GHC(STG,Cmm,asm) illustrated

for hardware person

exploring some mental models and implementations

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Rev. 0.00.3
WIP

"Any sufficiently advanced technology is indistinguishable from magic."

Arthur C. Clarke

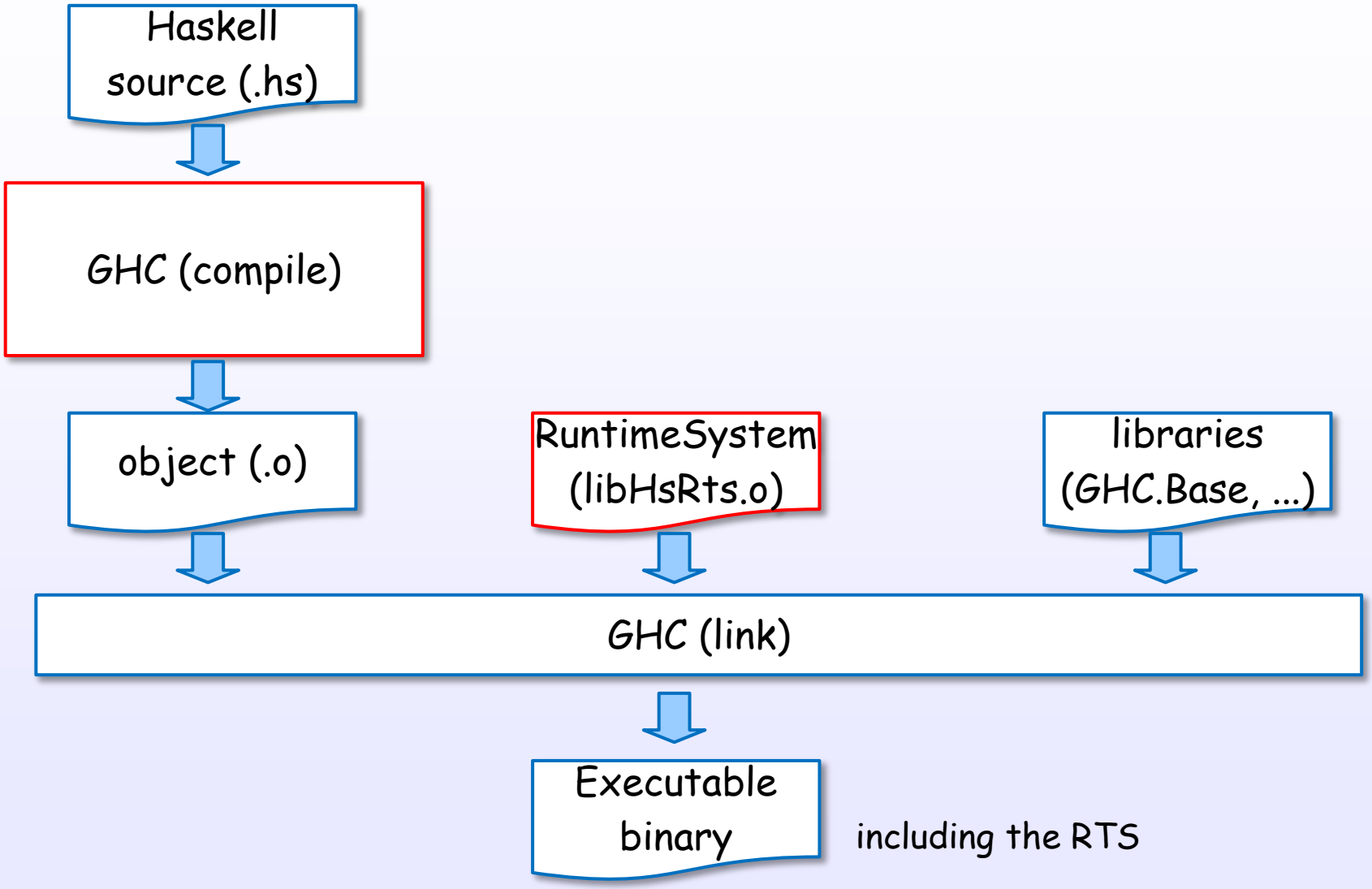
NOTE

- 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 7.8 (and ghc 7.10).

Contents

Executable binary

The GHC = Compiler + Runtime System (RTS)

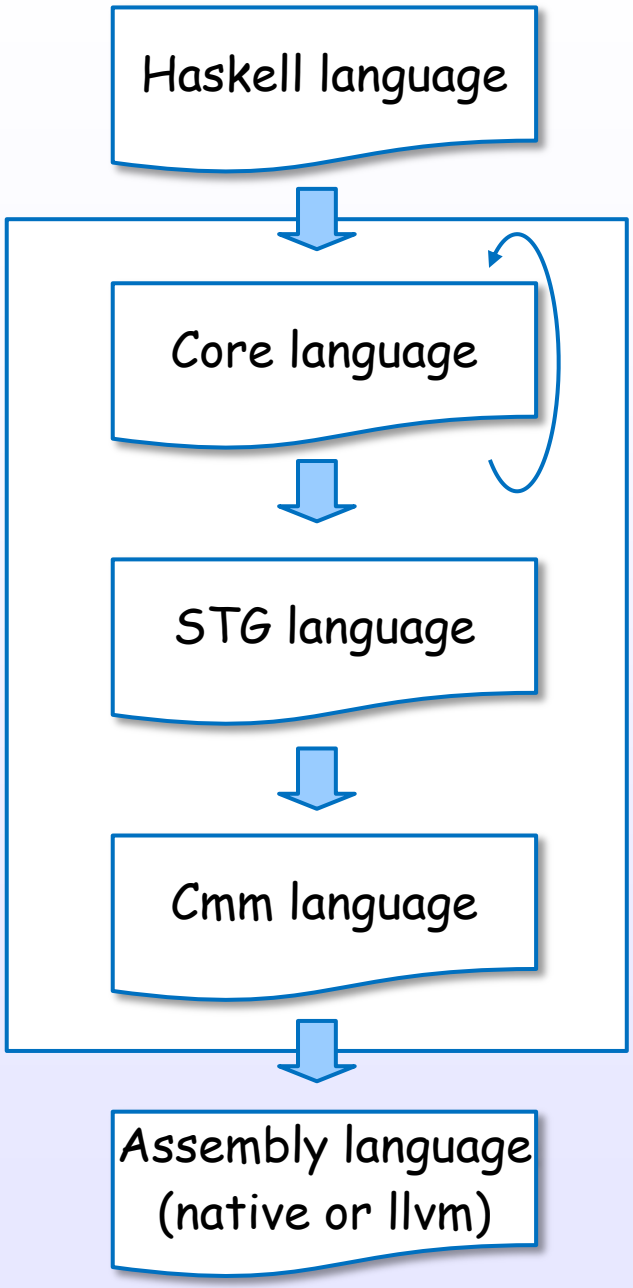


References : [1], [C1], [C3], [C10], [C19], [S7]

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
```

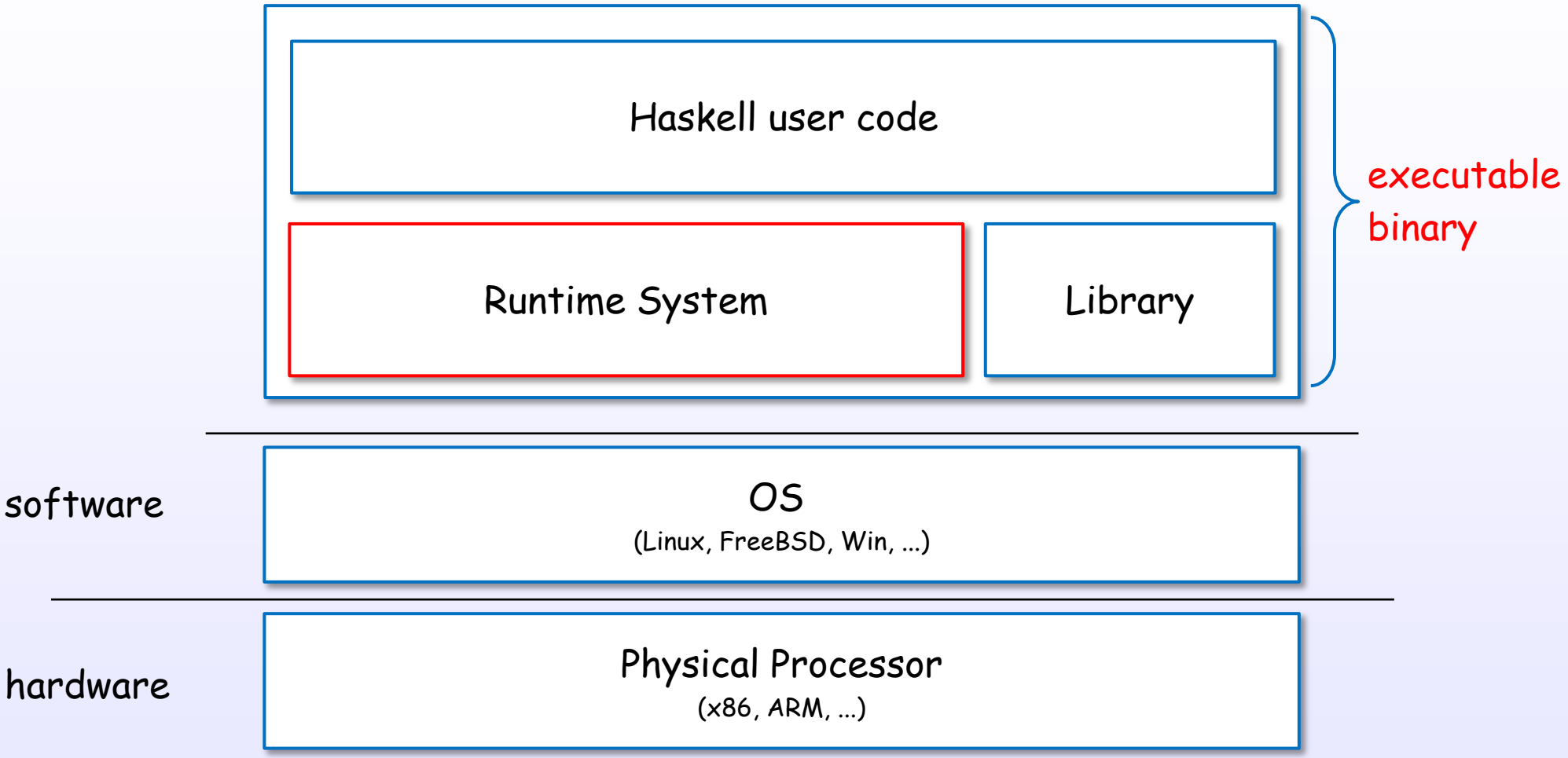
```
% ghc -ddump-cmm
% ghc -ddump-opt-cmm
```

```
% ghc -ddump-llvm
% ghc -ddump-asm
```

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

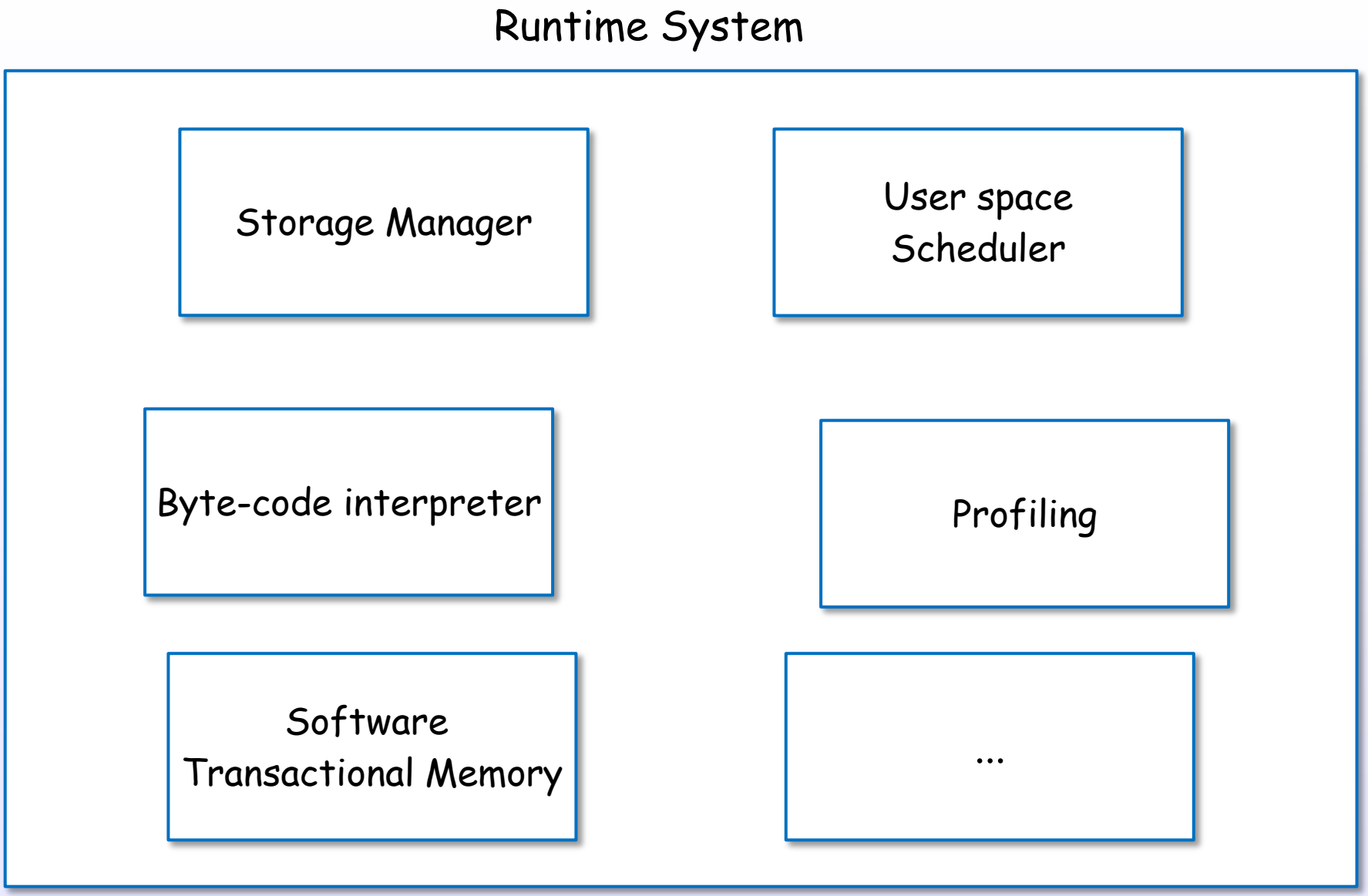
Runtime System

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]

Machine layer/models

Machine layer

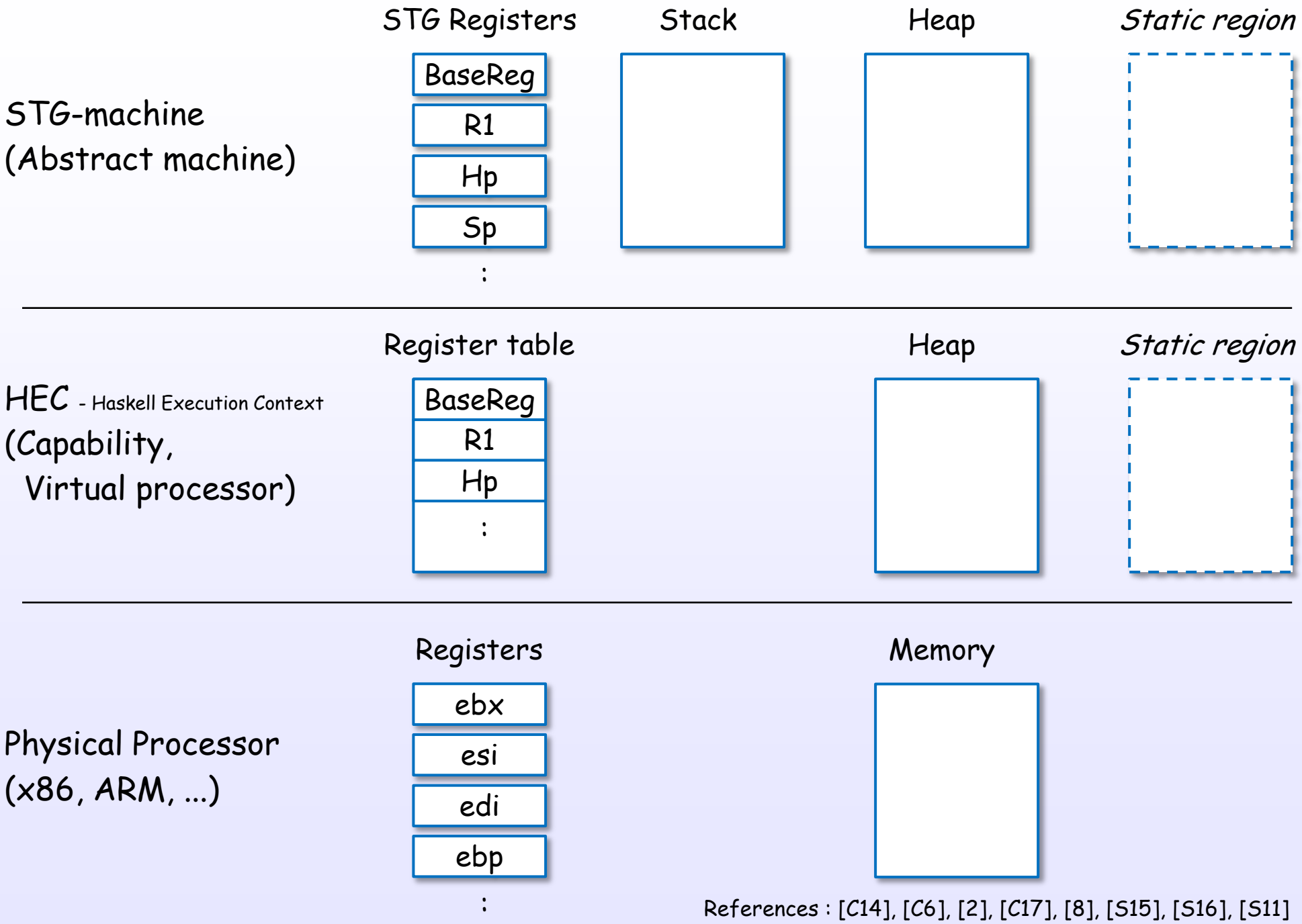
STG-machine
(Abstract machine)

HEC - Haskell Execution Context
(Capability, Virtual processor)

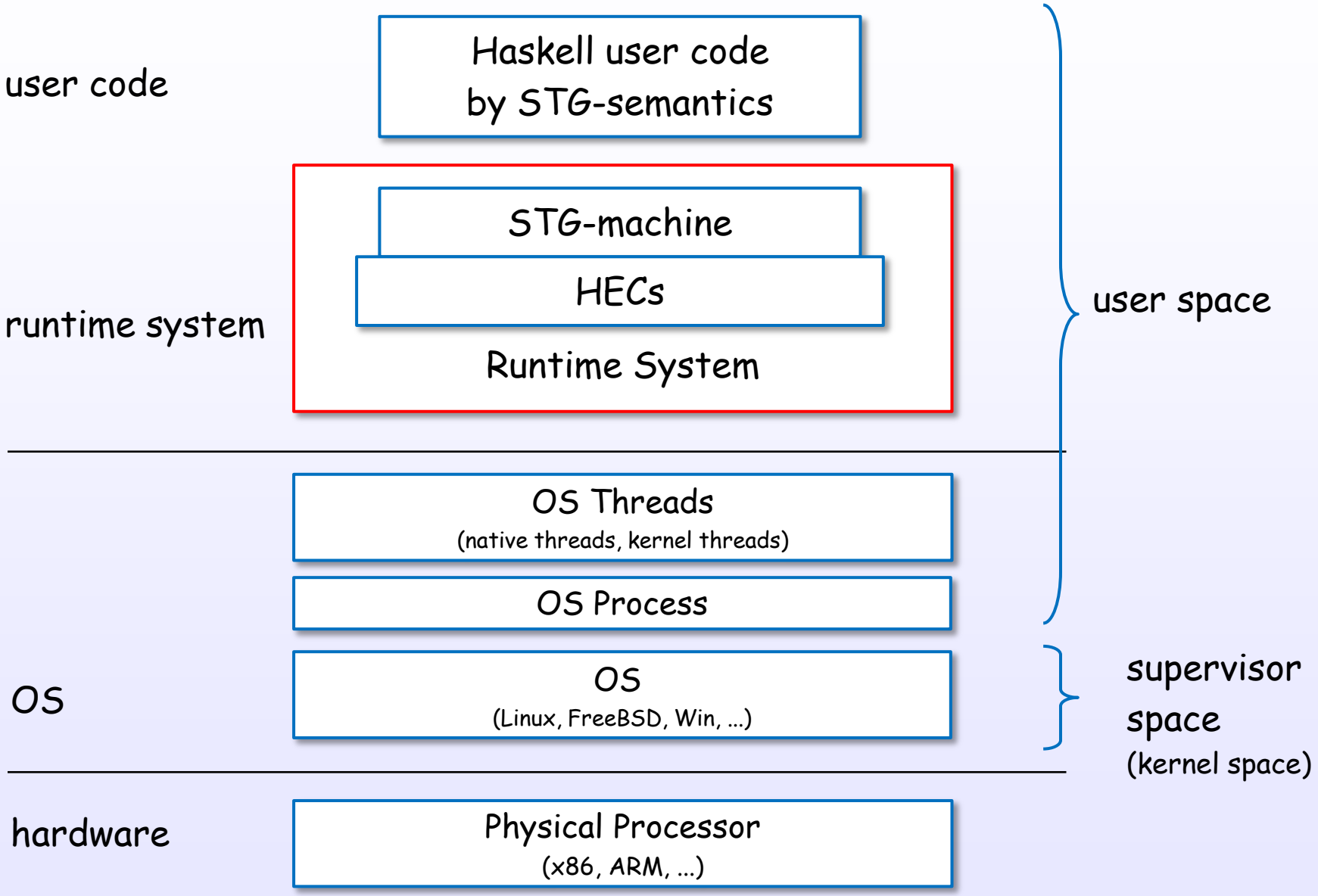
Physical Processor
(x86, ARM, ...)

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

Machine layer



Runtime system and HEC

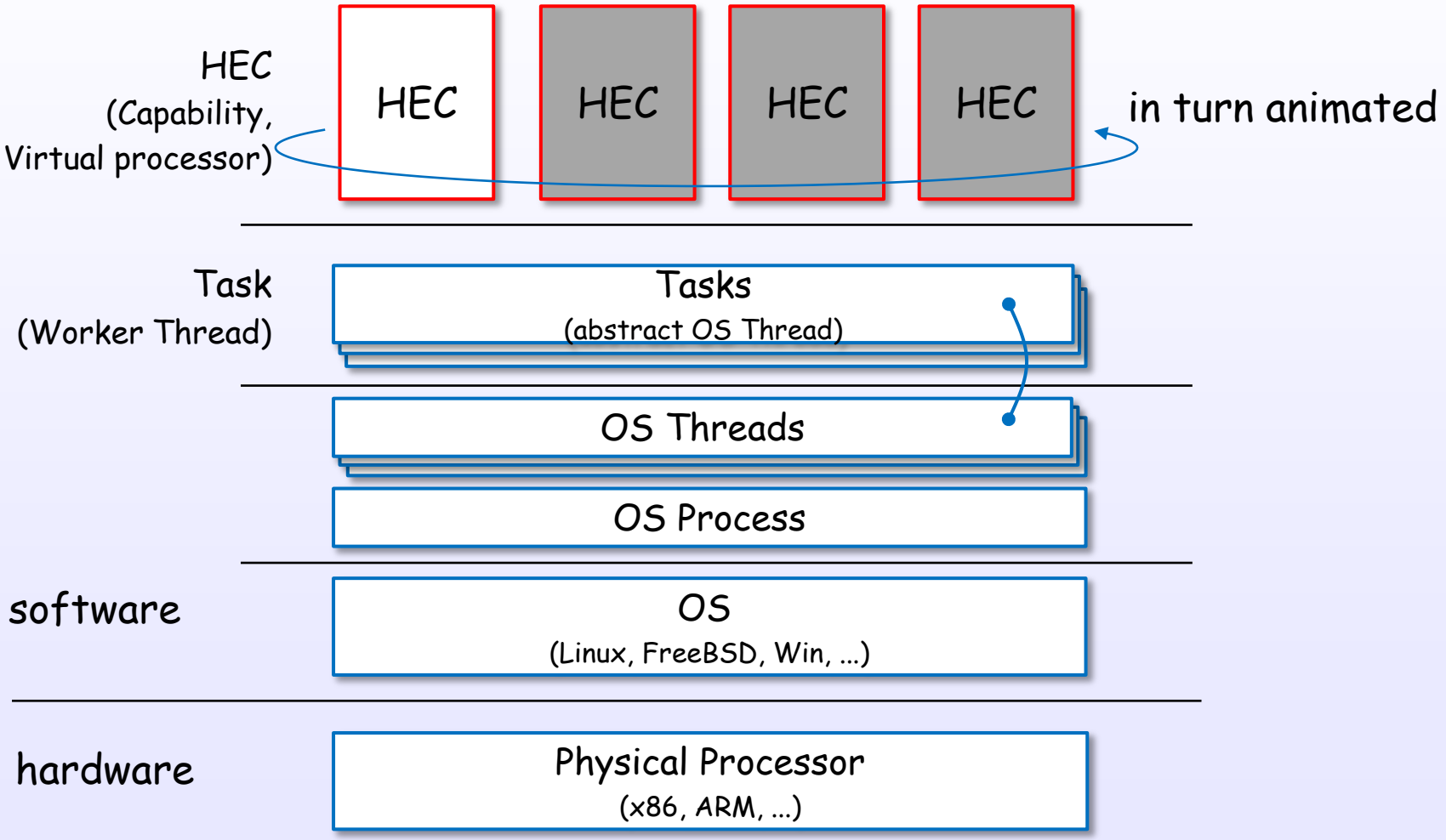


References : [C14], [C6], [2], [C17], [8], [S15], [S16], [S11]

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 7.8)

