreign call (FFI)

(2) move the HEC to other OS thread

(3) spawn or draw an OS thread

(4) move Haskell threads

(5) call the foreign C code

References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

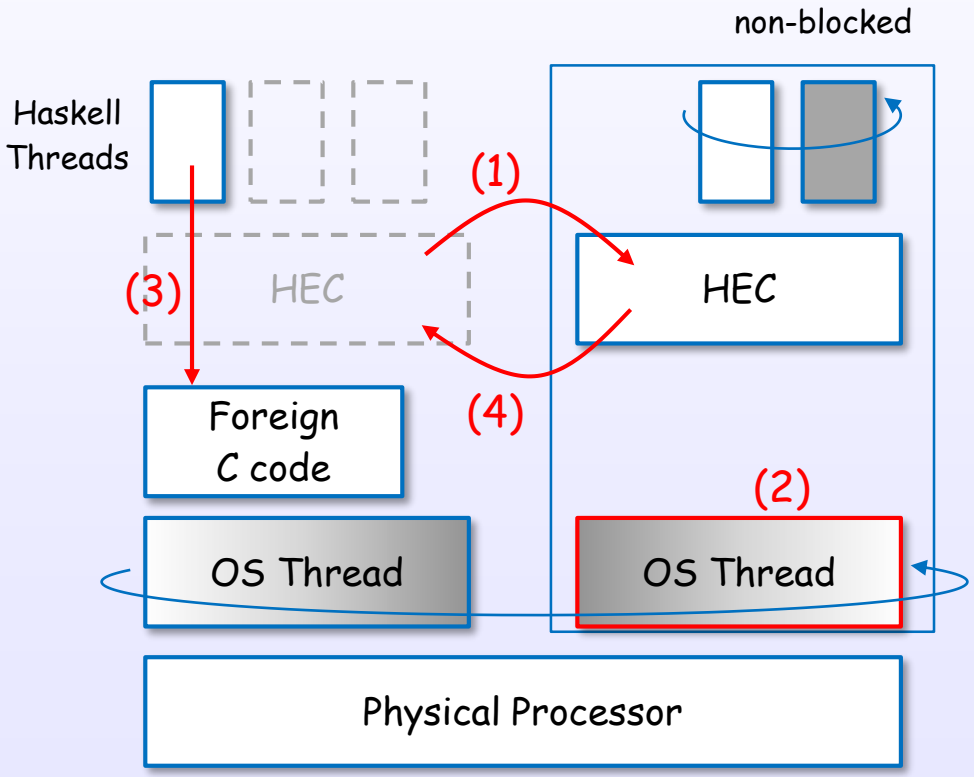
# A safe foreign call (code)

Haskell Threads

```
ccall suspendThread
ccall FOREIGN_C_CODE   ... (3)
ccall resumeThread
```

```
releaseCapability_
    giveCapabilityToTask   ... (1)
    startWorkerTask
        createOSThread     ... (2)
```

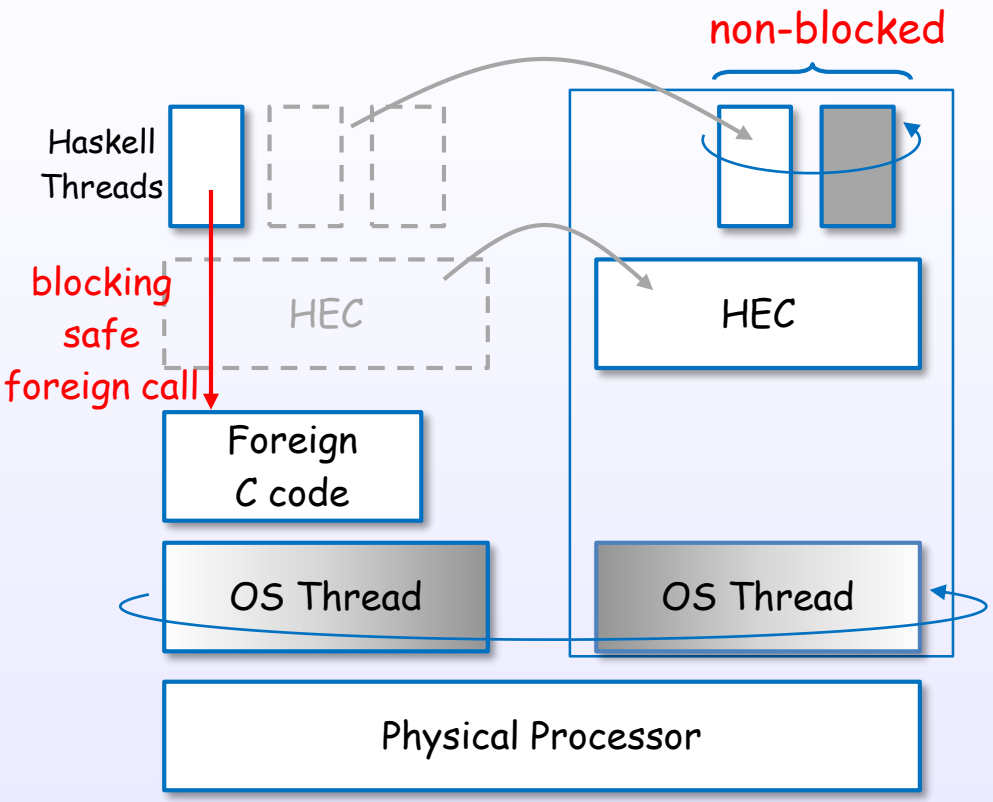
```
waitForReturnCapability   ... (4)
```