```
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;
    int context_switch;
    int interrupt;

#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;
    SparkCounters spark_stats;
#endif

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

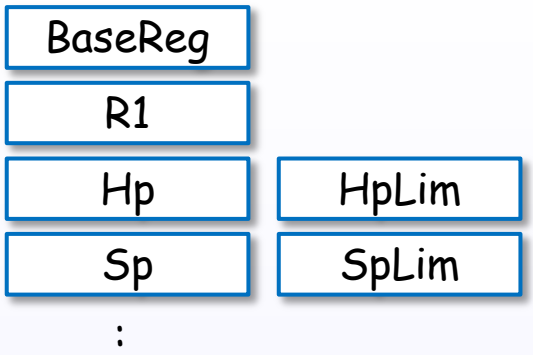
Each HEC (Capability) has a register table and a run queue and ...
Each HEC (Capability) is initialized at initCapabilities [rts/rts/Capability.c]

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

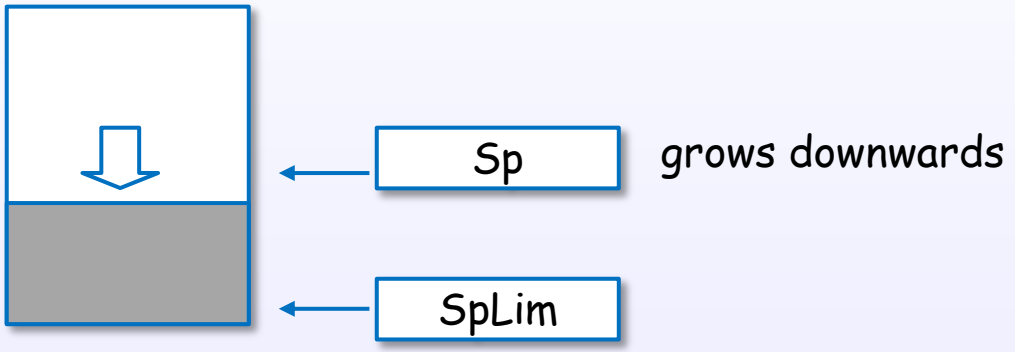
STG-machine

STG-machine

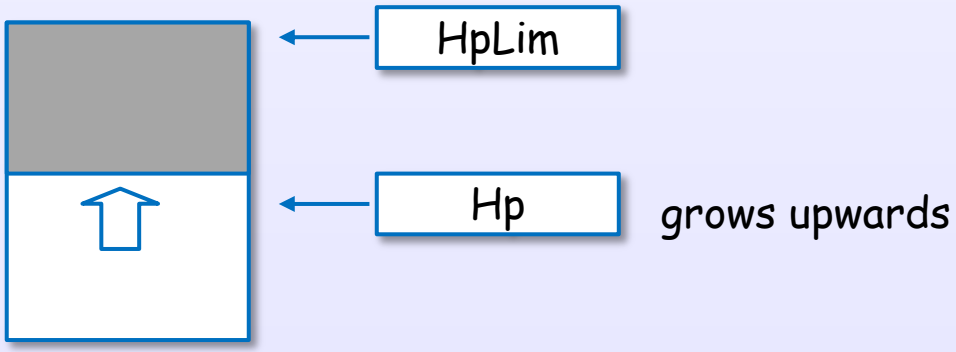
STG Registers



Stack



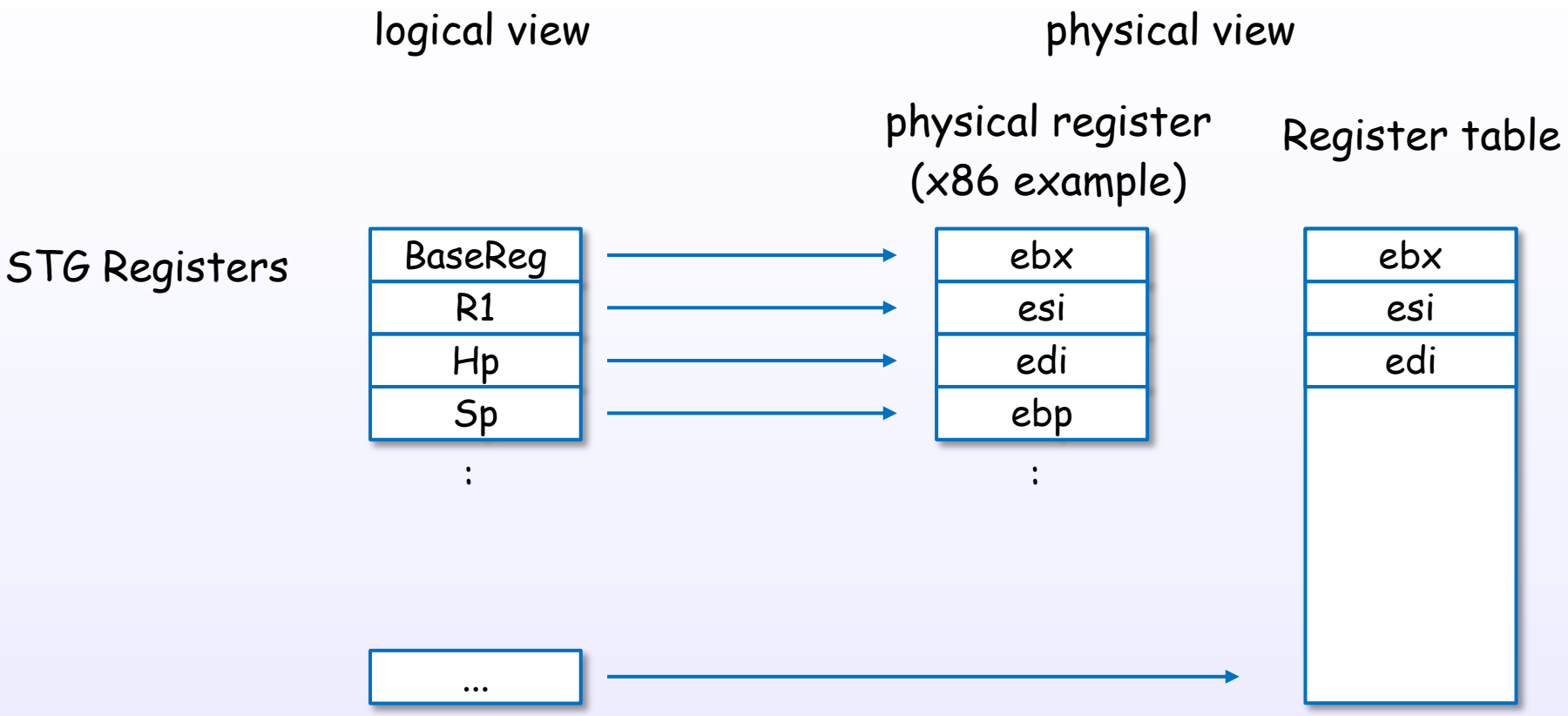
Heap



Each real Haskell code is executed in STG semantics.

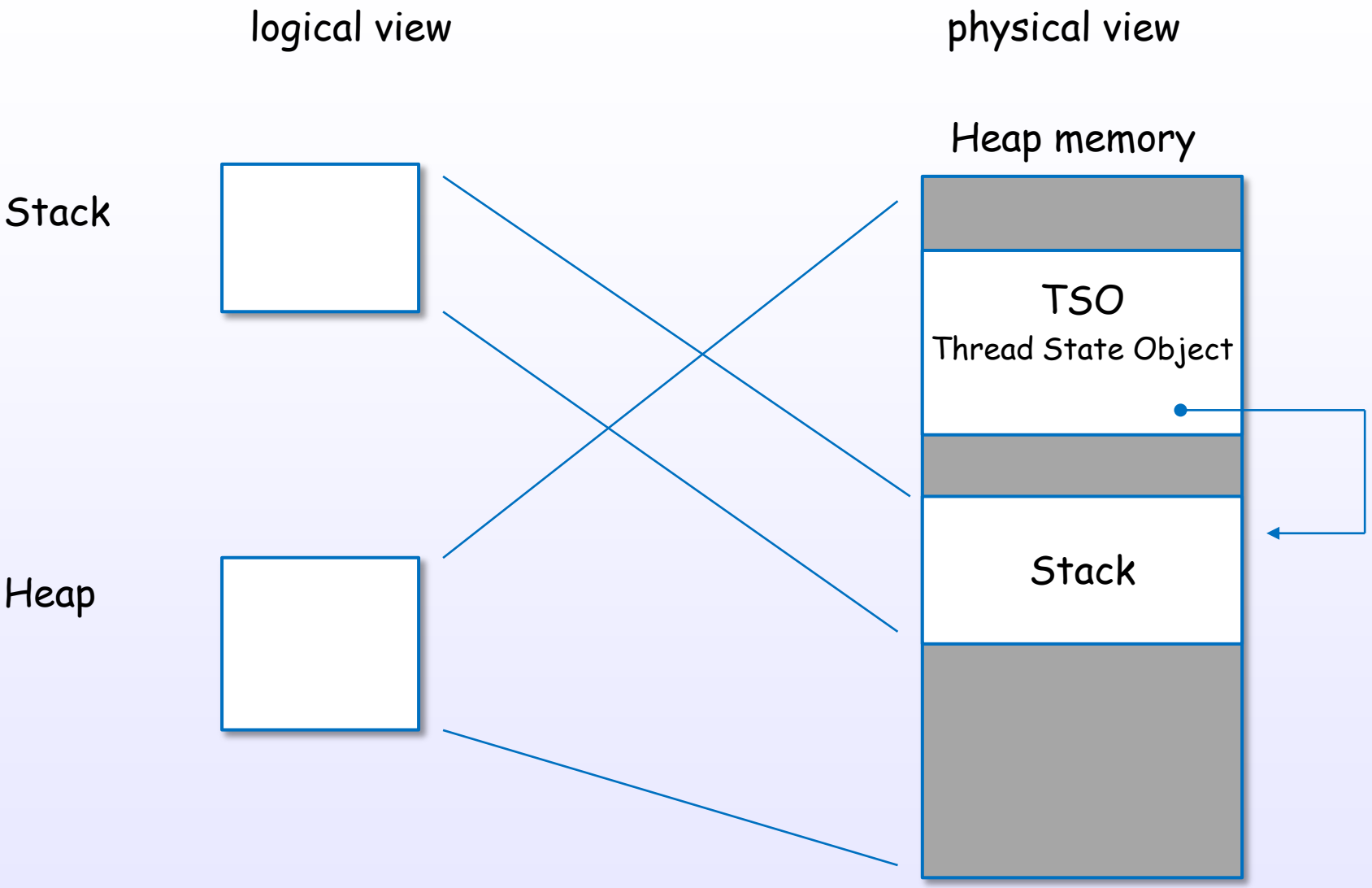
References : [2], [C15], [C11], [C12]

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 7.8)

```
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;
   StgWord32  tot_stack_size;
} *StgTSOPtr;
```

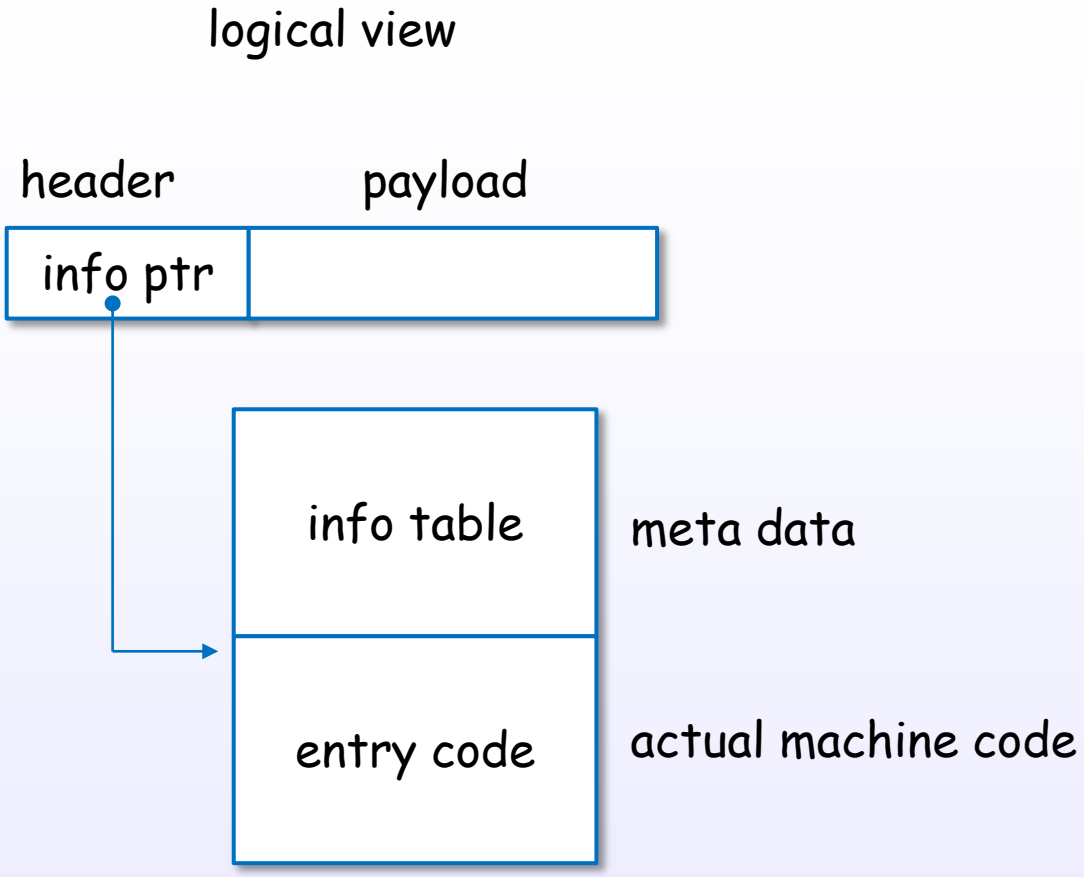

link to stack object

A TSO object is only ~17words + stack. Lightweight!

References : [S5]

Heap objects in STG-machine

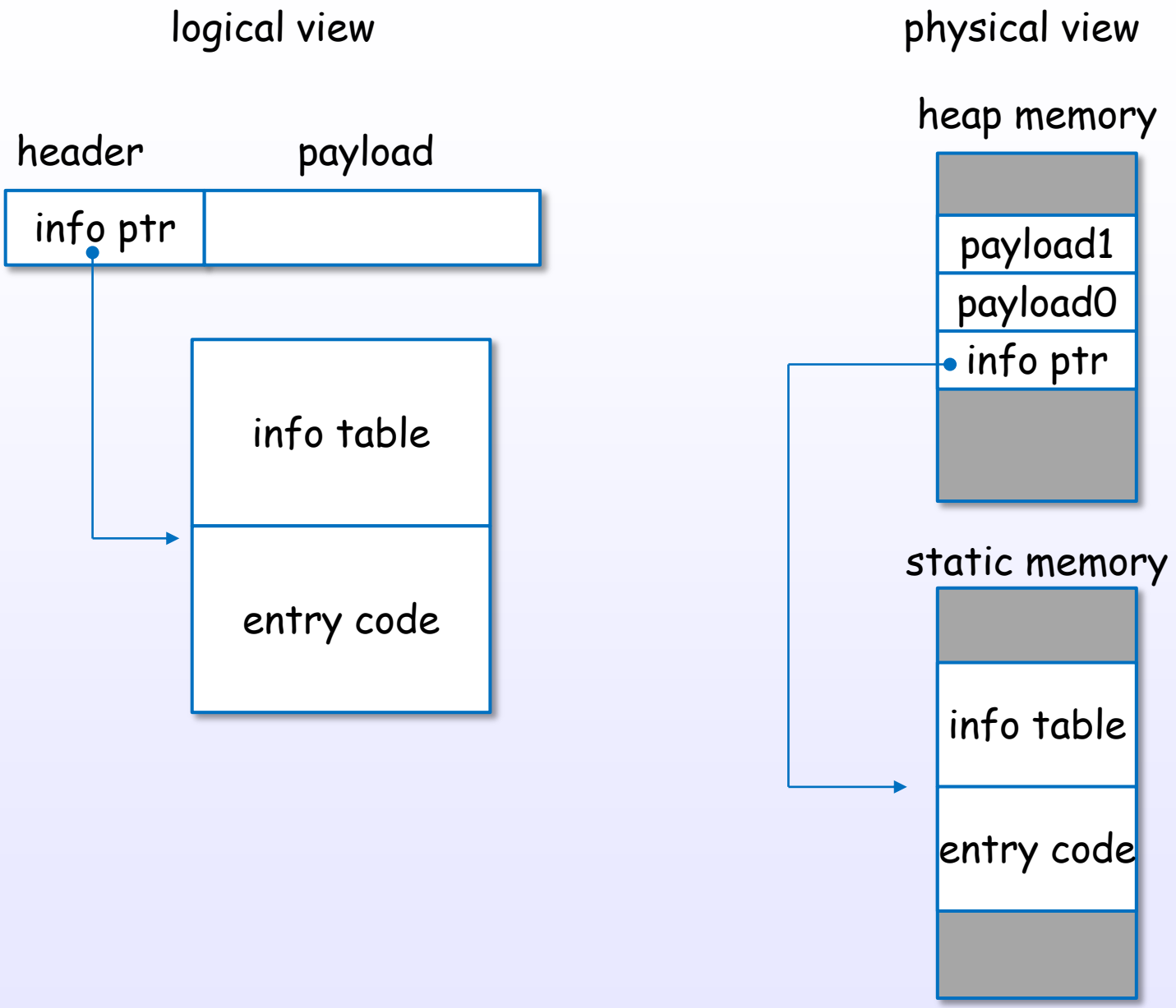
Heap object (closure)



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

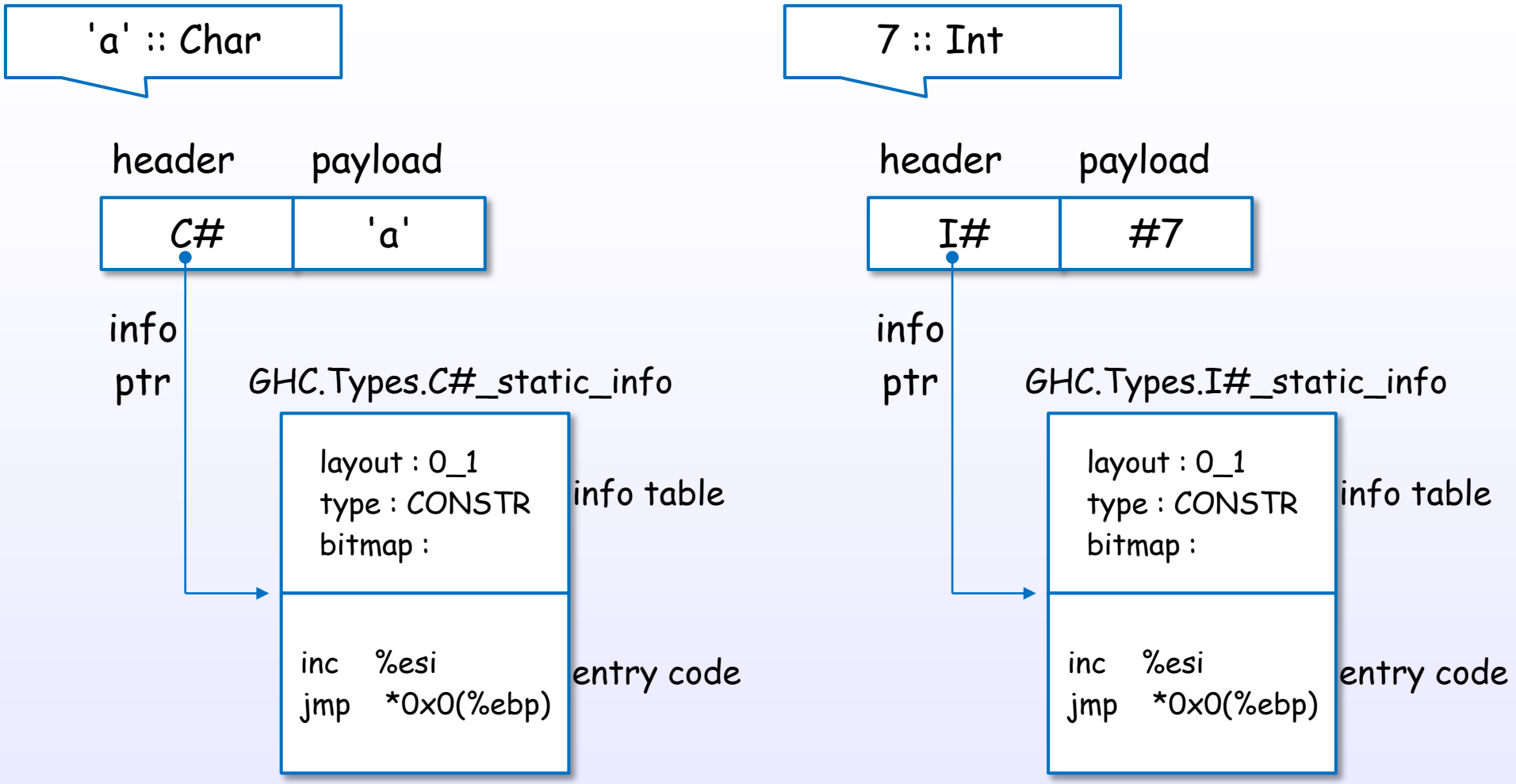
References : [C11], [S3], [S4], [S6], [2]

Heap object (closure)



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

Closure examples : Char, Int



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

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#! [8];
```

Cmm

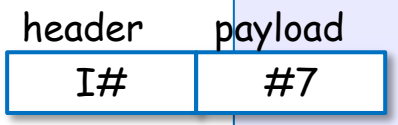
[ghc -O -ddump-opt-cmm Example.hs]