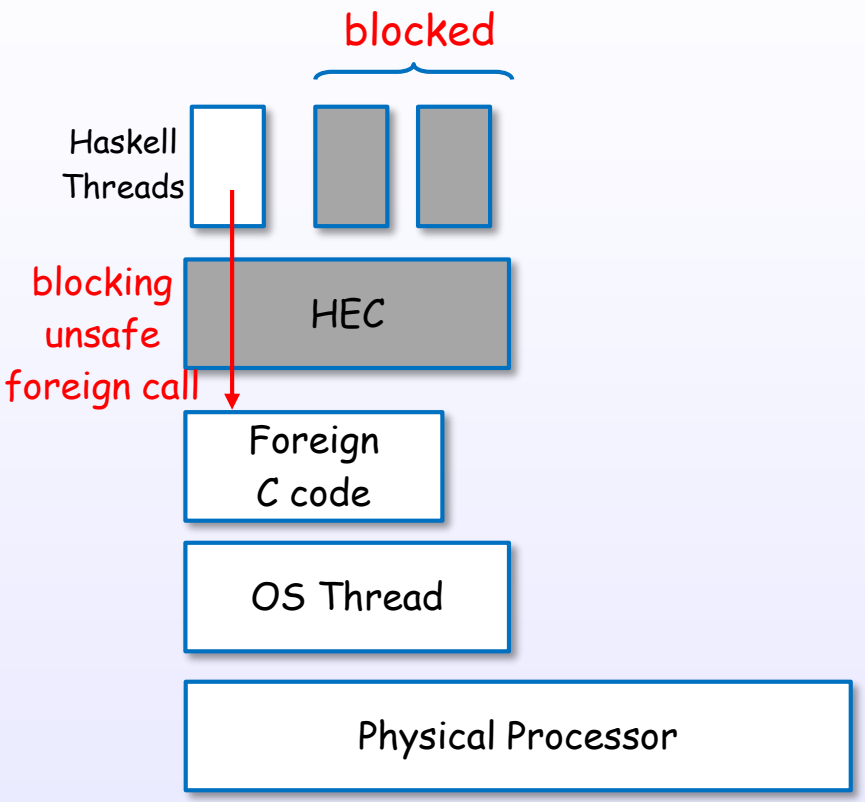

References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

# a safe and an unsafe foreign call

a safe foreign call



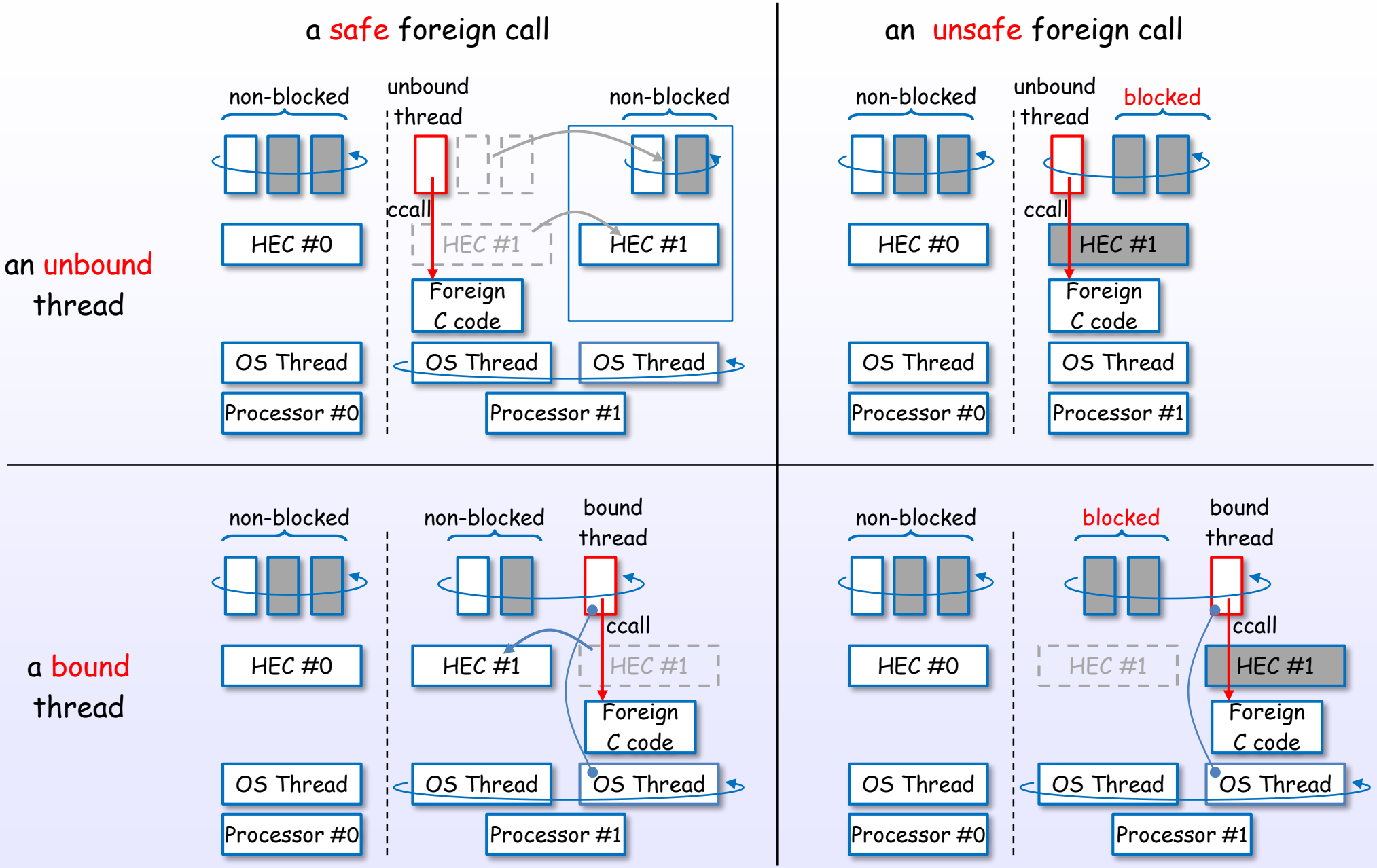

an unsafe foreign call




faster,
but blocking to the other Haskell threads

References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

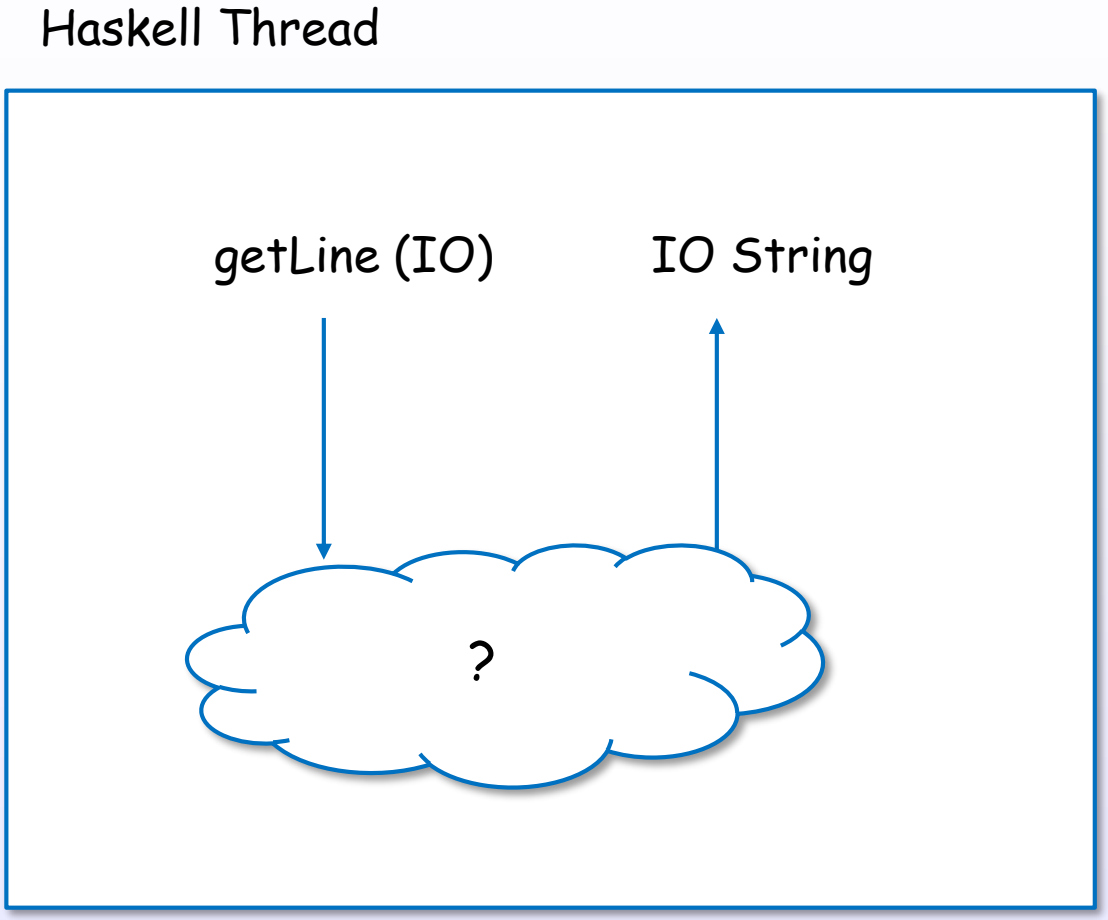
# Safe/unsafe foreign call and bound/unbound thread




References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

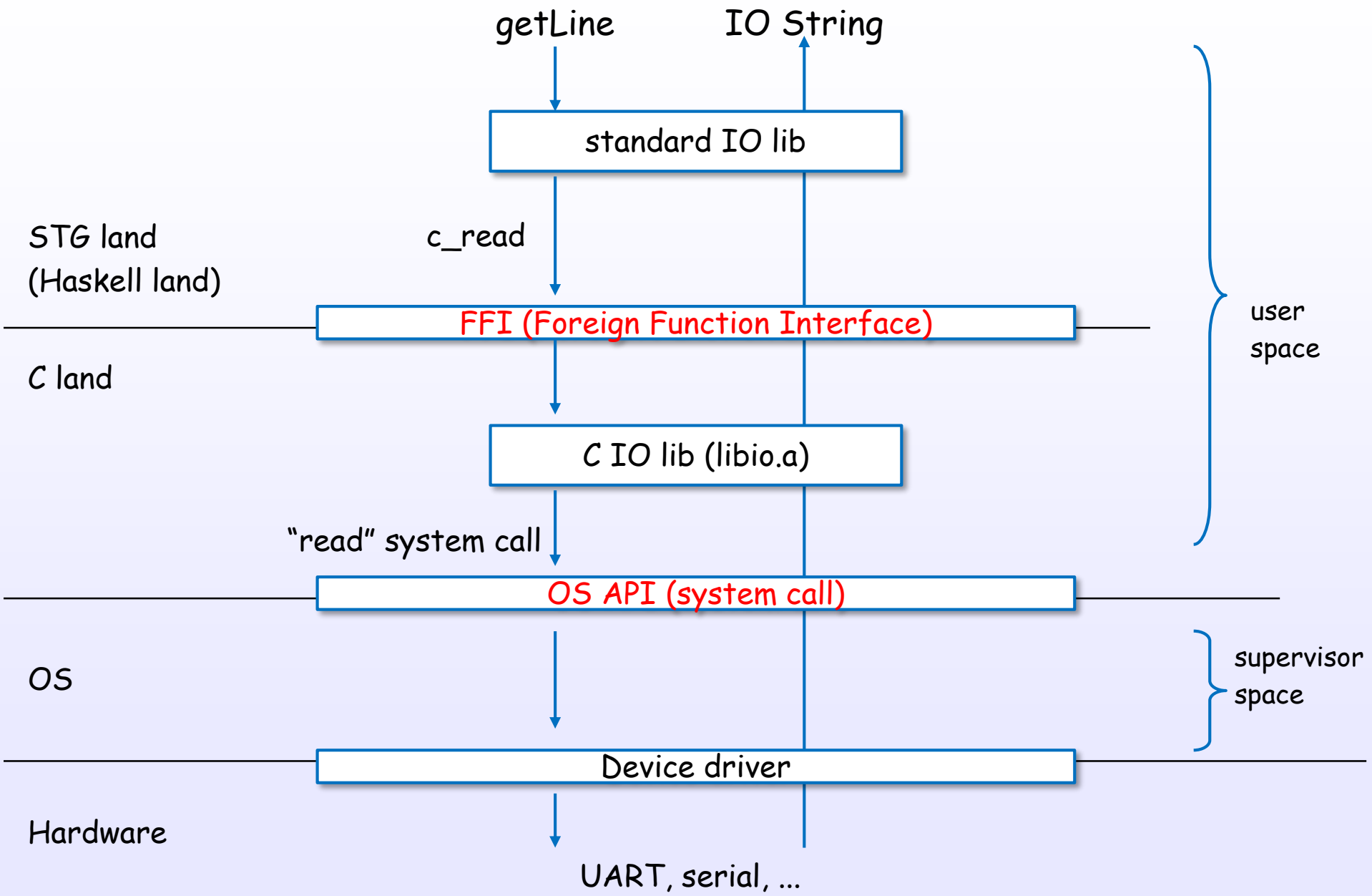
# IO and FFI

# IO



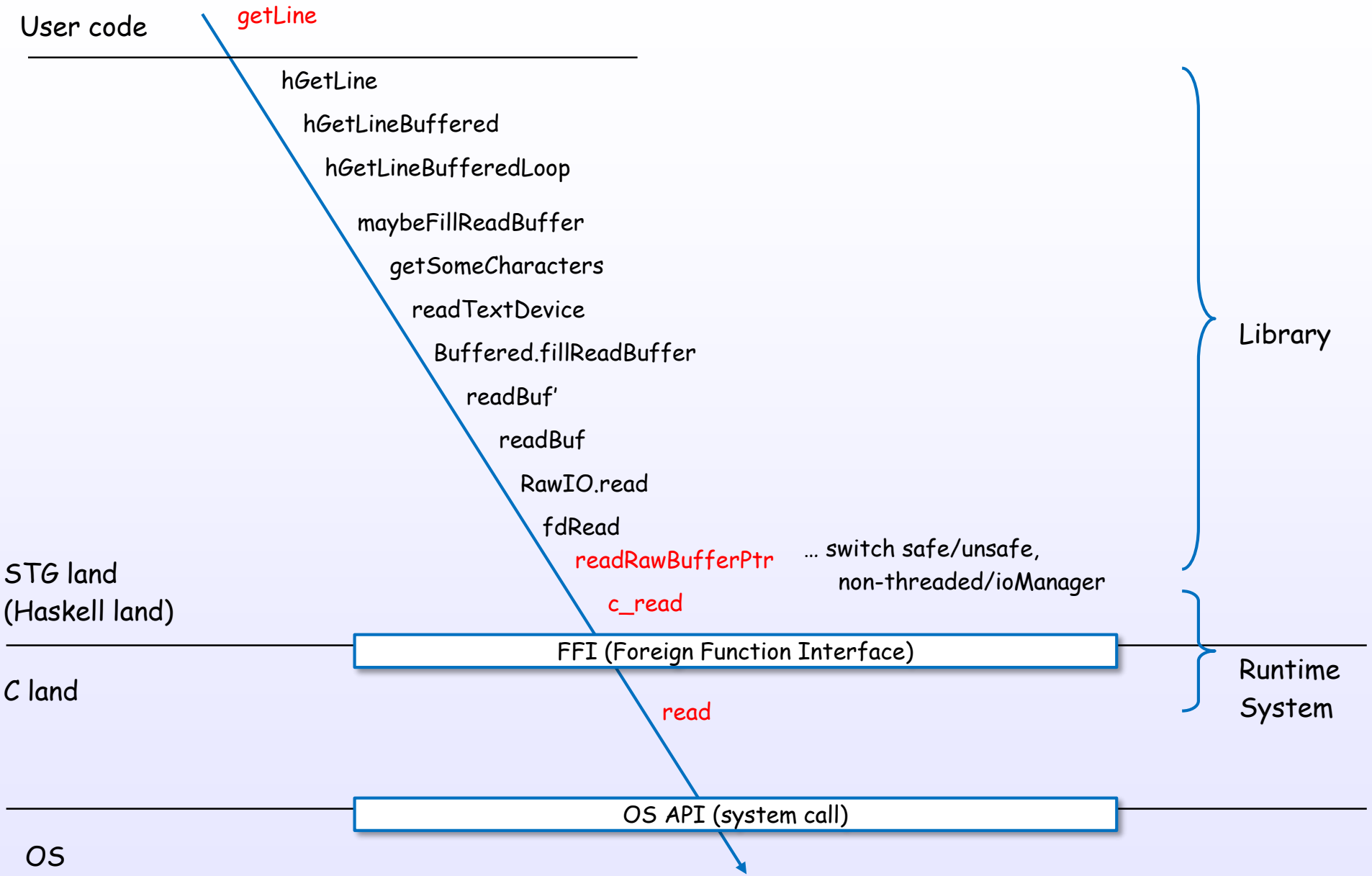