```
section "data" { __stginit_main:Example:
}

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

section "relreadonly" { SMc_srt:
}
```

asm

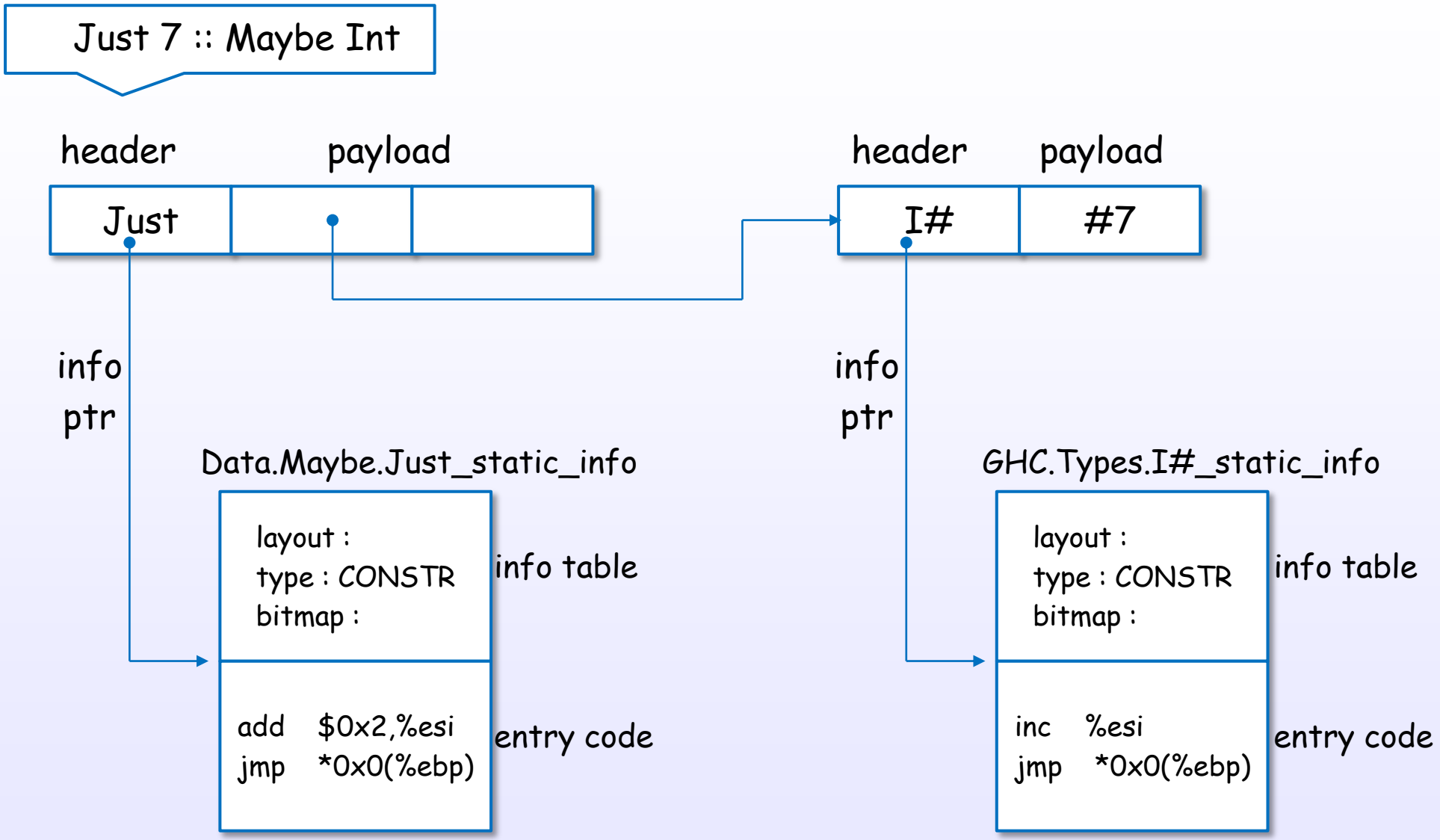
[ghc -O -ddump-asm Example.hs]

```
.data
        .align 4
.align 1
.globl __stginit_main:Example
__stginit_main:Example:
.data
        .align 4
.align 1
.globl Example.value1_closure
Example.value1_closure:
        .long   GHC.Types.I#_static_info
        long    7
.section .data
        .align 4
.align 1
SMd_srt:
```



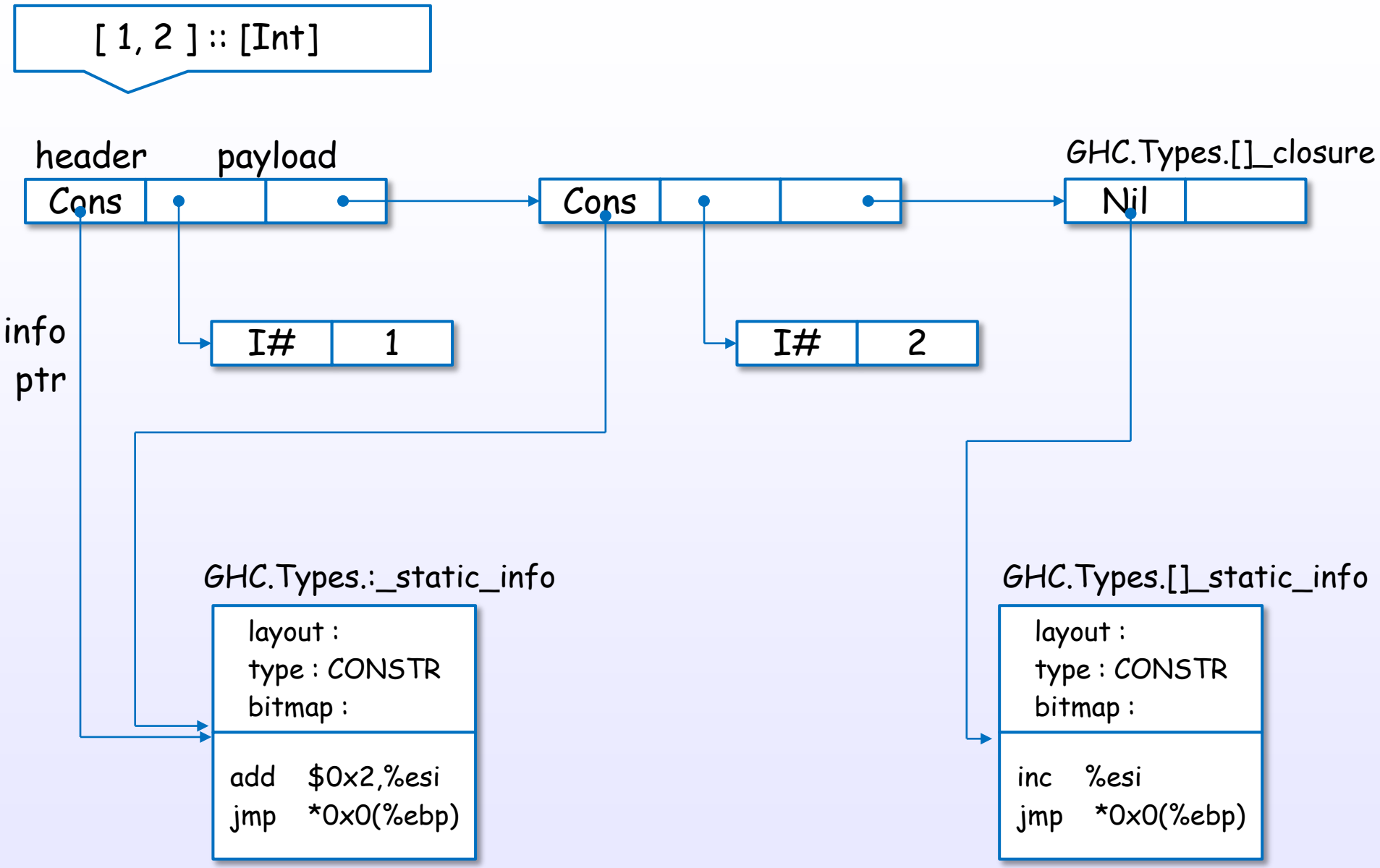
References : [C11], [S3], [C9], [C8], [2], [S20]

Closure examples : Maybe



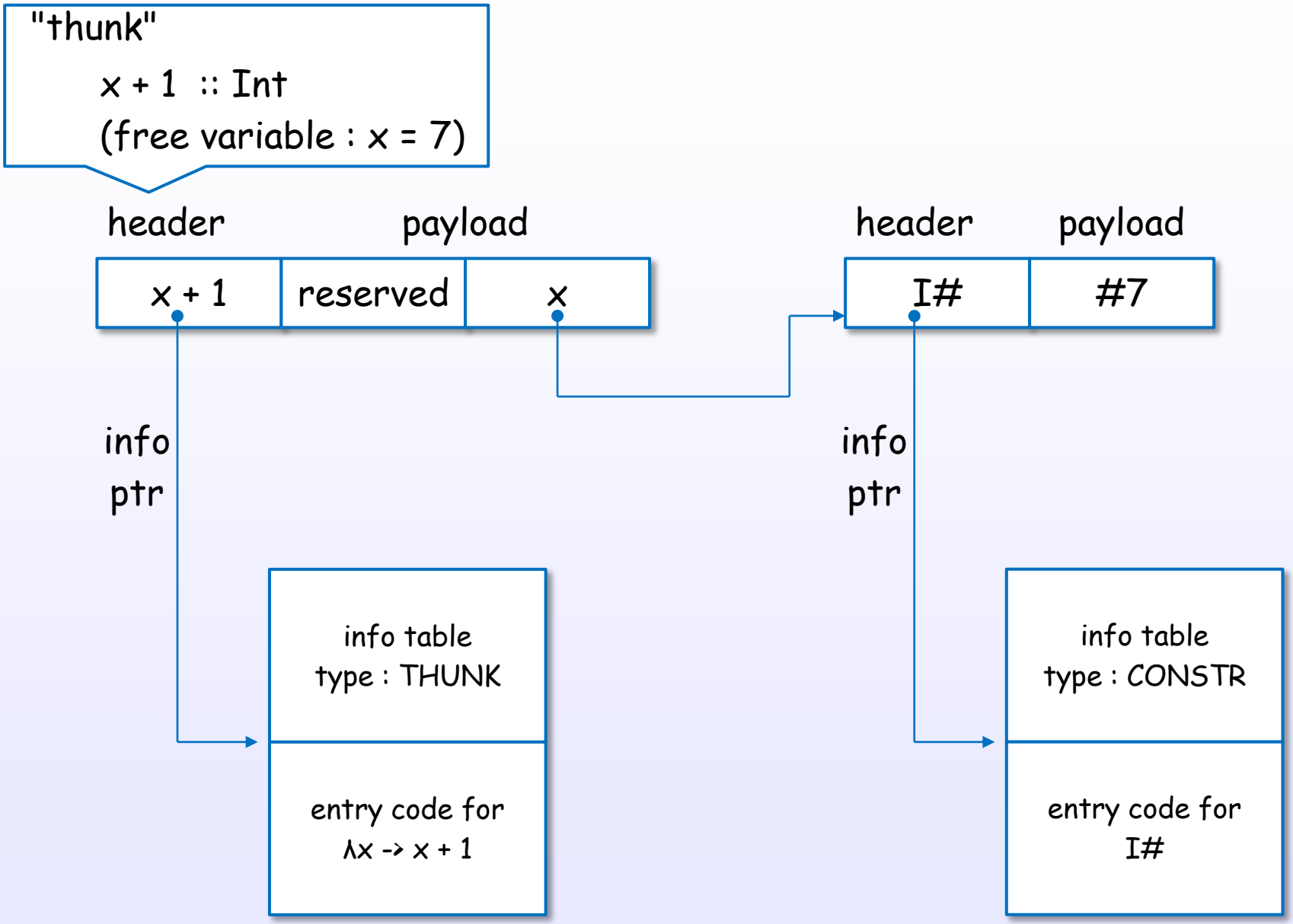
References : [C11], [S3], [C9], [C8], [2], [S20]

Closure examples : List



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

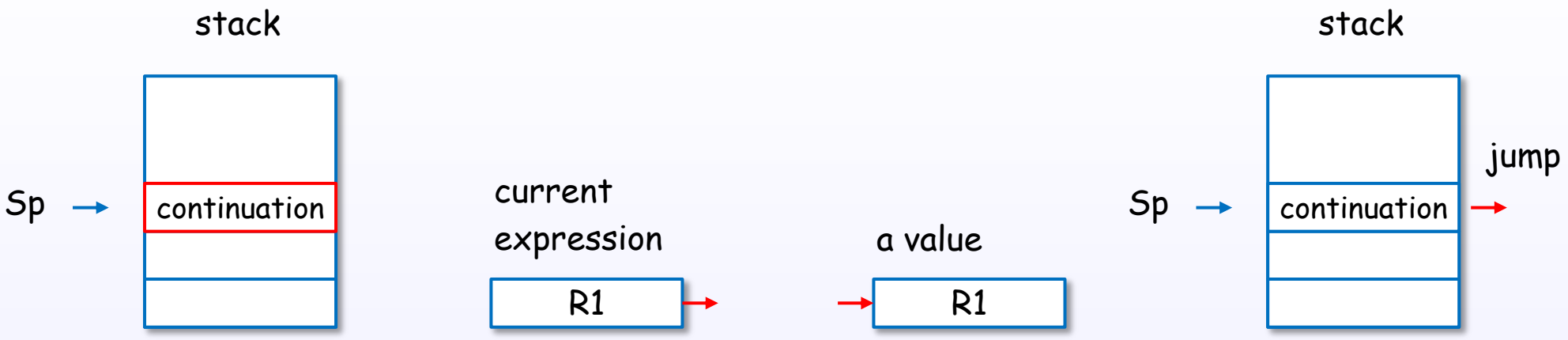
Closure examples : Thunk



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

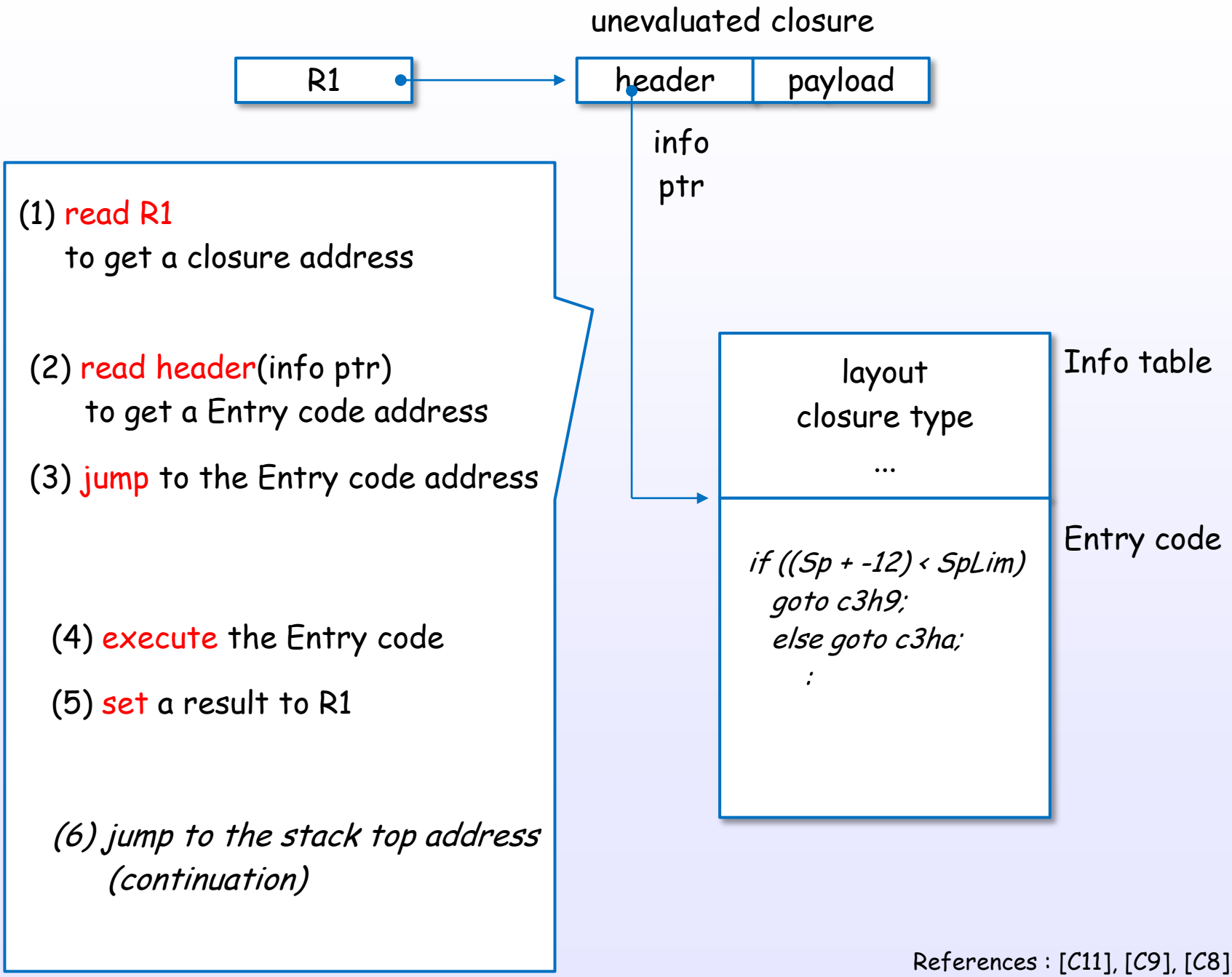
(3)
set a result to R1

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

(5)
repeat from (1)

References : [C8], [3]

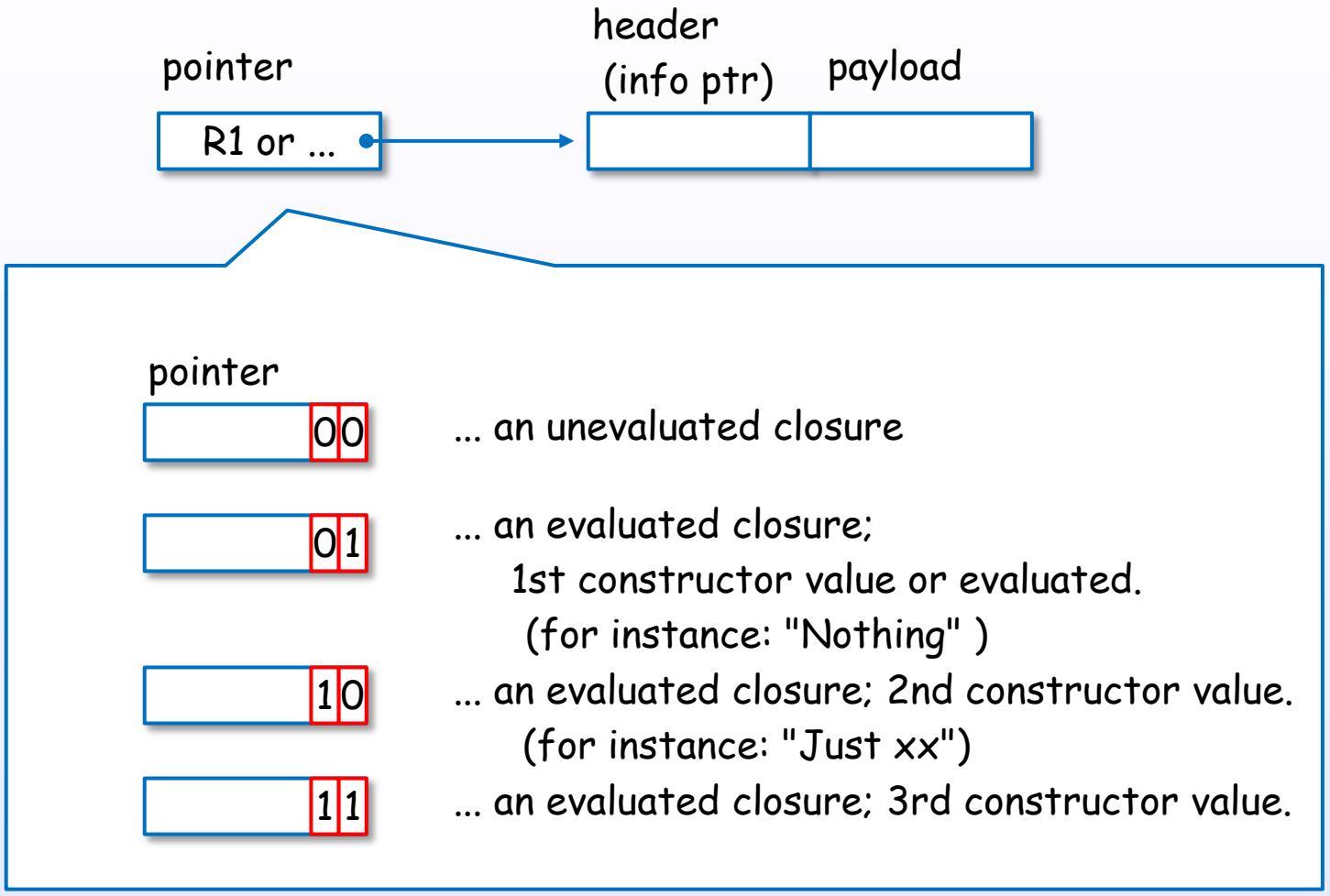
Enter to a closure



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

Pointer tagging

Pointer tagging



* 32bit machine case

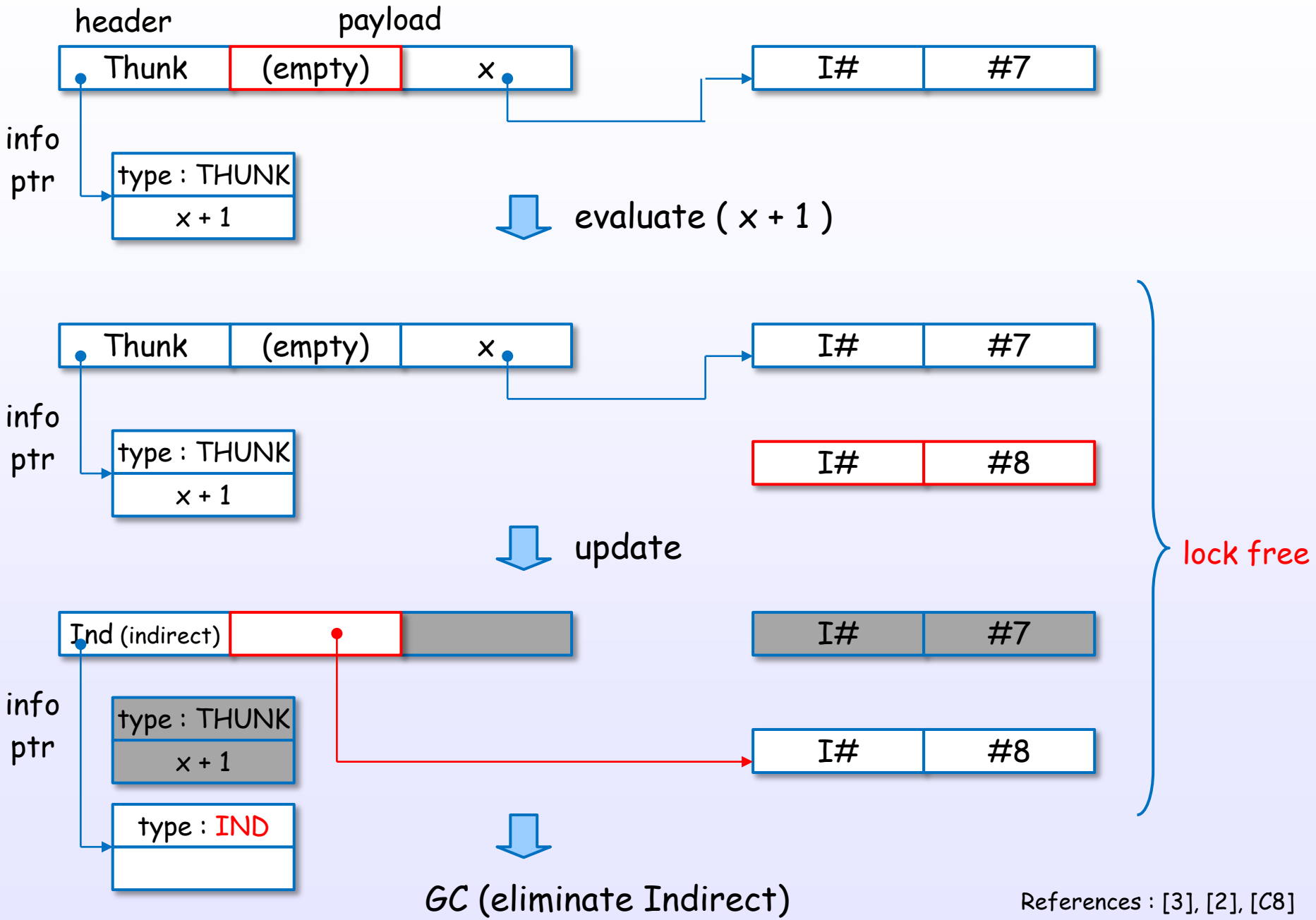
fast judgment!
checking only pointer's lower bits without evaluating the closure.

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

Thunk and update

Thunk and update

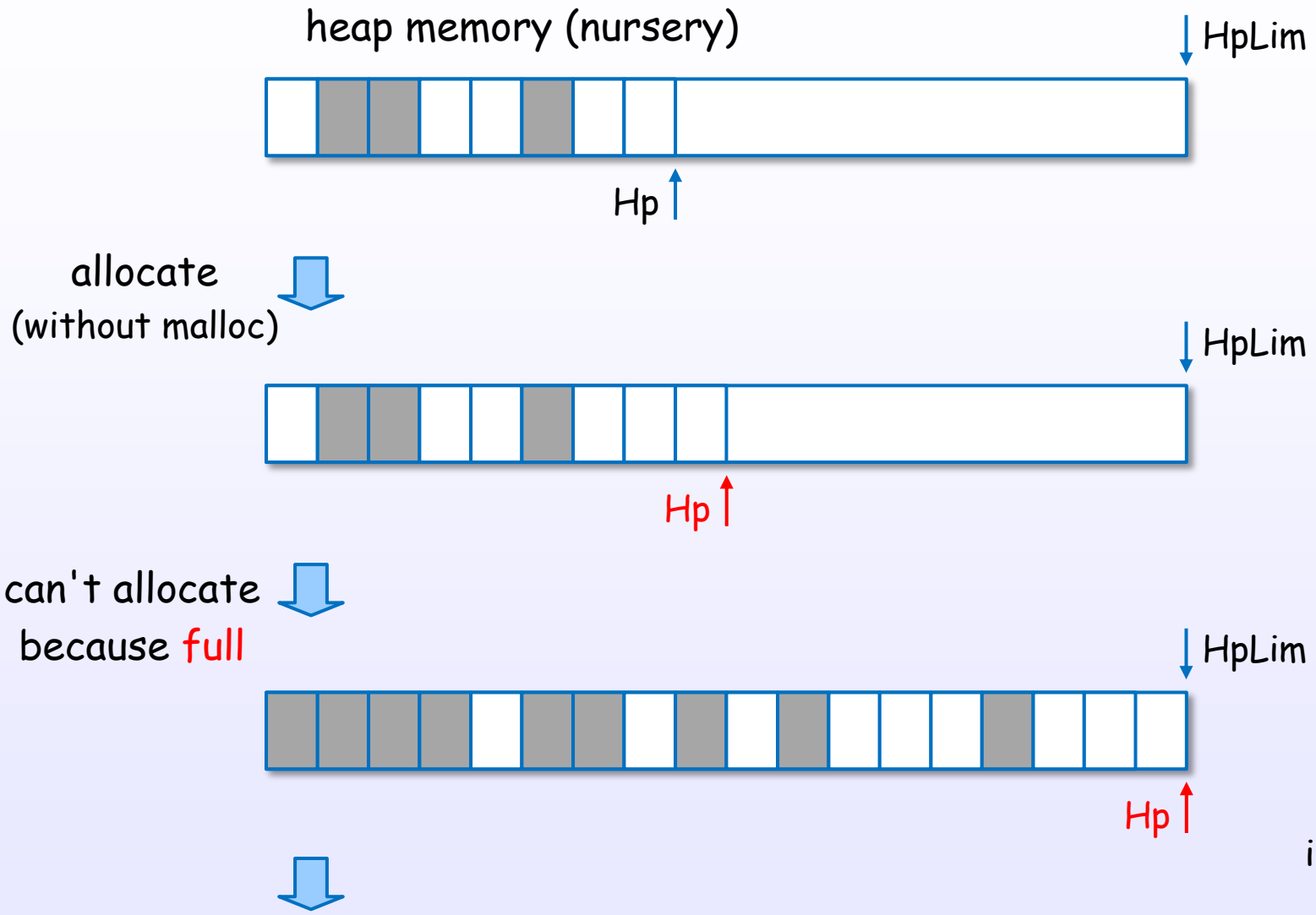
"thunk" x + 1 :: Int (free variable : x = 7)



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

Allocate and free heap objects

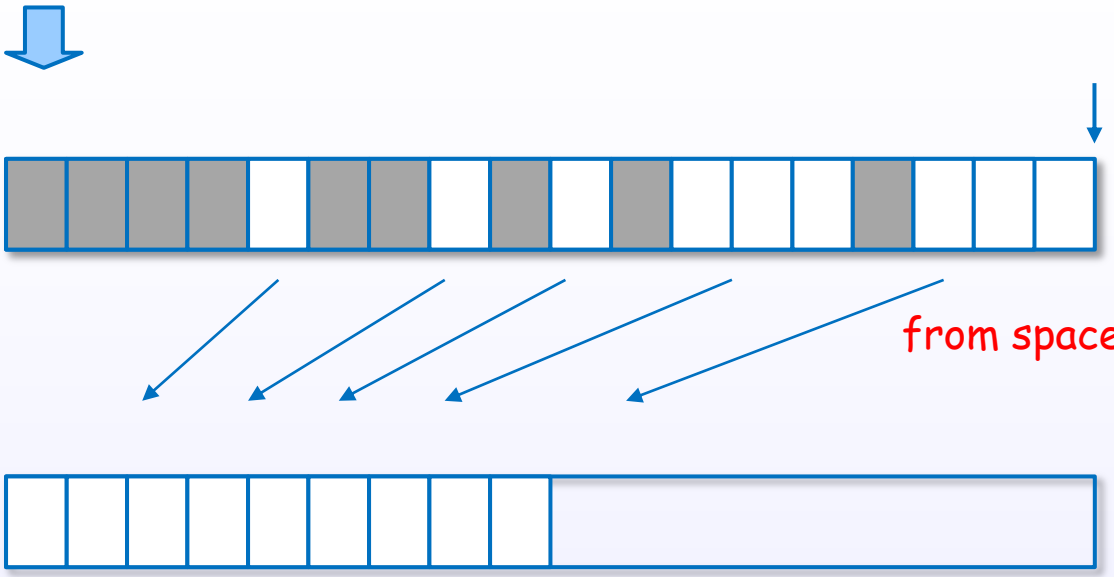
Allocate heap objects