References : [6], [11]

# IO example: getLine




References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

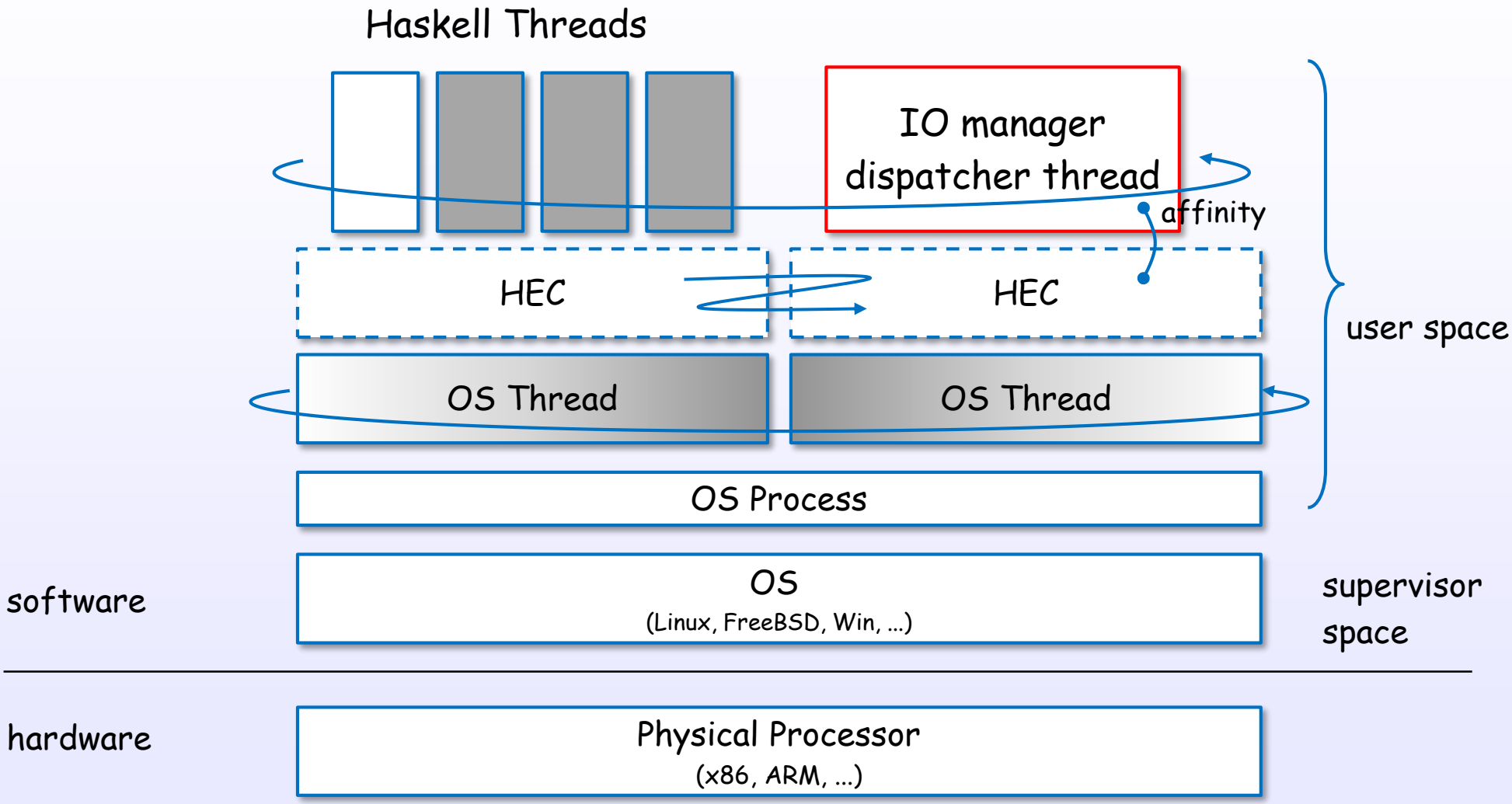
# IO example: getLine (code)




References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

# IO manager

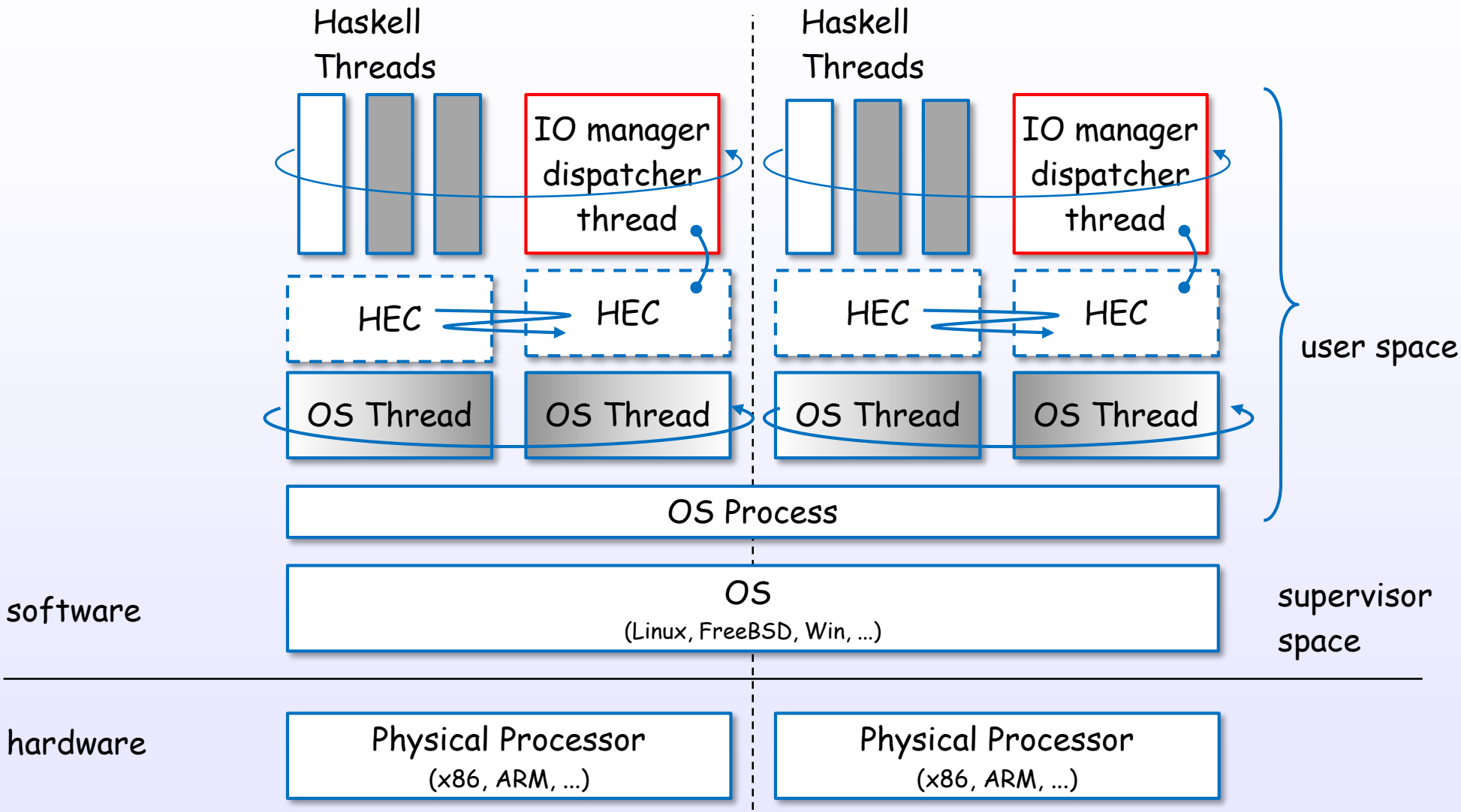
# IO manager (single core)




*Threaded option case (ghc -threaded)

References : [7], [5], [8]

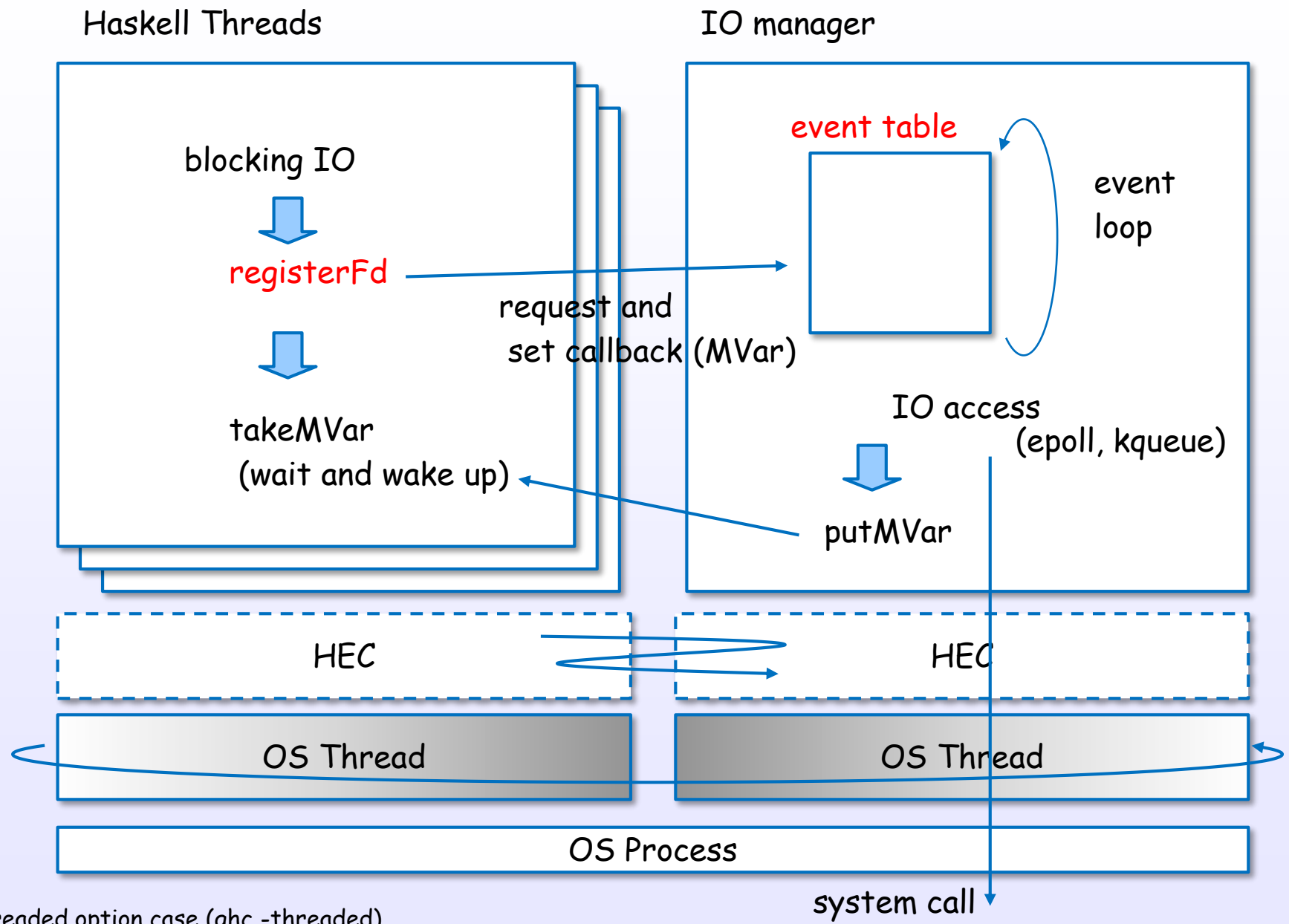
# IO manager (multi core)