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

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

free and collect heap objects



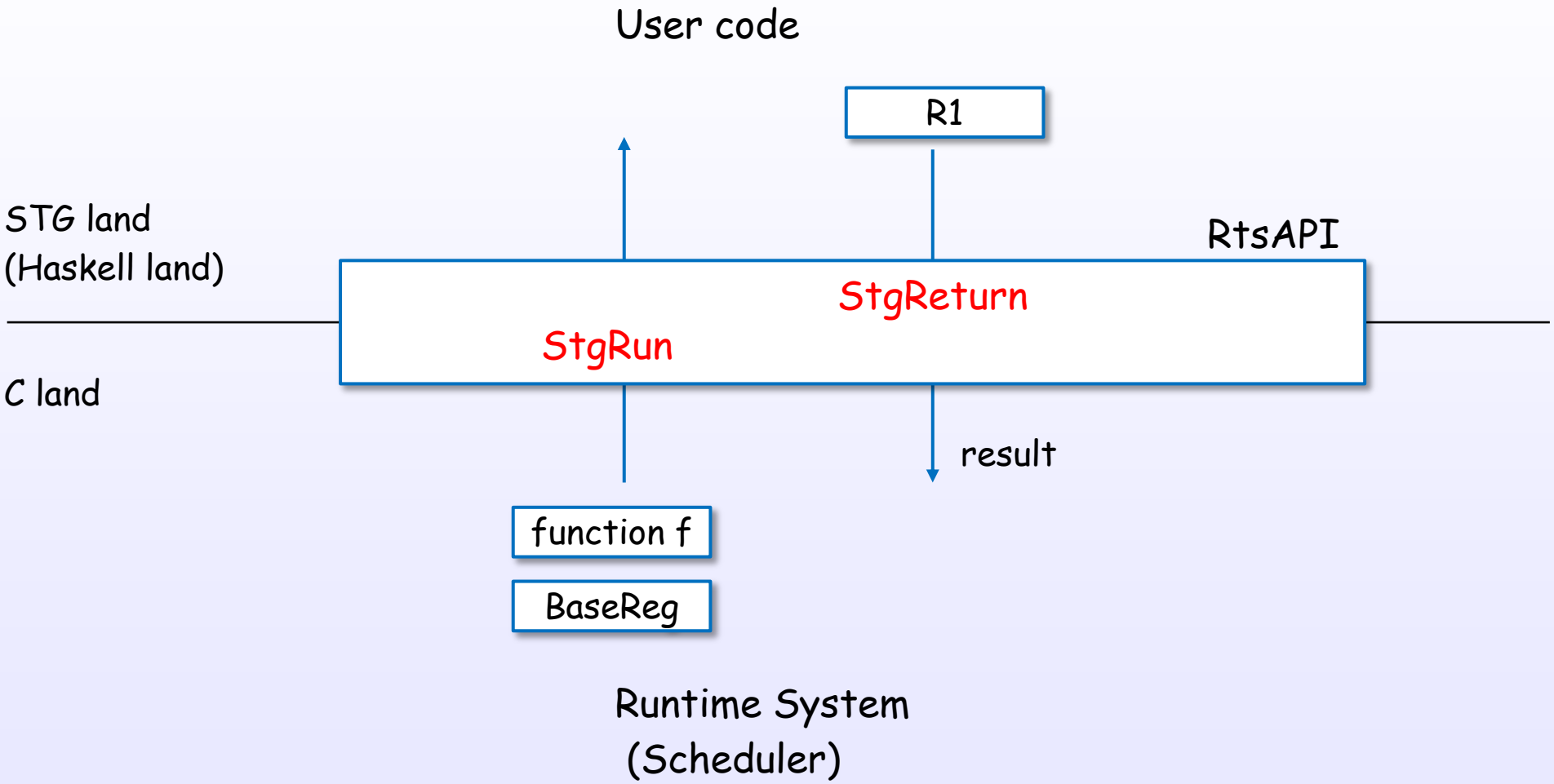
copying collection (minor GC)

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

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

STG - C land interface

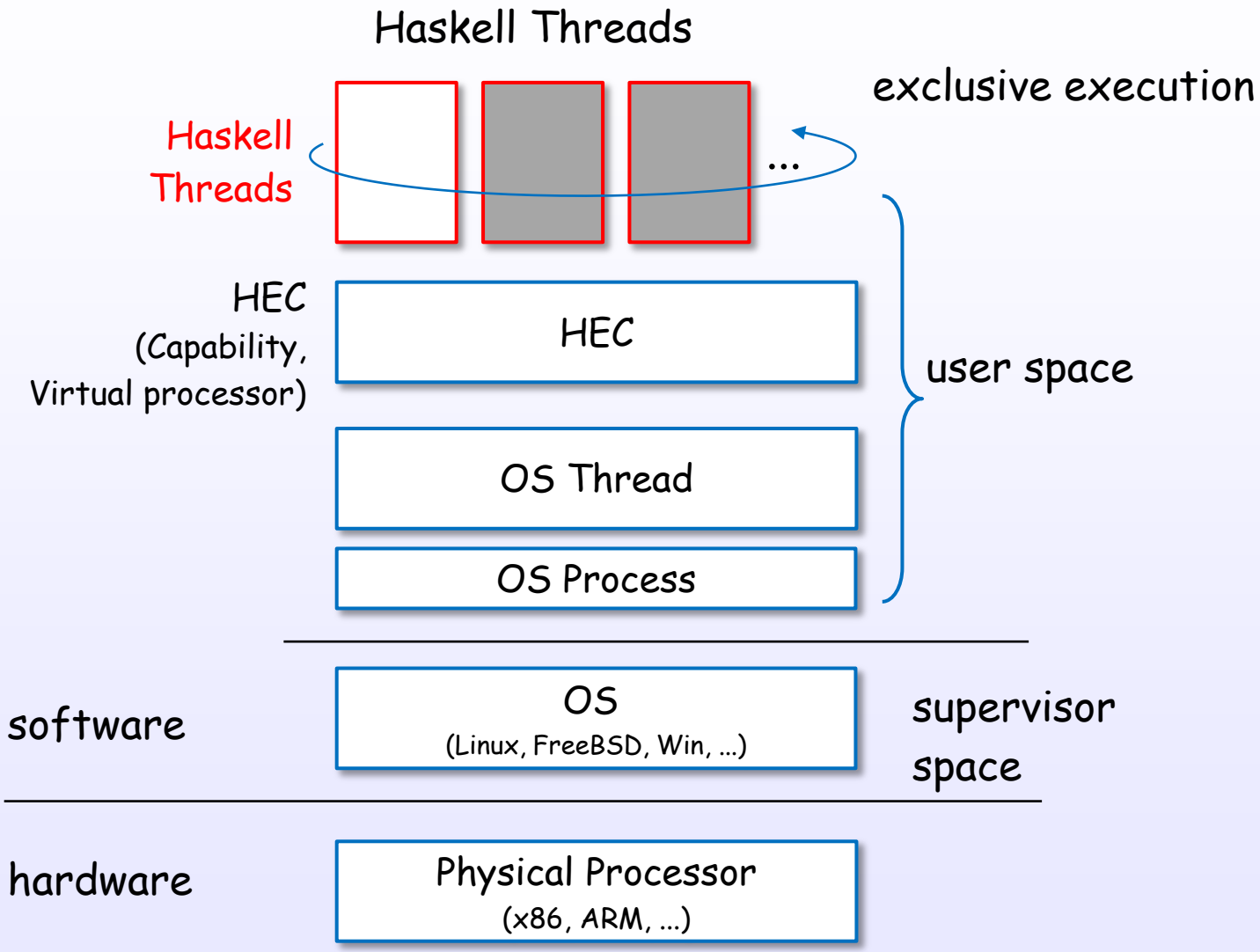
STG (Haskell) land - C land interface



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

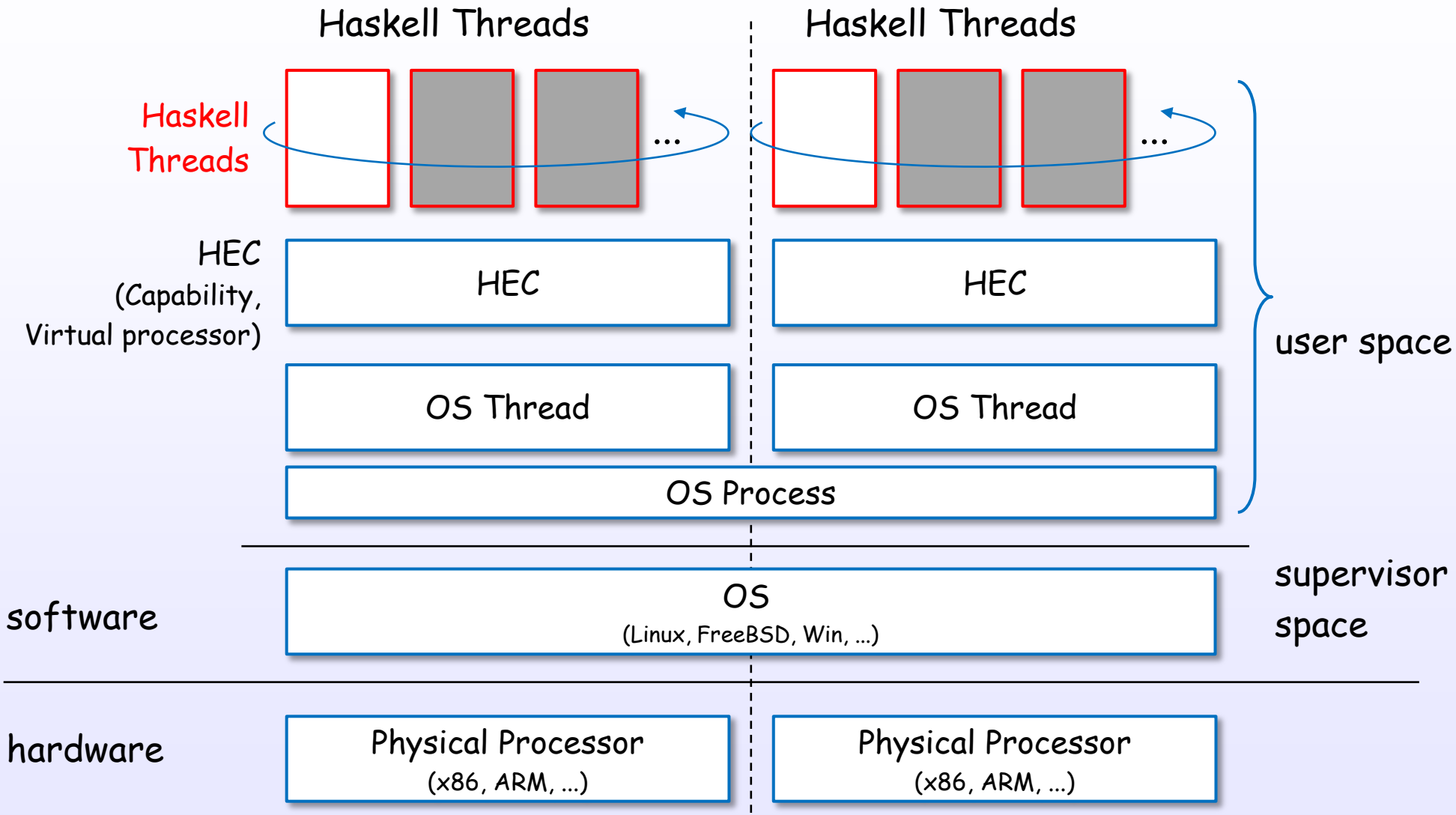
Thread

Thread layer (single core)



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

Thread layer (multi core)

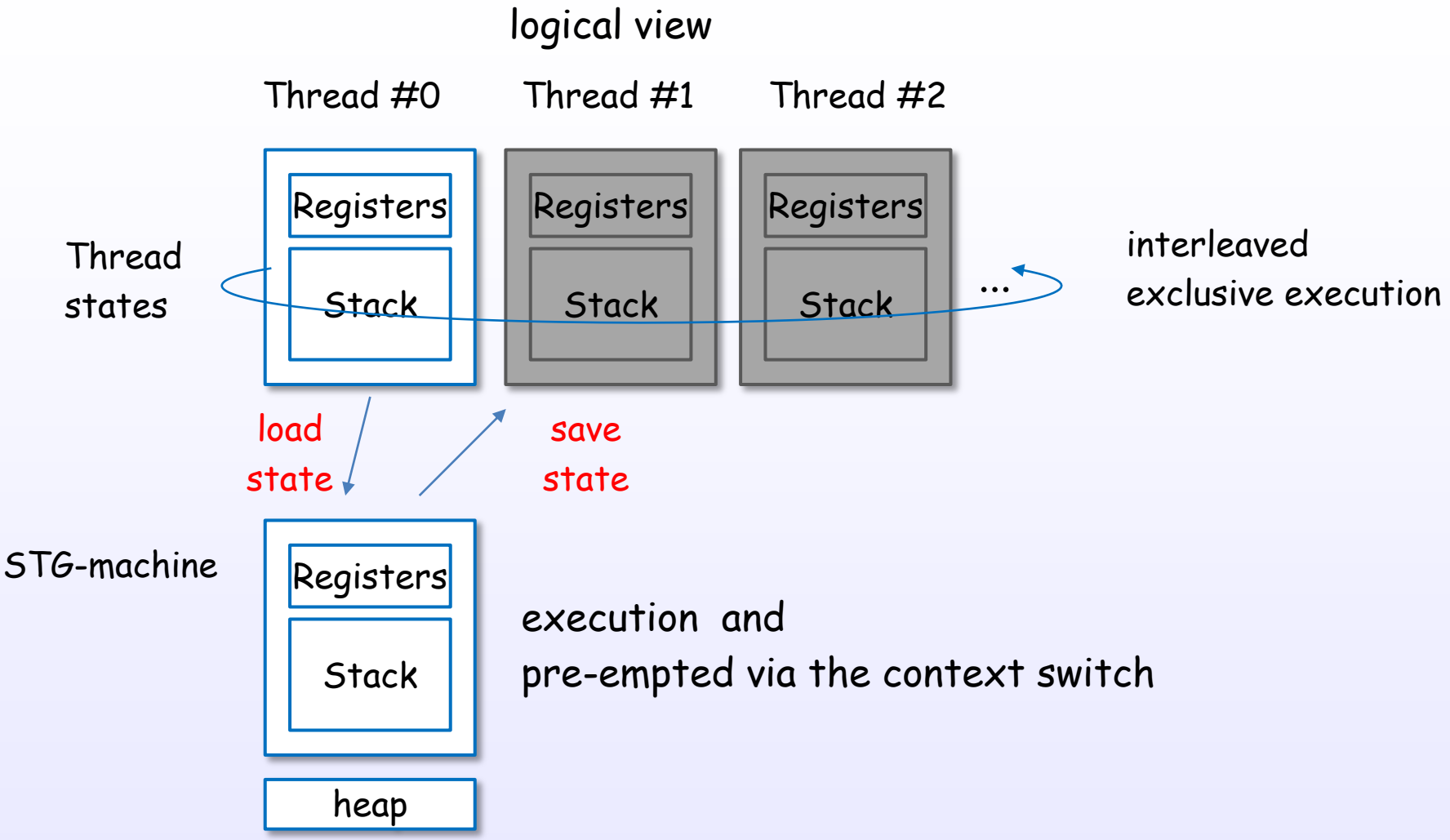


*Threaded option case (ghc -threaded)

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

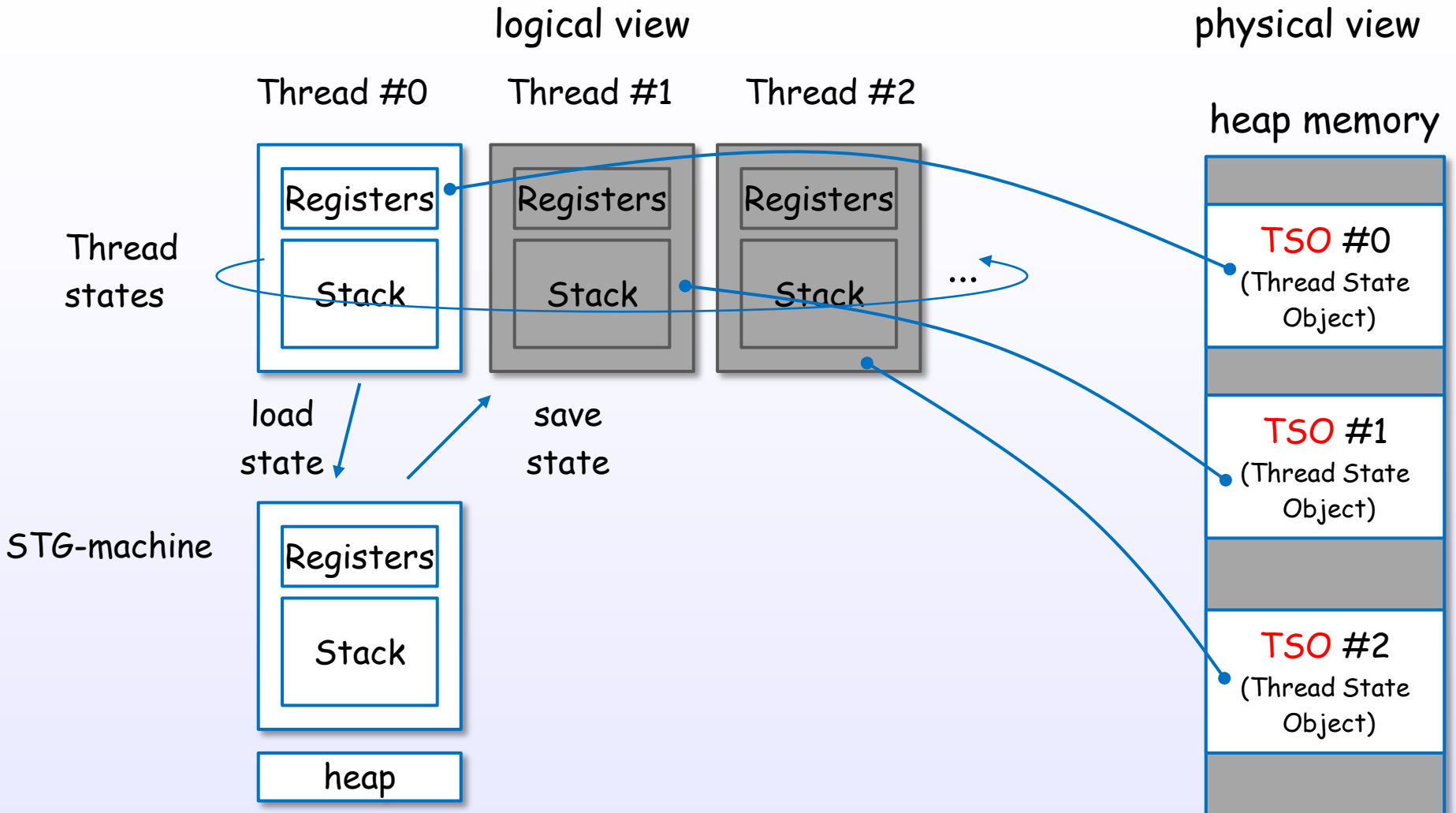
Thread context switch

Threads and context switch



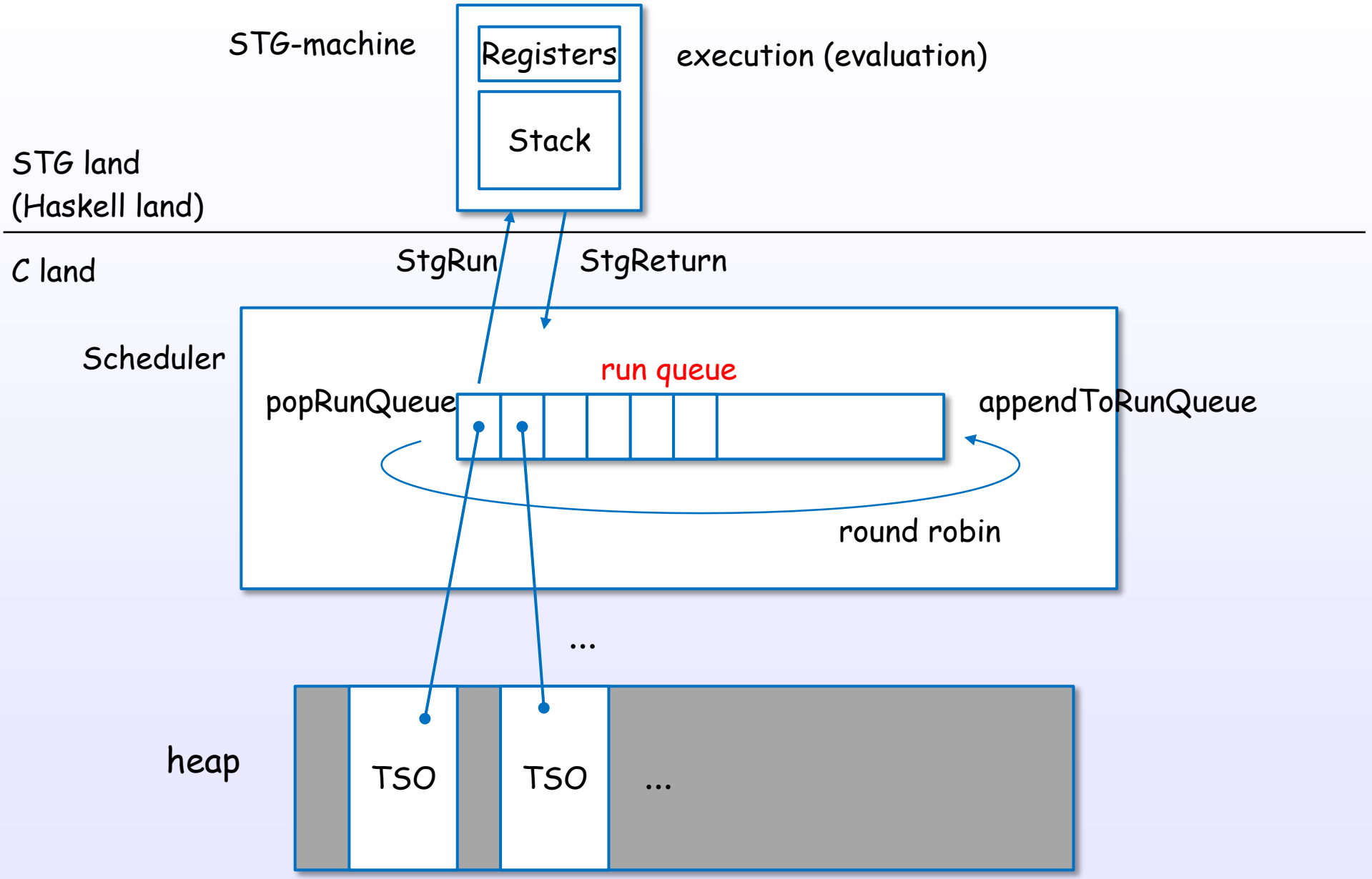
References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

Threads and TSOs



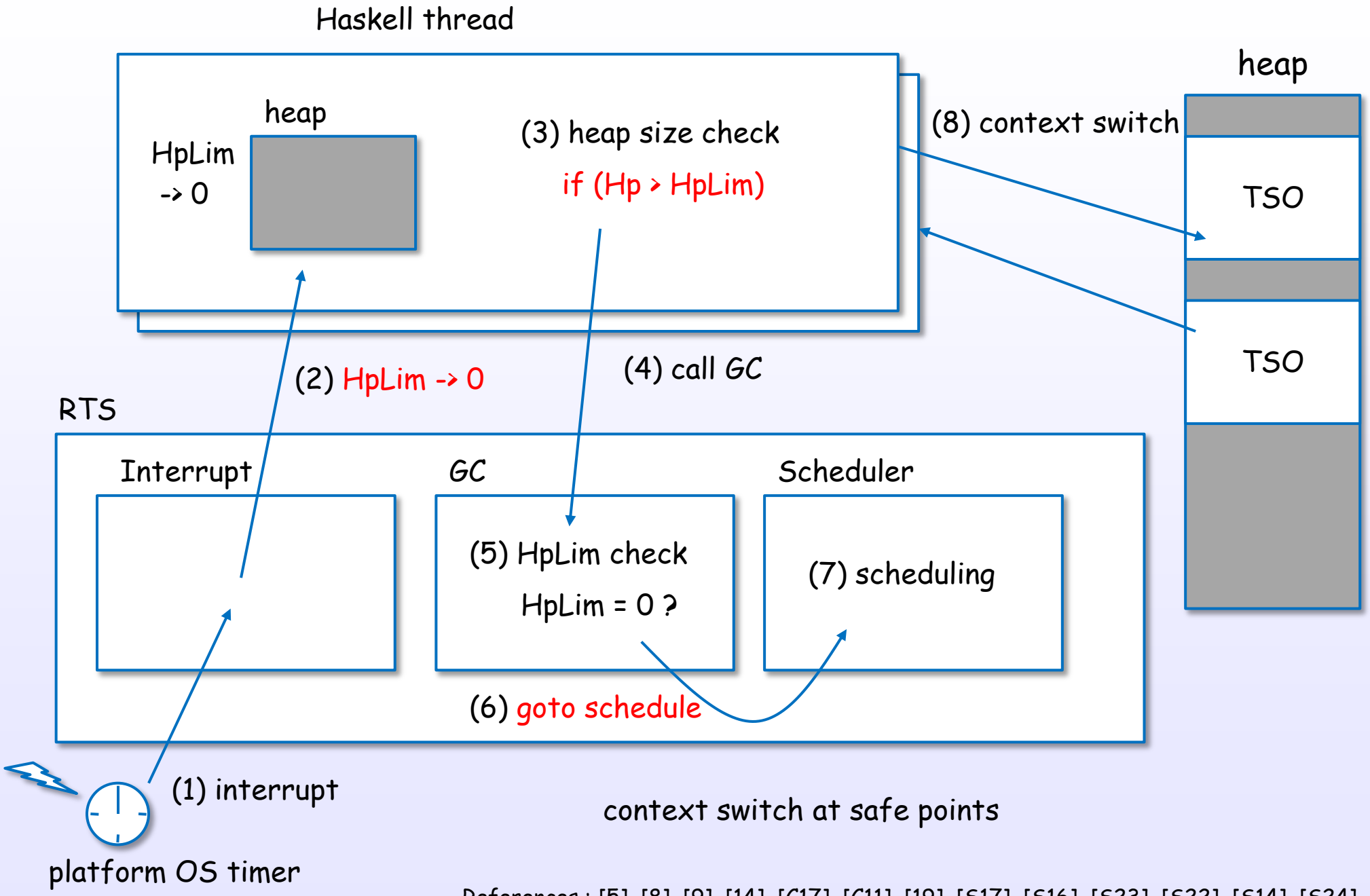
References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

Scheduling by run queue



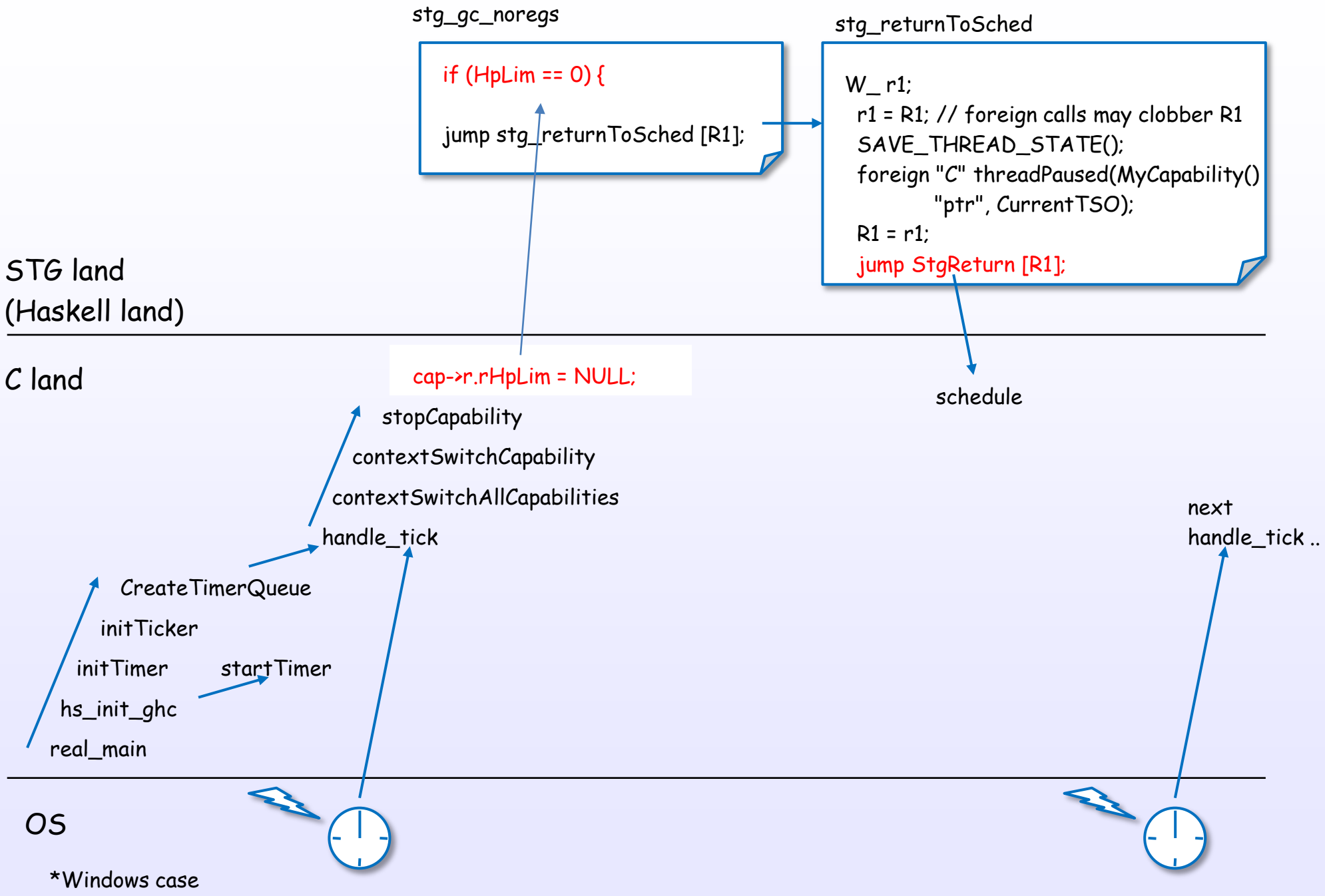
References : [5], [8], [9], [14], [C17], [C11], [19], [S17], [S16], [S23], [S22], [S14]

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], [S23], [S22], [S14], [S24]

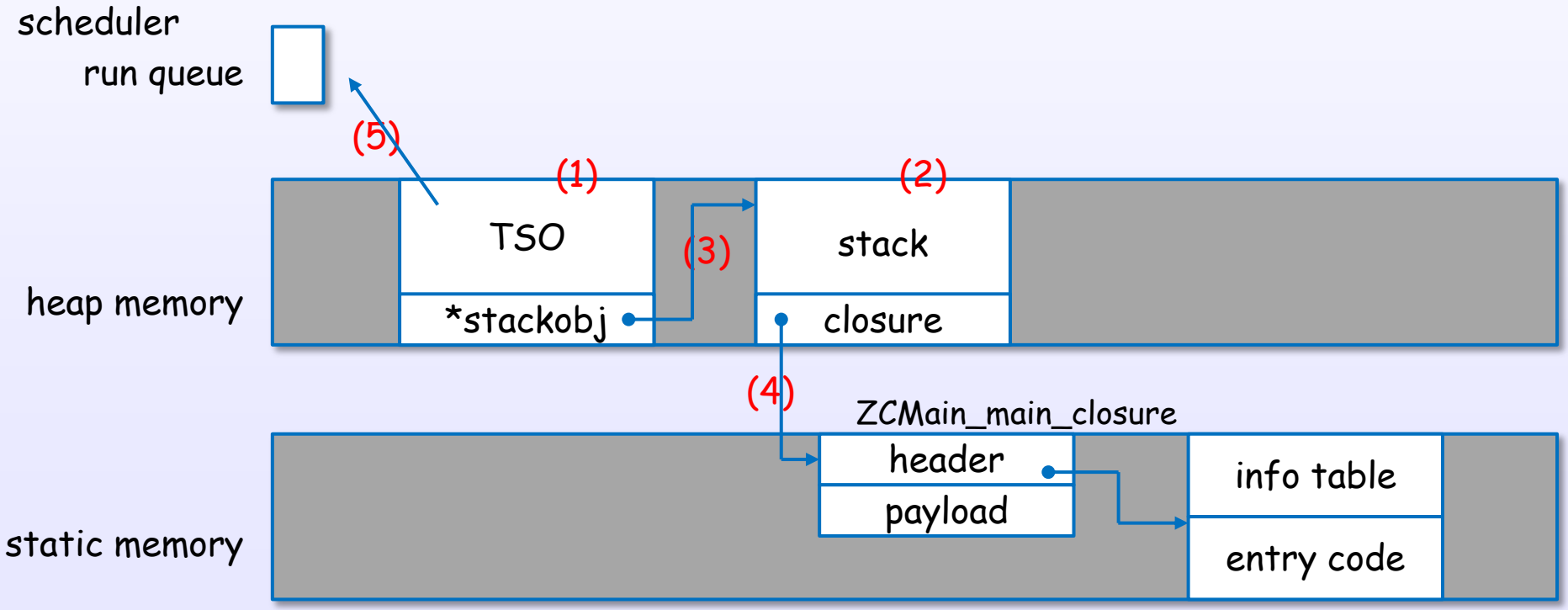
Creating main and sub threads

Create a main thread

Runtime System

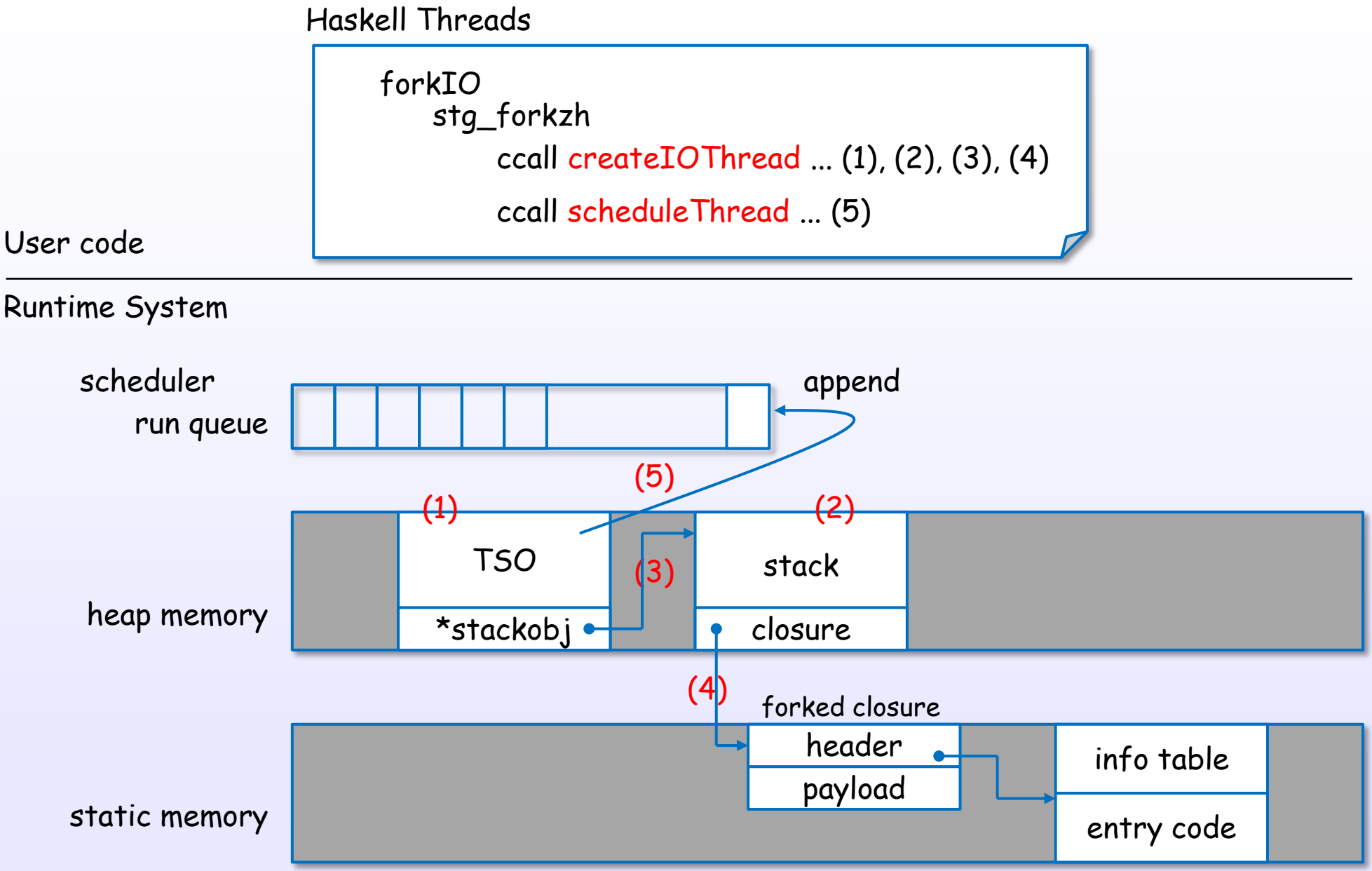
Runtime system bootstrap code [rts/RtsAPI.c]