*Threaded option case (ghc -threaded)

References : [7], [5], [8]

# IO manager

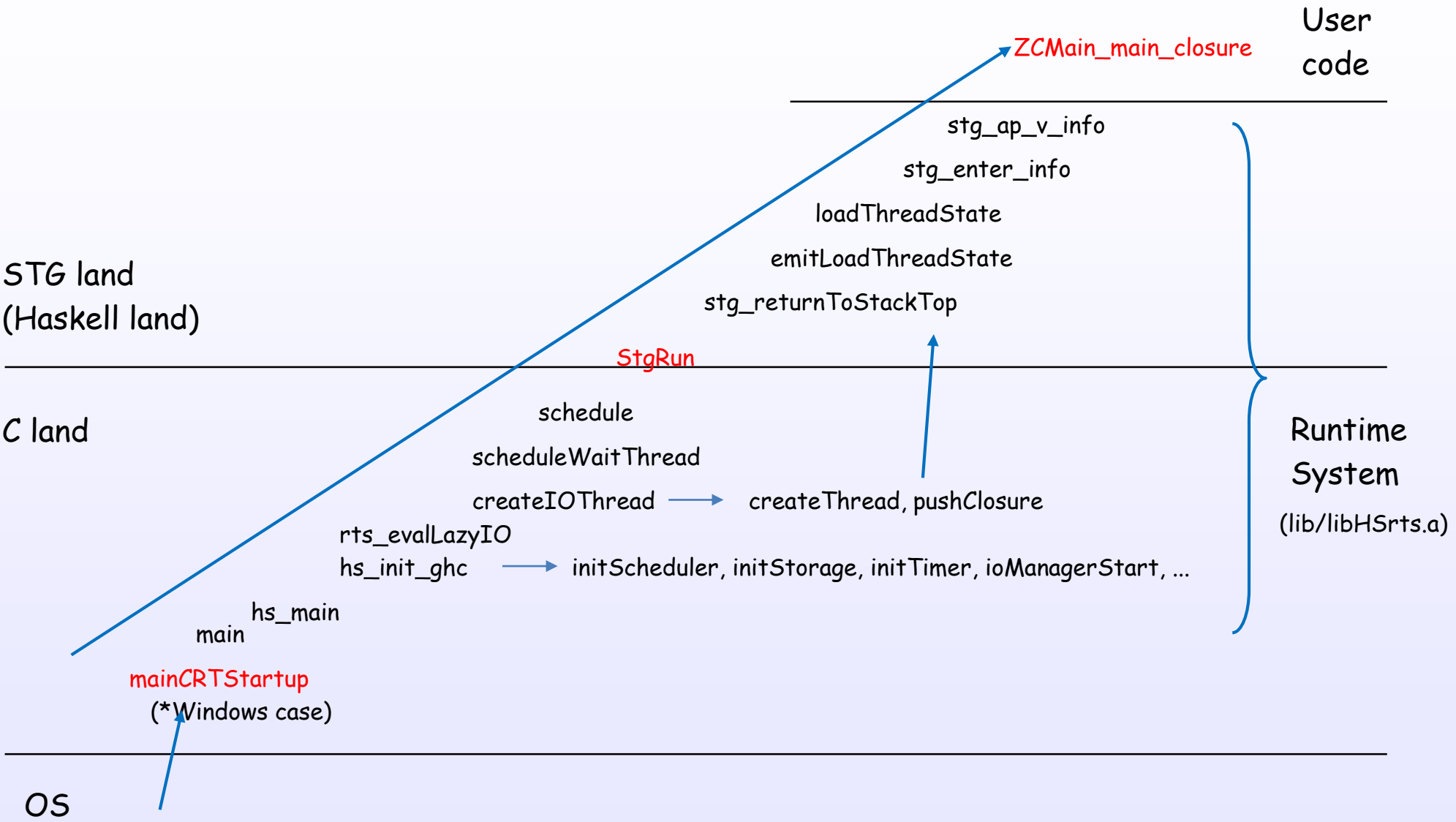



*Threaded option case (ghc -threaded)

References : [7], [5], [8], [S29], [S30], [S32], [S37], [S35], [S3]

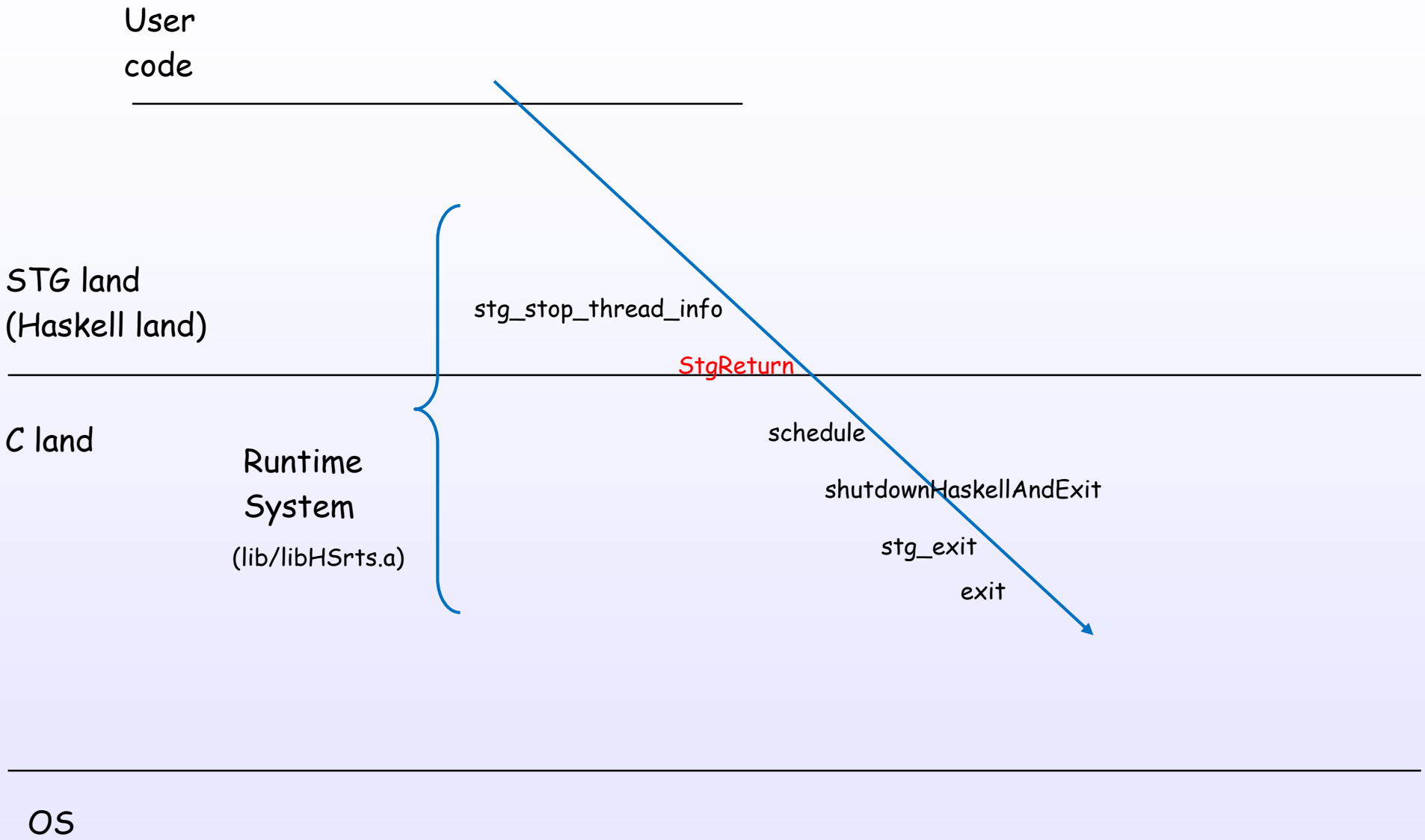
# Bootstrap

# Bootstrap sequence



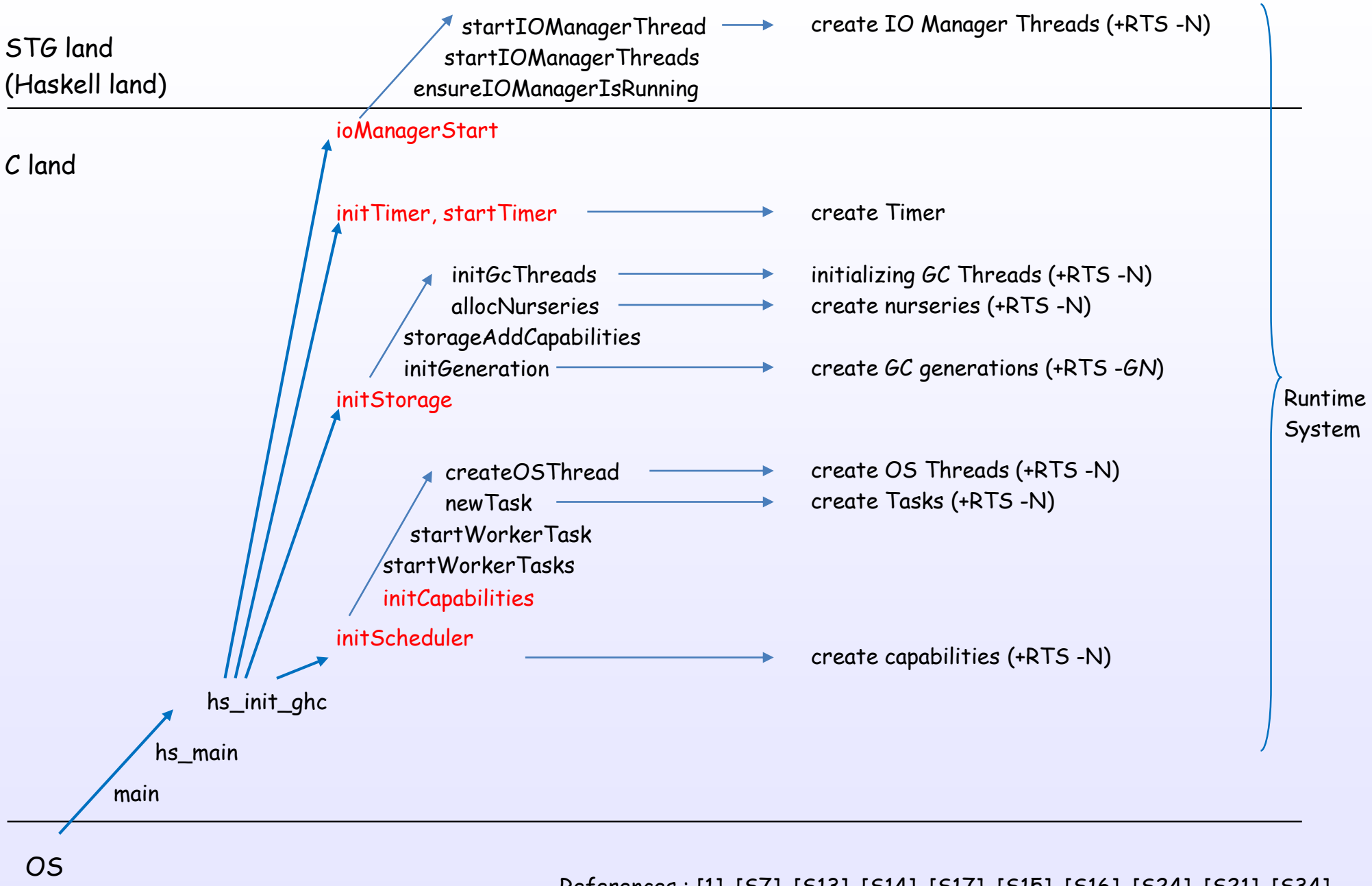

References : [S7], [S13], [S14], [S17], [S18], [S19], [S9], [S10], [S21], [S41]