```
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]

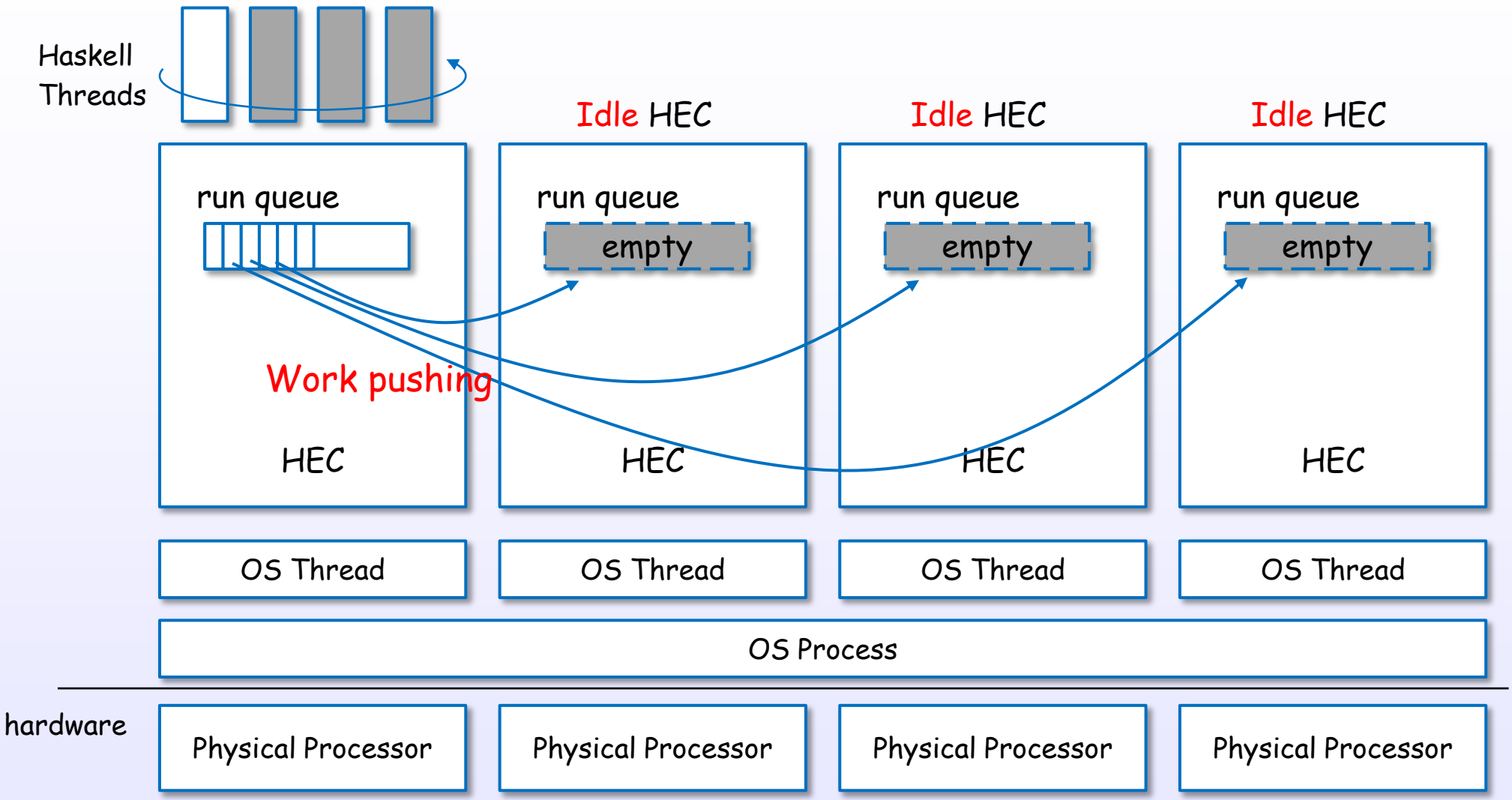
Create a sub thread by forkIO



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

Thread migration

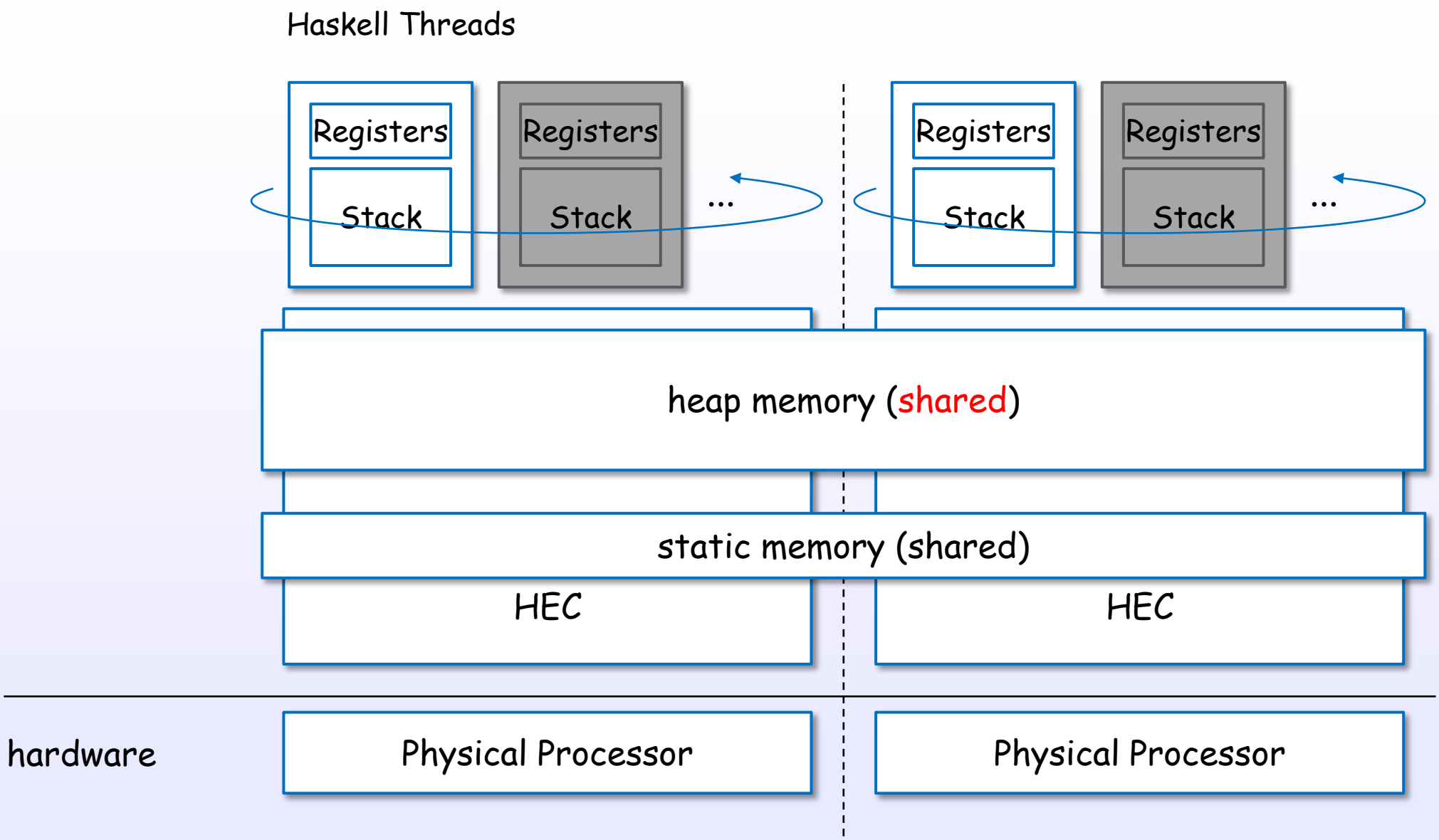
Threads are migrated to idle HECs



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

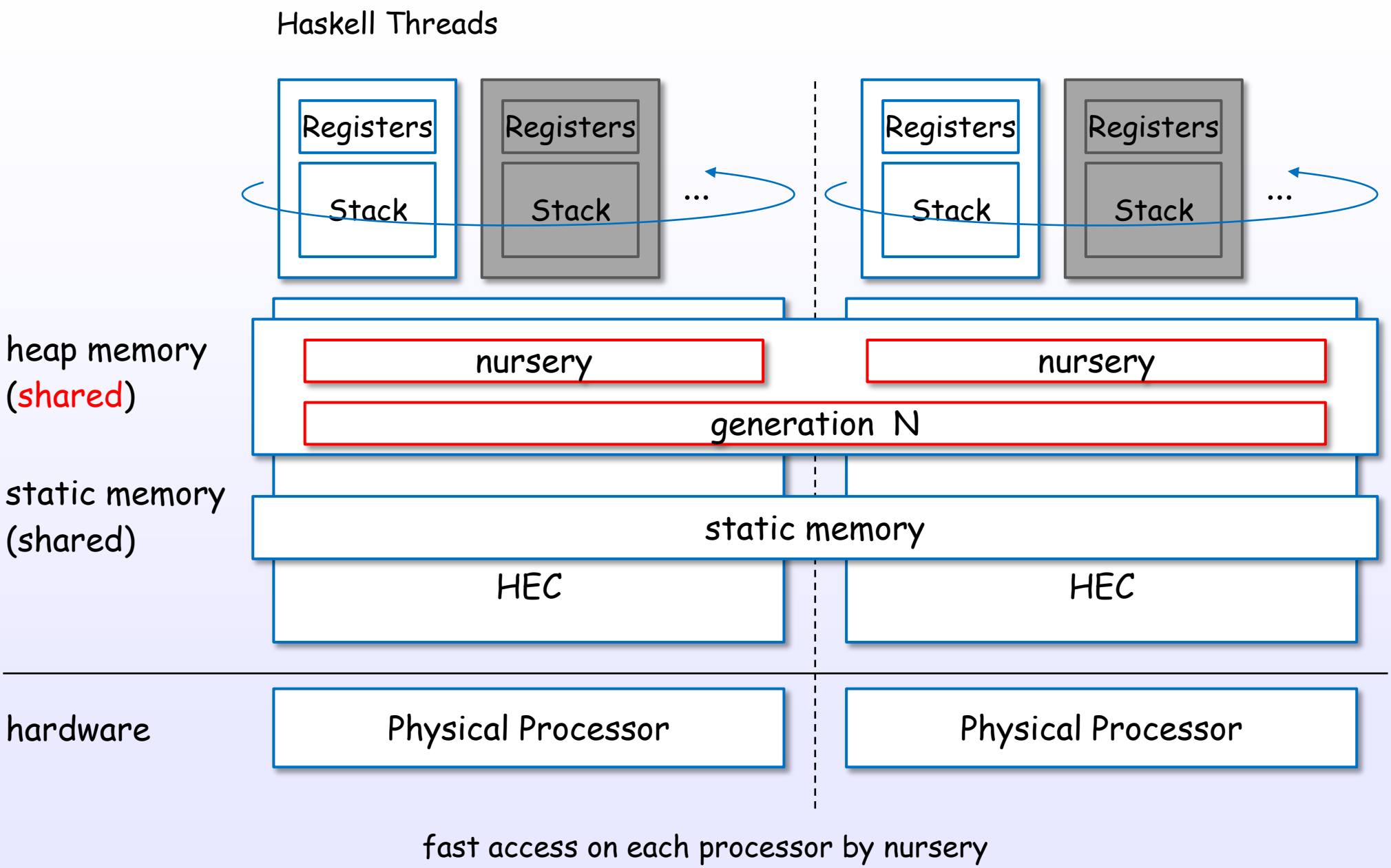
Heap and Threads

Threads and a shared heap



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

Local allocation area (nursery)

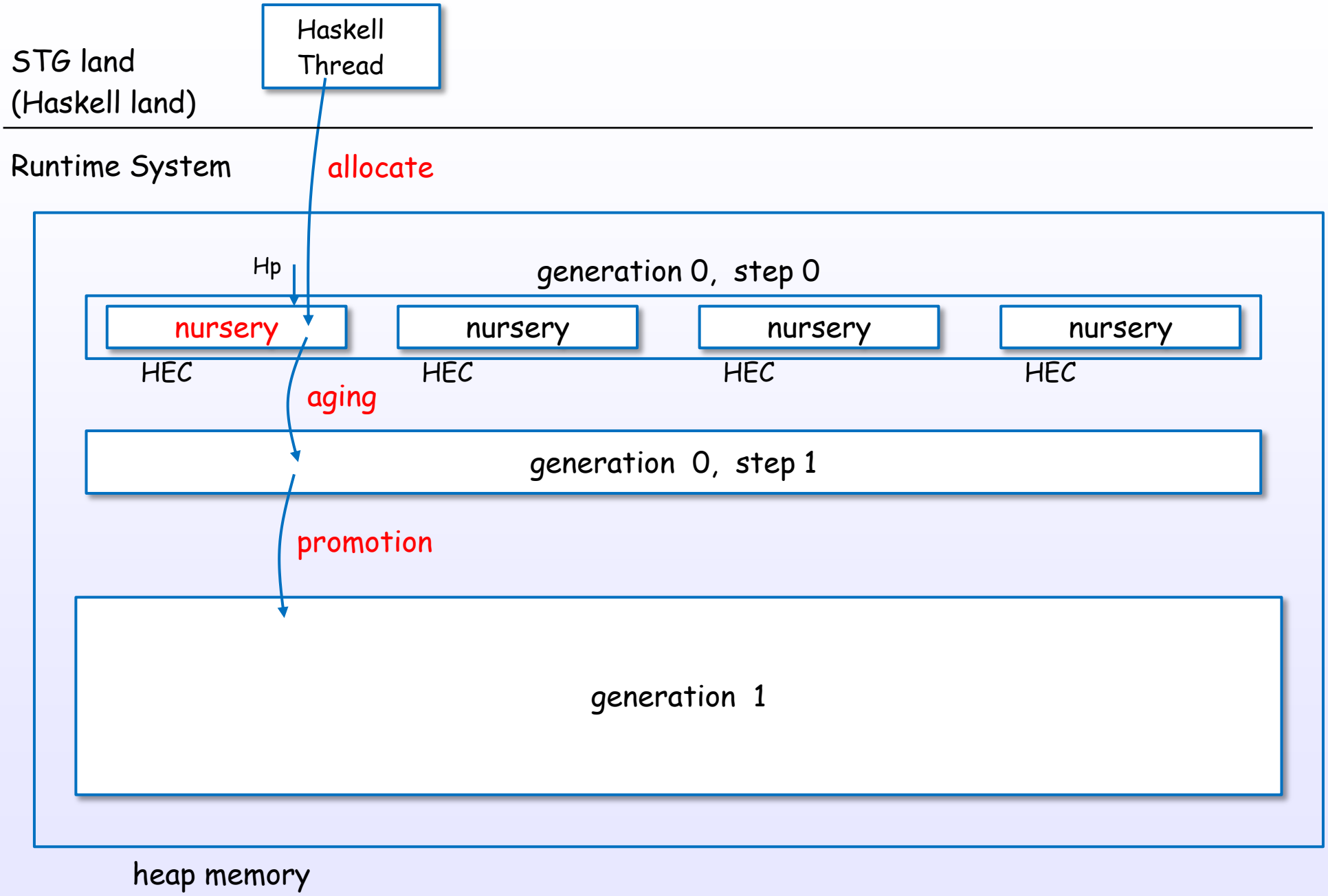


fast access on each processor by nursery

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

Threads and GC

GC, nursery, generation, aging, promotion

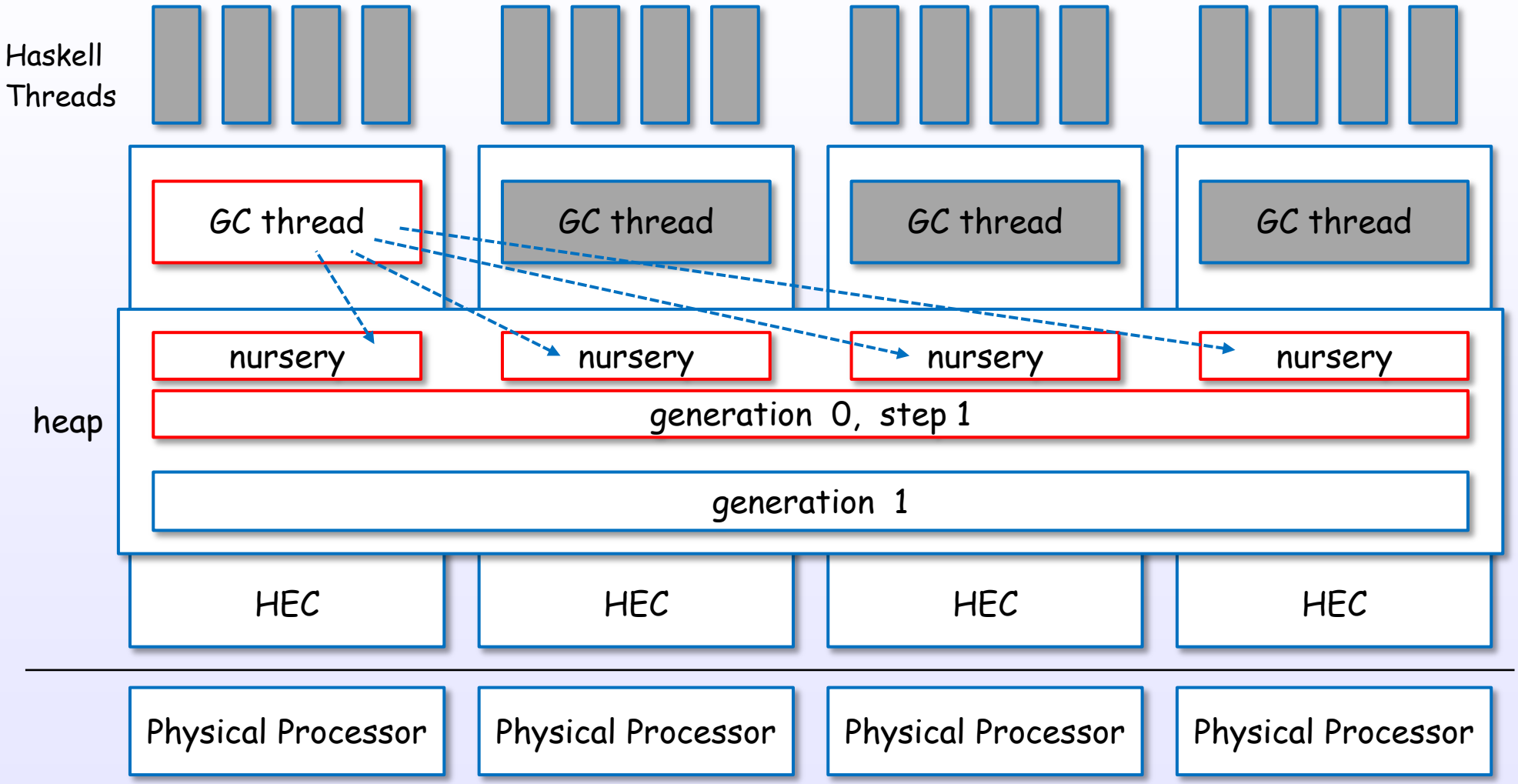


References : [8], [9], [15], [C13], [C11], [S25]

Threads and minor GC

sequential GC for young generation (minor GC)

"stop-the-world" GC

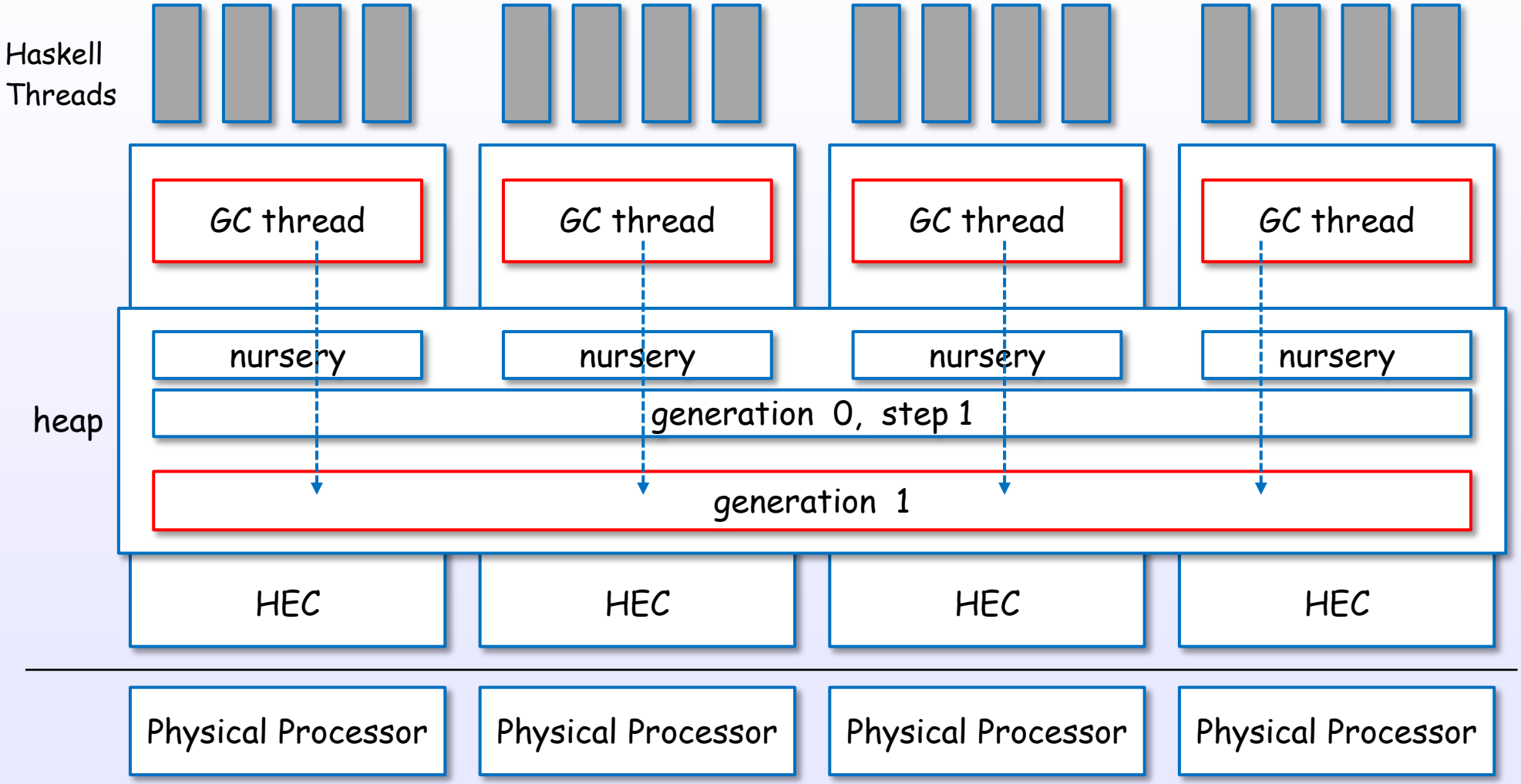


References : [8], [9], [15], [C13], [C11], [S25]

Threads and major GC

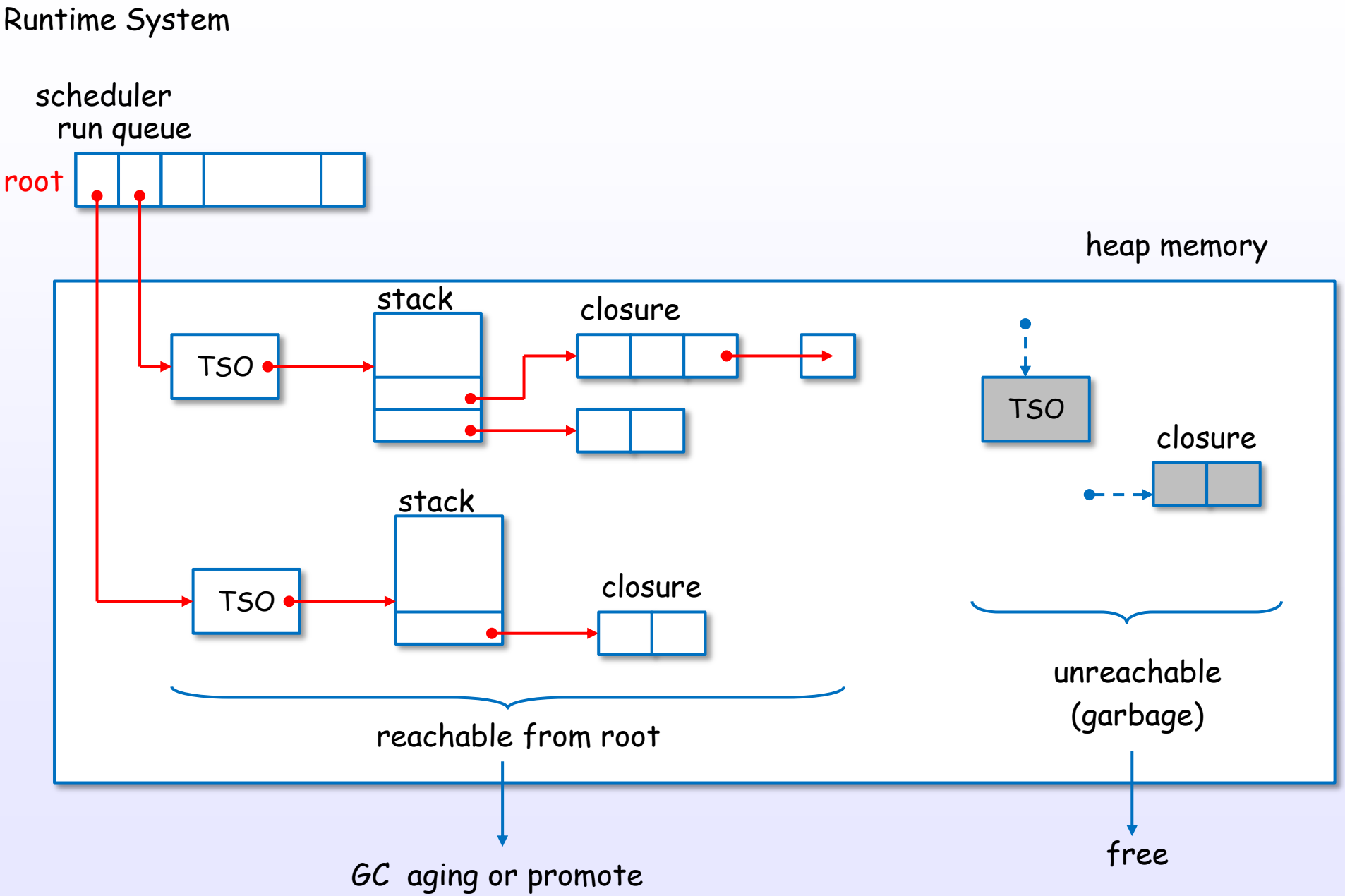
parallel GC for oldest generation (major GC)

"stop-the-world" GC



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

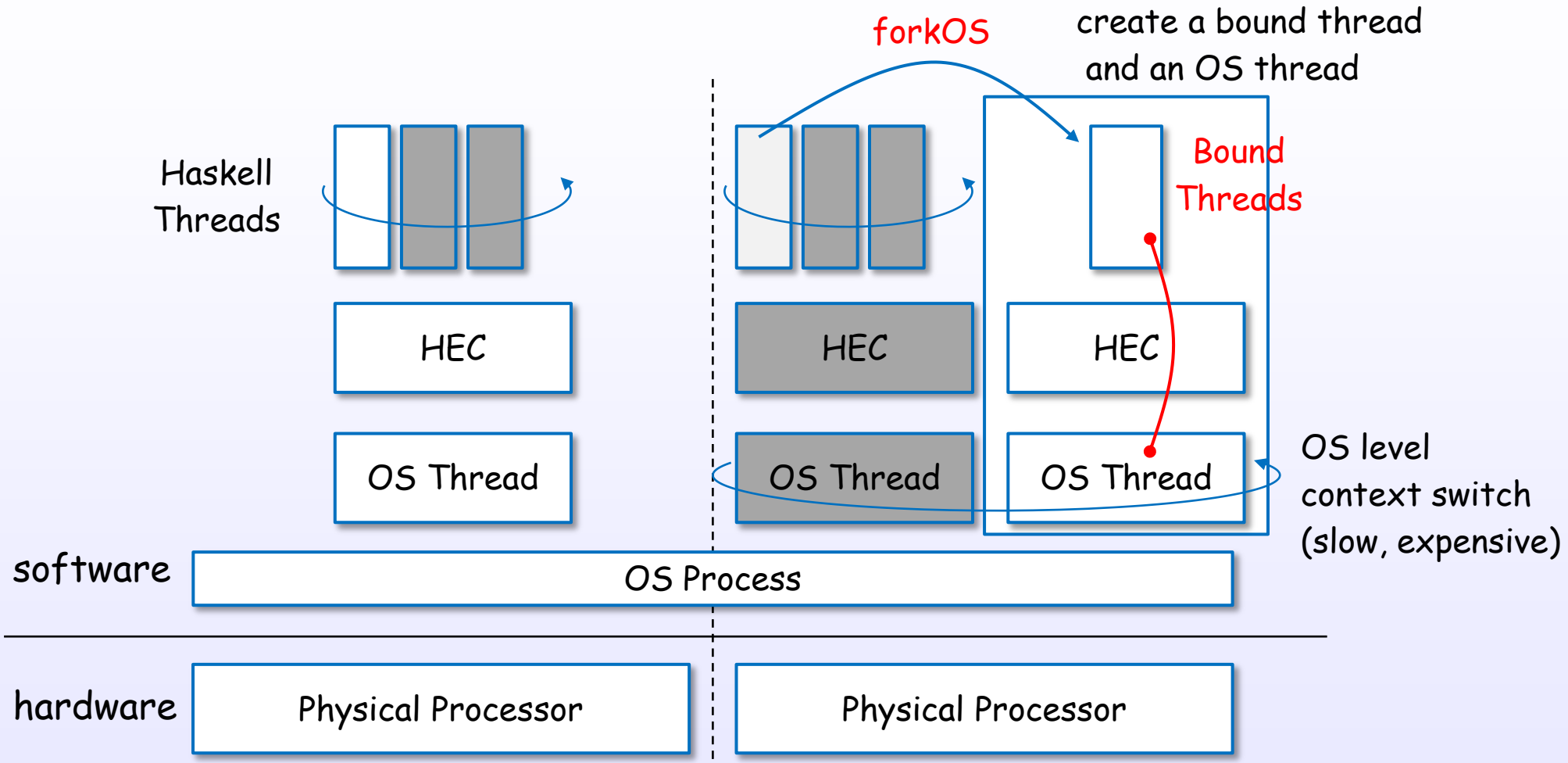
GC discover live objects from the root



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

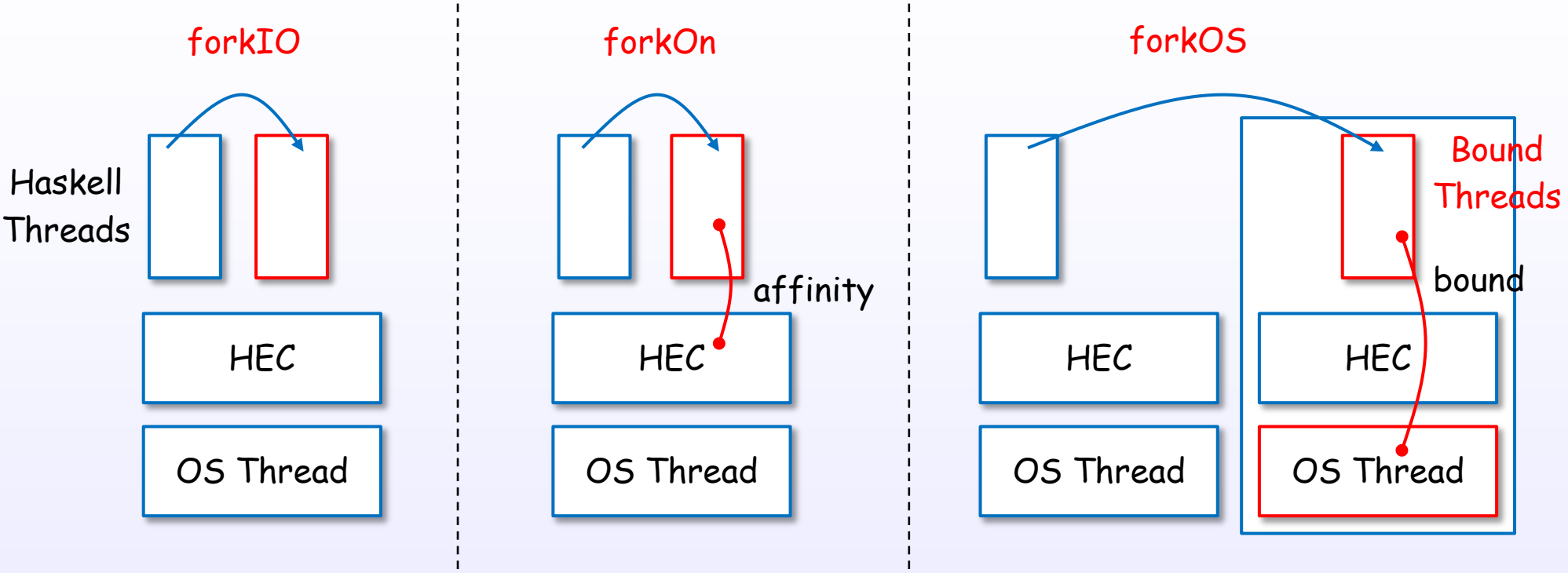
Bound thread

Create a bound thread by forkOS



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

forkIO, forkOn, forkOS



create a haskell thread

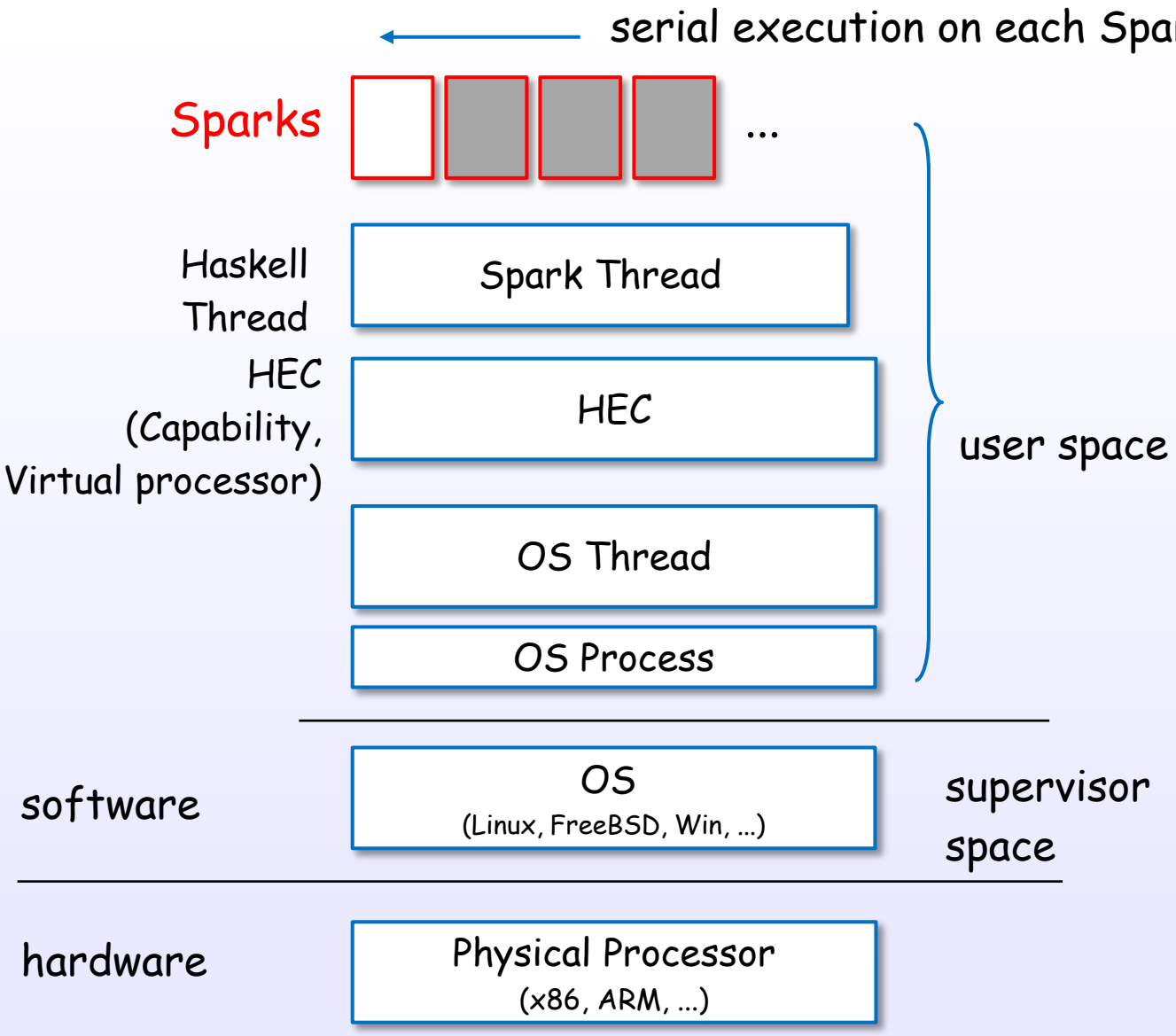
create a haskell thread on specified HEC

create a haskell thread and an OS thread

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

Spark

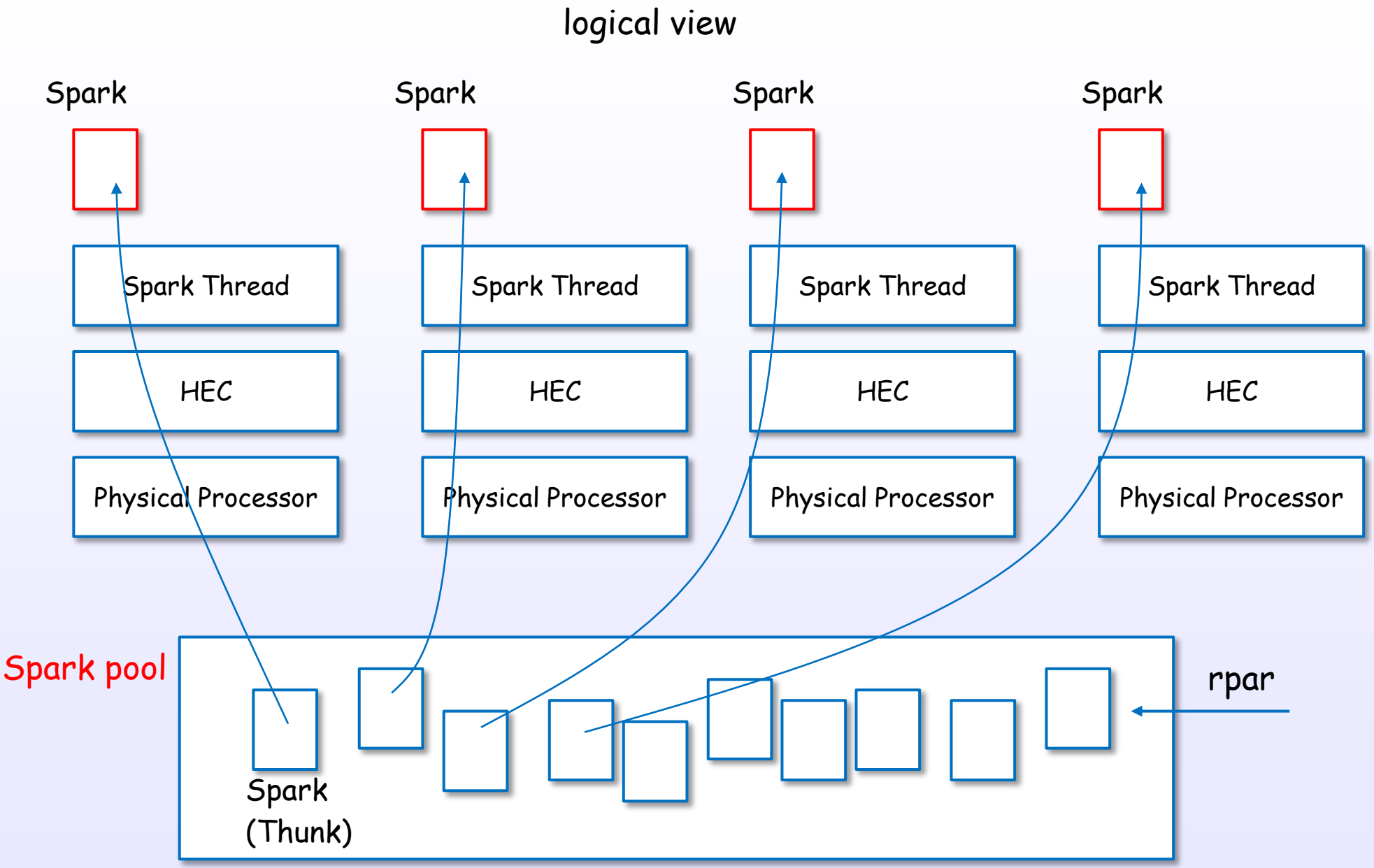
Spark layer



Spark Threads are generated on idle HECs.

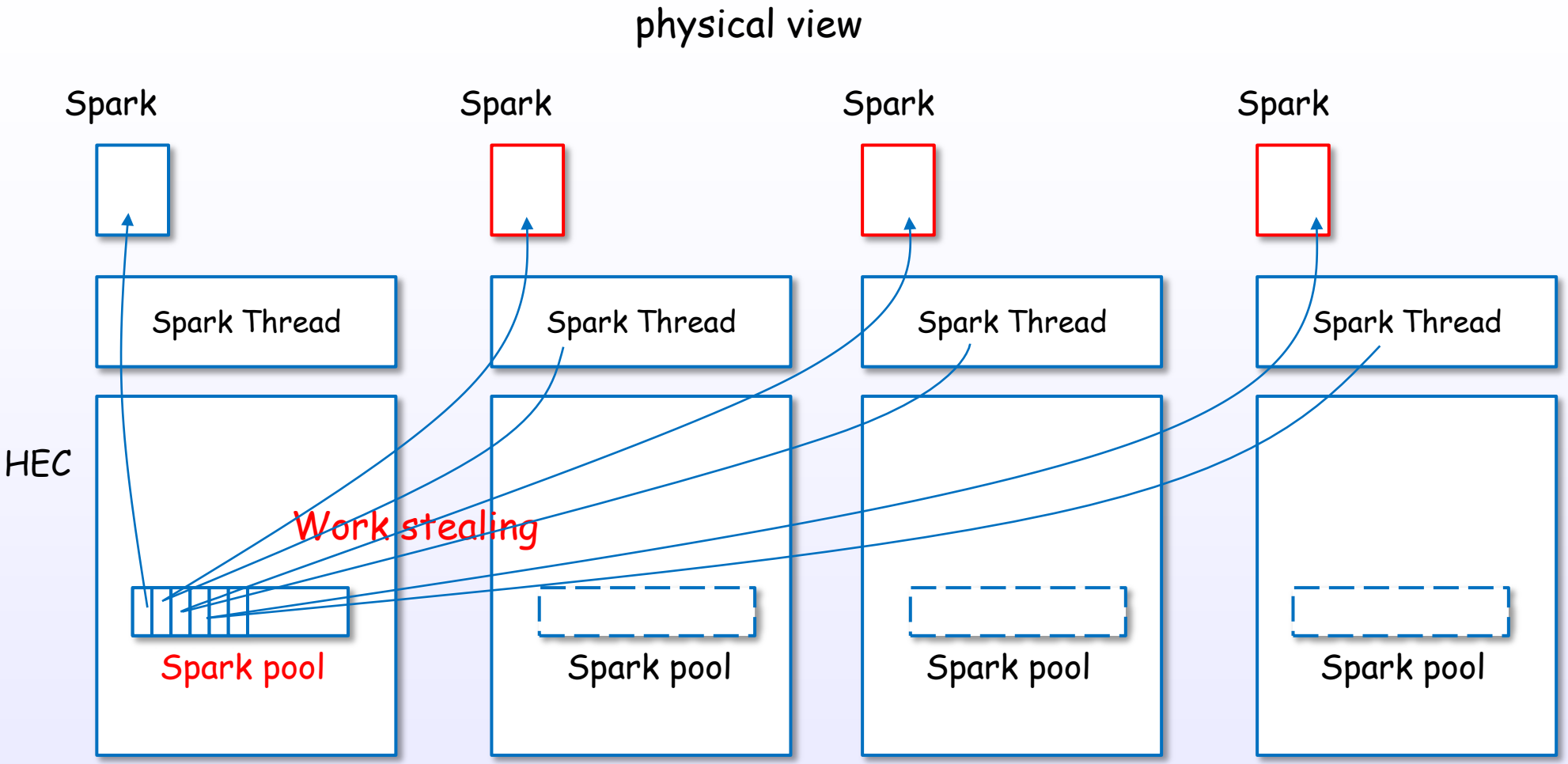
References : [C17], [19], [S17], [S26], [S27], [S33], [S12]

Sparks and Spark pool



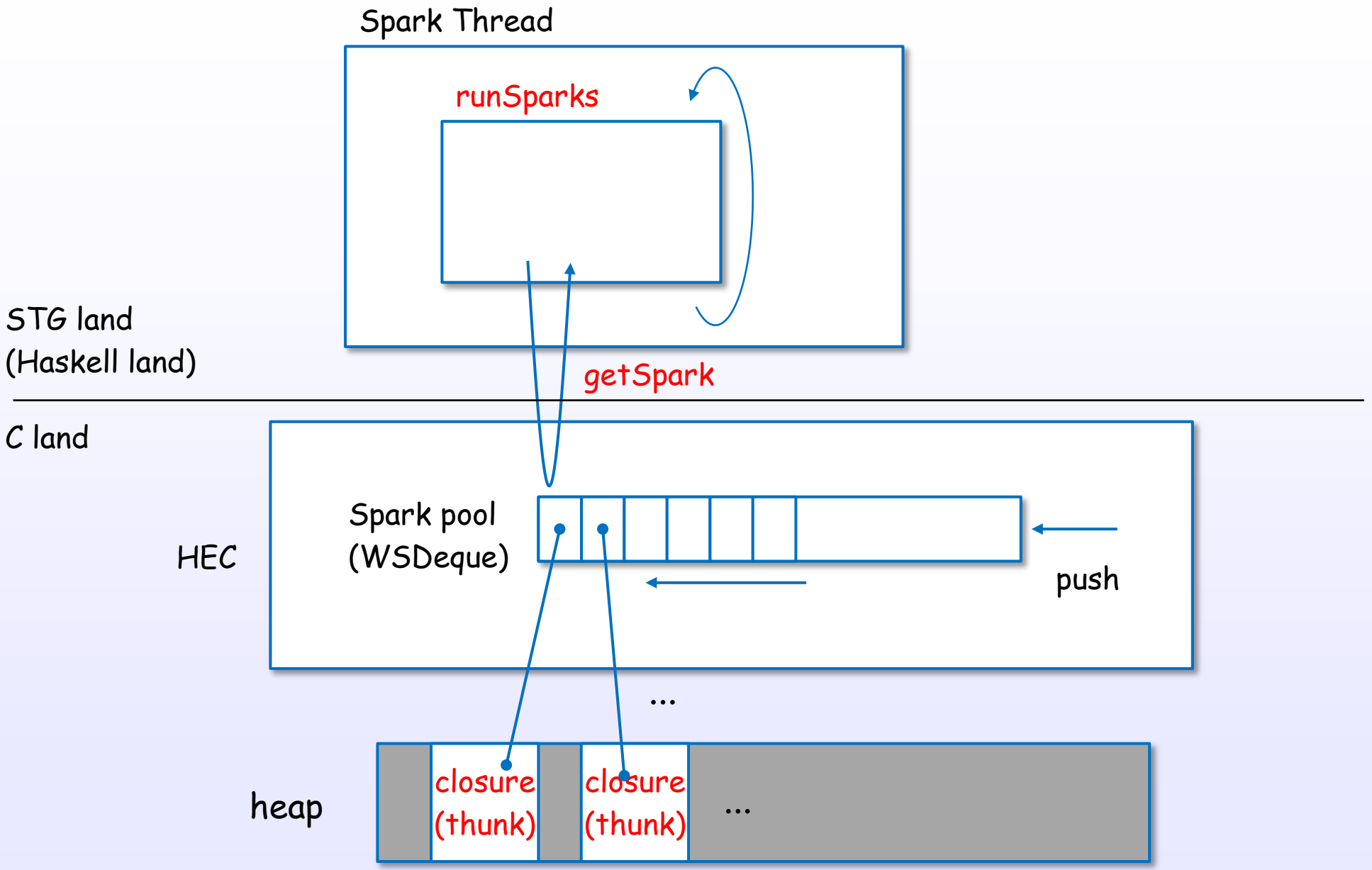
References : [C17], [19], [S17], [S26], [S27], [S33], [S12]

Spark pool and work stealing



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

Sparks and closures

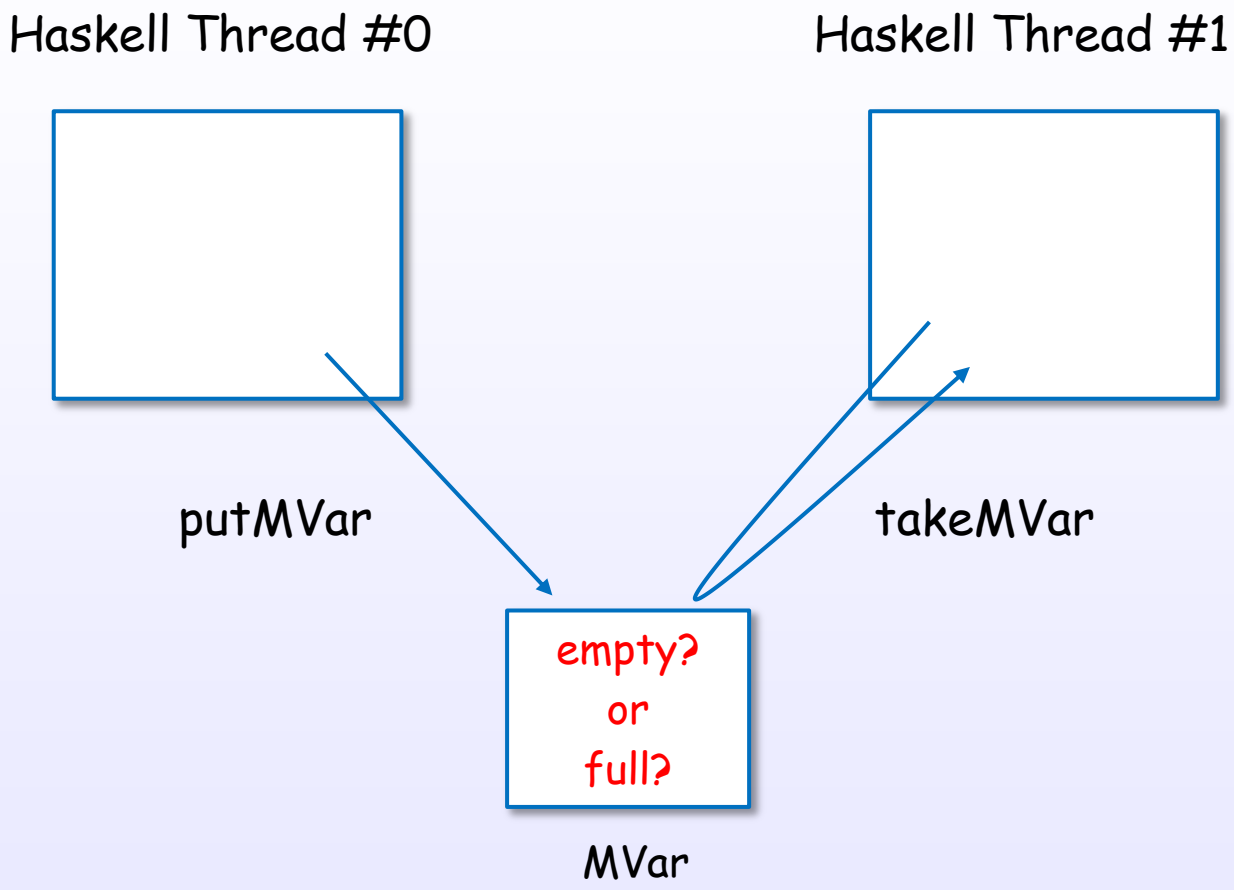


(not TSO objects, but closures. therefore very lightweight)