# Exit sequence



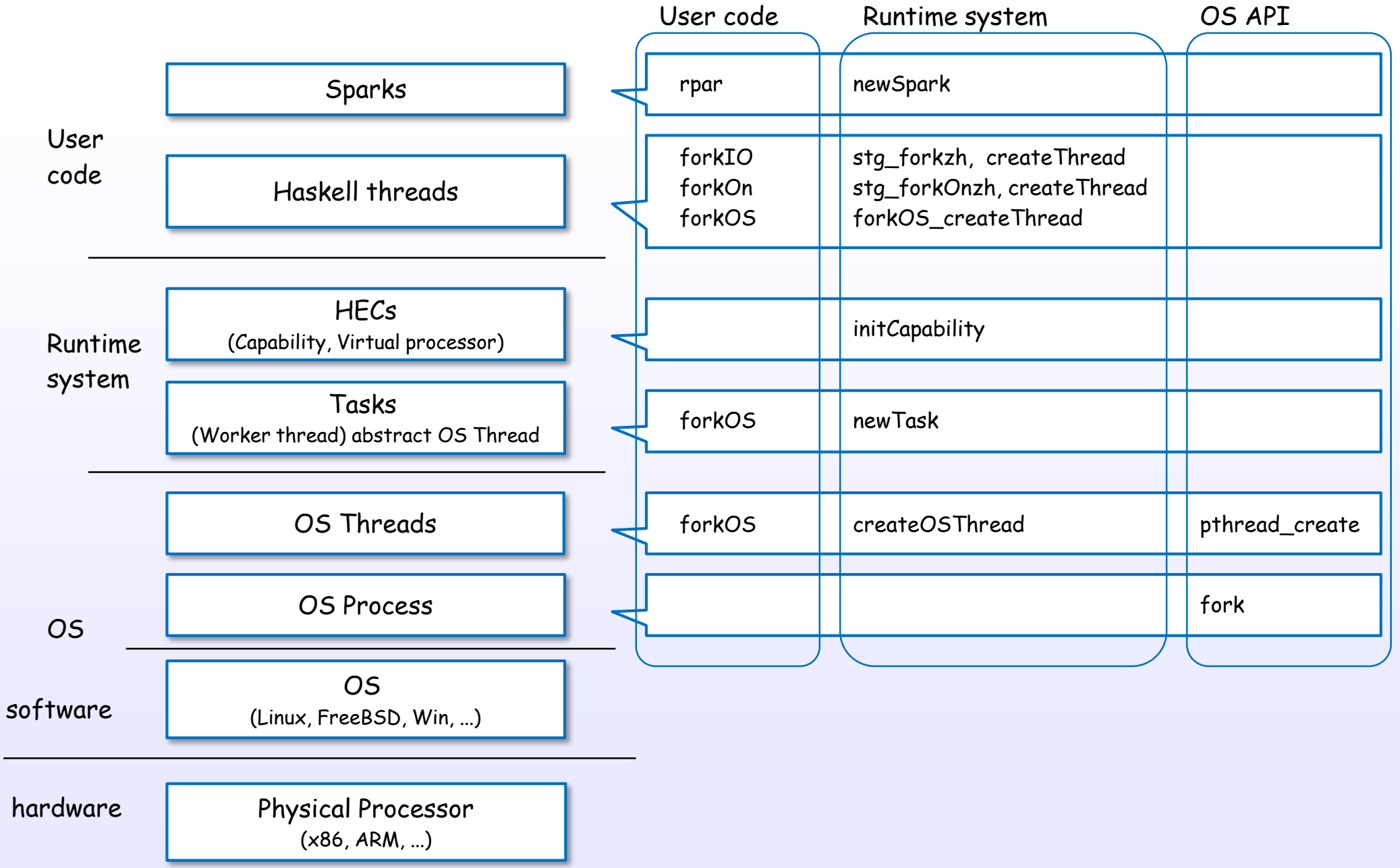

References : [S19], [S18], [S17]

# Initializing




References : [1], [S7], [S13], [S14], [S17], [S15], [S16], [S24], [S21], [S34]

# Create each layers




References : [1], [5], [8], [9], [C11], [C17], [S12], [S26], [S22], [S15], [S23]

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http://research.microsoft.com/en-us/um/people/simonpj/papers/eval-apply/

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# References

The GHC Commentary


[C1] https://ghc.haskell.org/trac/ghc/wiki/Commentary
[C2] https://ghc.haskell.org/trac/ghc/wiki/Commentary/SourceTree
[C3] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler
[C4] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler/HscMain
[C5] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler/CoreSynType
[C6] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler/StgSynType
[C7] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler/CmmType
[C8] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler/GeneratedCode
[C9] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Compiler/SymbolNames
[C10] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts
[C11] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/Storage/HeapObjects
[C12] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/Storage/Stack
[C13] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/Storage/GC
[C14] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/HaskellExecution
[C15] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/HaskellExecution/Registers
[C16] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/HaskellExecution/PointerTagging
[C17] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/Scheduler
[C18] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Rts/STM
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# References

Source code


[S1] includes/stg/Regs.h
[S2] includes/stg/MachRegs.h
[S3] includes/rts/storage/ClosureTypes.h
[S4] includes/rts/storage/Closures.h
[S5] includes/rts/storage/TSO.h
[S6] includes/rts/storage/InfoTables.h
[S7] compiler/main/DriverPipeline.hs
[S8] compiler/main/HscMain.hs
[S9] compiler/cmm/CmmParse.y.source
[S10] compiler/codeGen/StgCmmForeign.hs
[S11] compiler/codeGen/Stg*.hs
[S12] rts/PrimOps.cmm
[S13] rts/RtsMain.c
[S14] rts/RtsAPI.c
[S15] rts/Capability.h
[S16] rts/Capability.c
[S17] rts/Schedule.c
[S18] rts/StgCRun.c
[S19] rts/StgStartup.cmm
[S20] rts/StgMiscClosures.cmm
[S21] rts/HeapStackCheck.cmm
[S22] rts/Threads.c
[S23] rts/Task.c
[S24] rts/Timer.c
[S25] rts/sm/GC.c
[S26] rts/Sparks.c
[S27] rts/WSDeque.c
[S28] rts/STM.h
[S29] rts/posix/Signals.c
[S30] rts/win32/ThrIOManager.c
[S31] libraries/base/GHC/MVar.hs
[S32] libraries/base/GHC/Conc/IO.hs
[S33] libraries/base/GHC/Conc/Sync.hs
[S34] libraries/base/GHC/Event/Manager.hs
[S35] libraries/base/GHC/Event/Thread.hs
[S36] libraries/base/GHC/IO/BufferedIO.hs
[S37] libraries/base/GHC/IO/FD.hs
[S38] libraries/base/GHC/IO/Handle/Text.hs
[S39] libraries/base/System/IO.hs
[S40] libraries/base/System/Posix/Internals.hs
[S41] AutoApply.o (utils/genapply/GenApply.hs)

*Connect the algorithm and transistor*