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

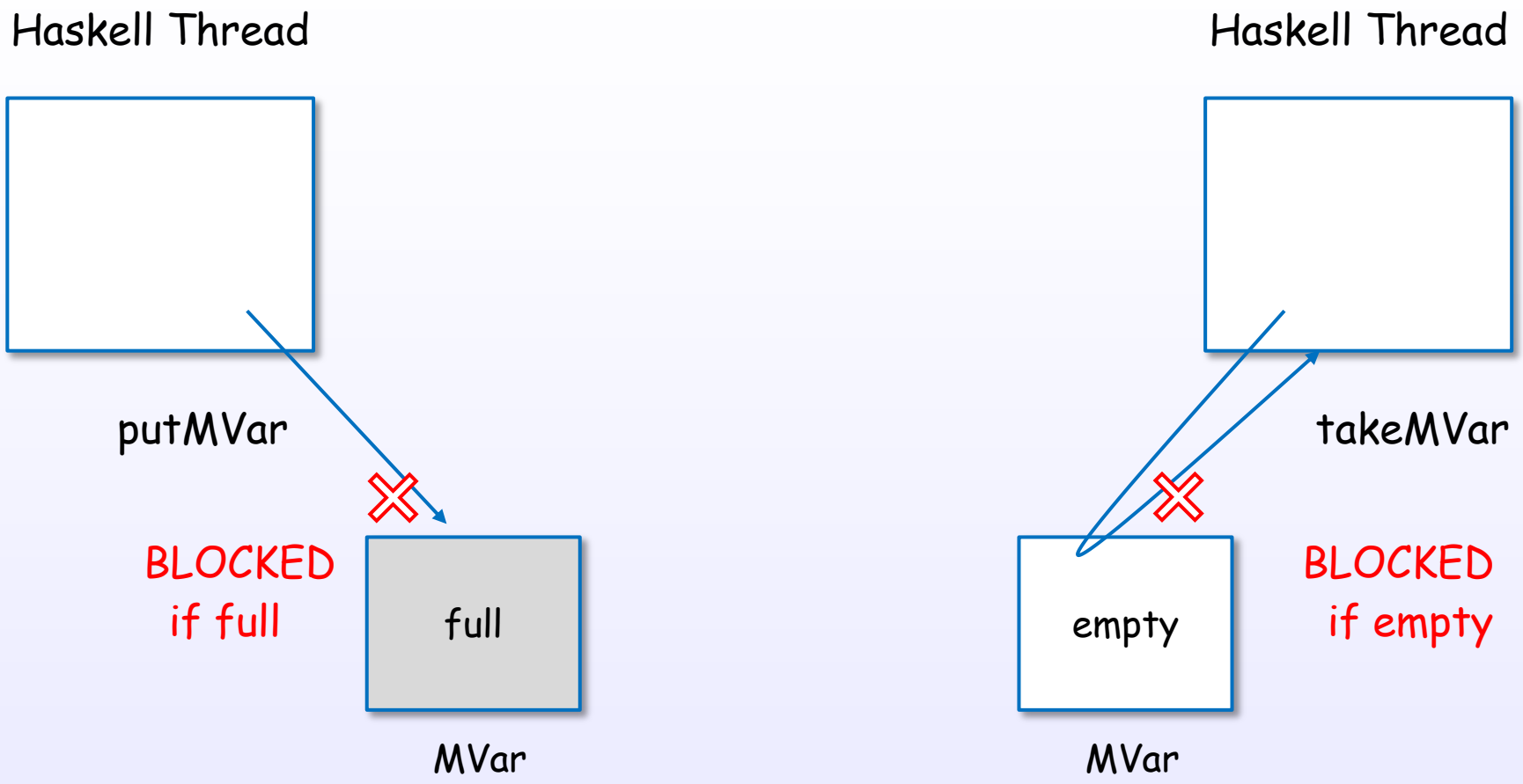
MVar

MVar



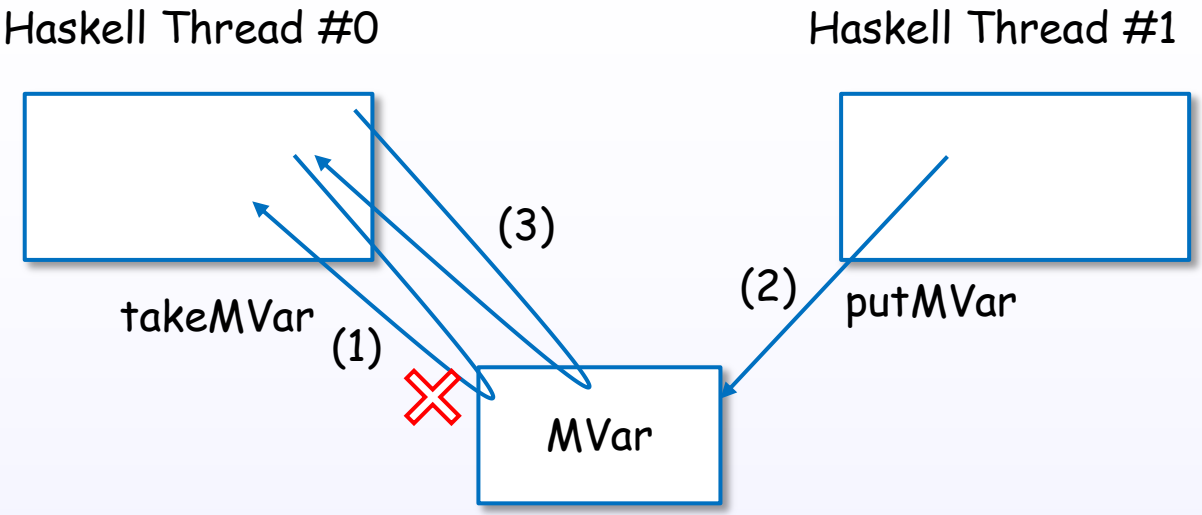
References : [16], [18], [19], [S31], [S12]

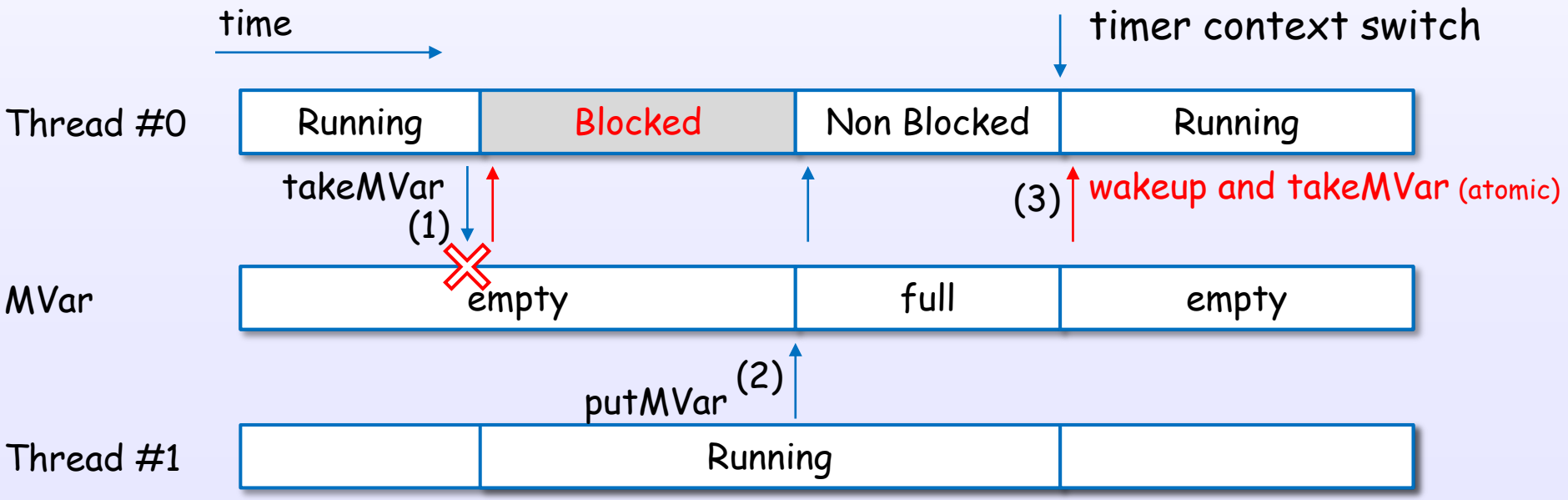
MVar and blocking



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

MVar example





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

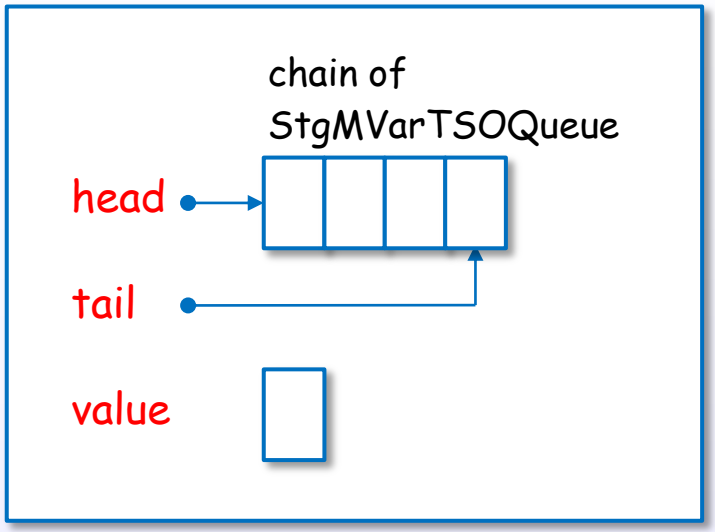
MVar object view

User view

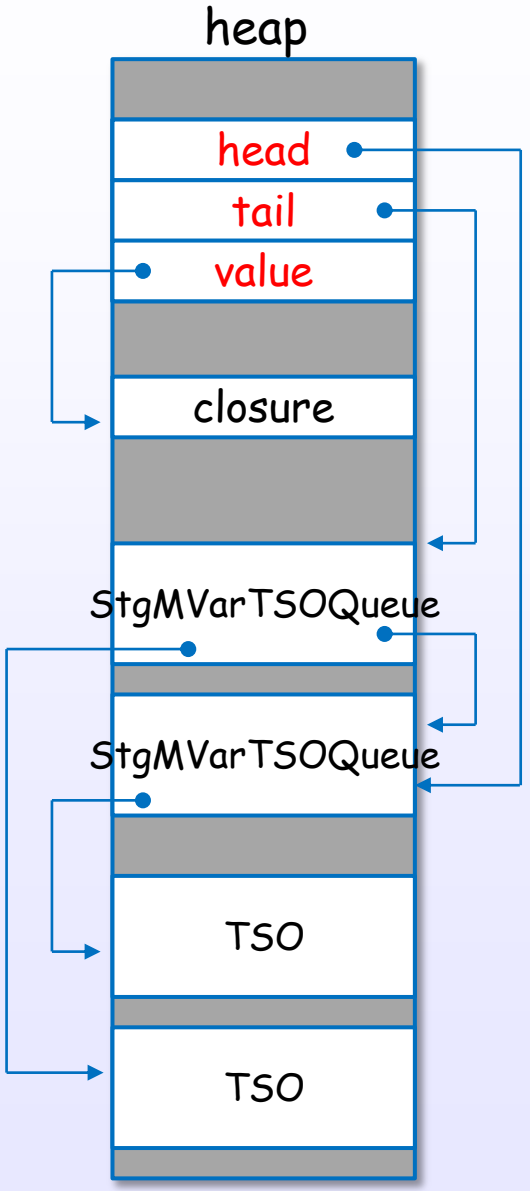
MVar

empty?
or
full?

logical MVar object

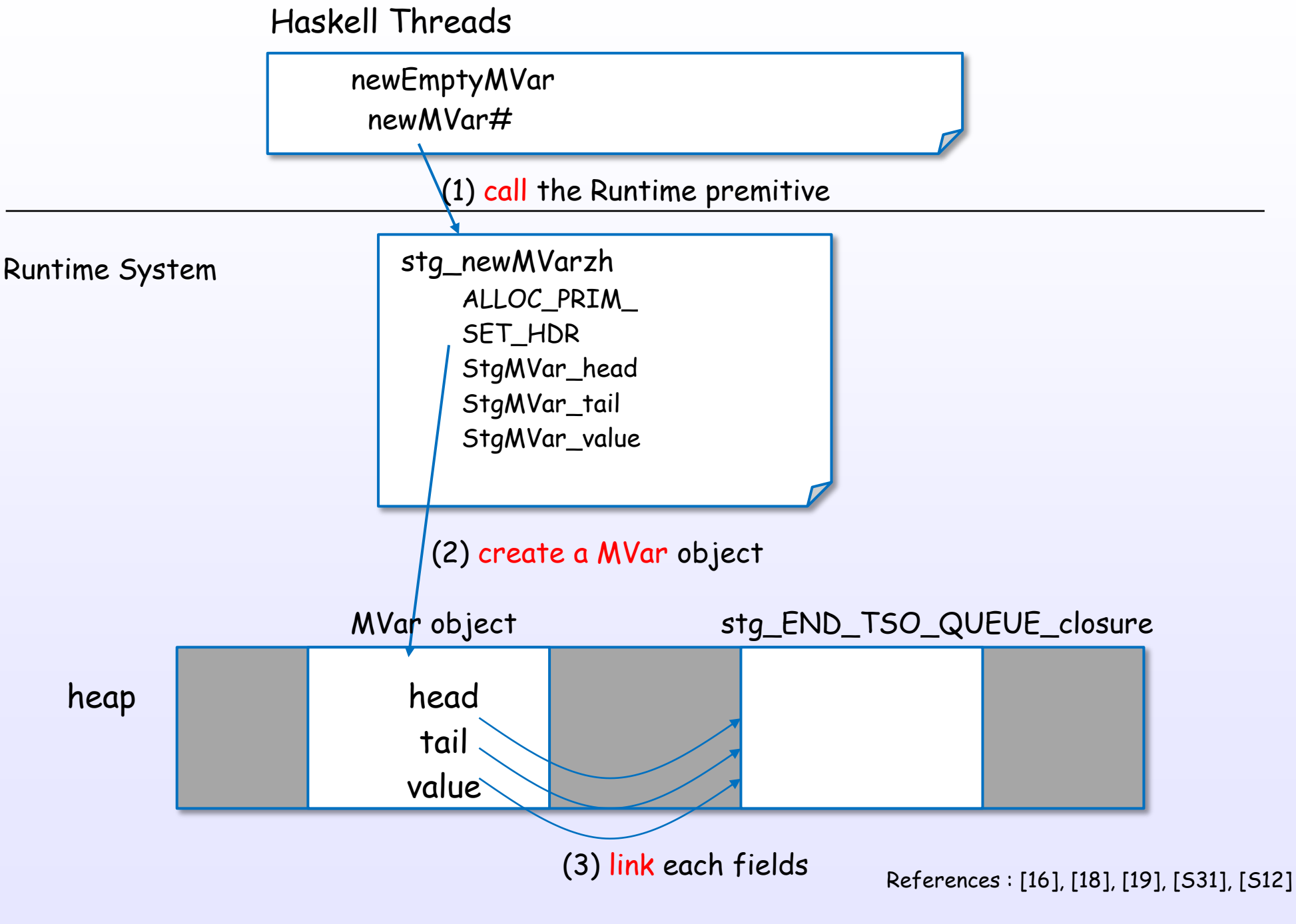


physical MVar object



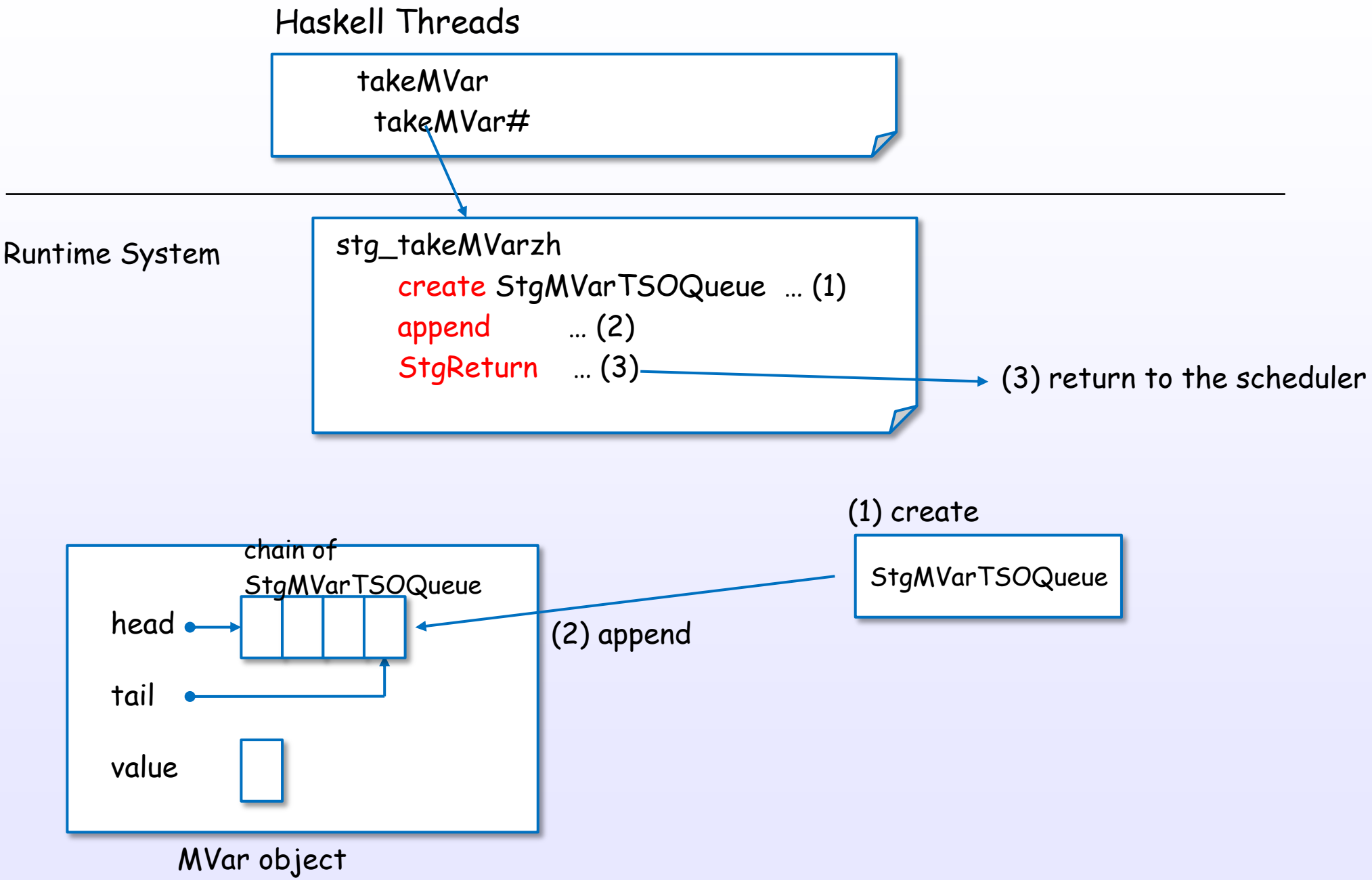
References : [16], [18], [19], [S31], [S12]

newEmptyMVar



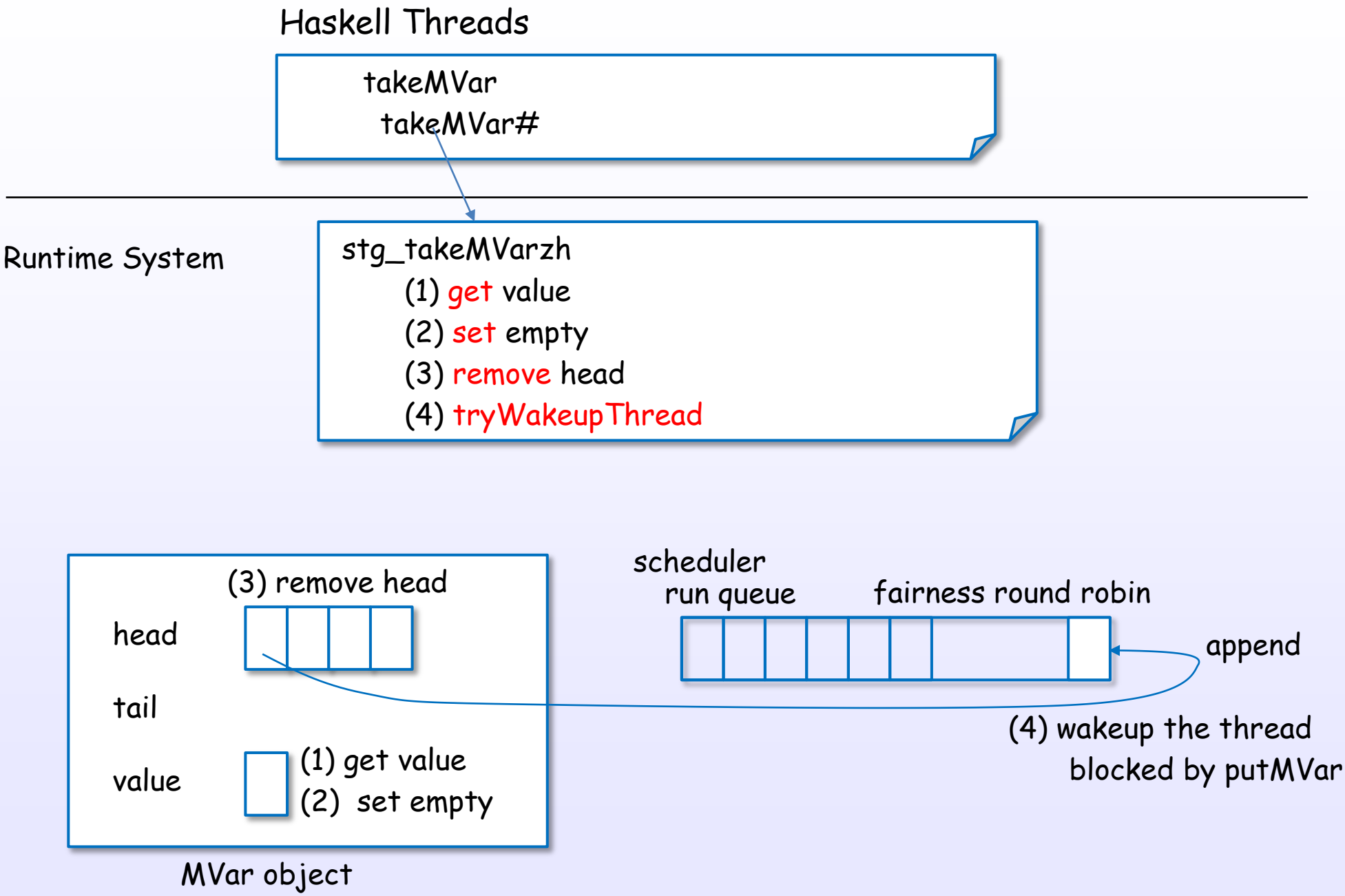
References : [16], [18], [19], [S31], [S12]

takeMVar (empty case)



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

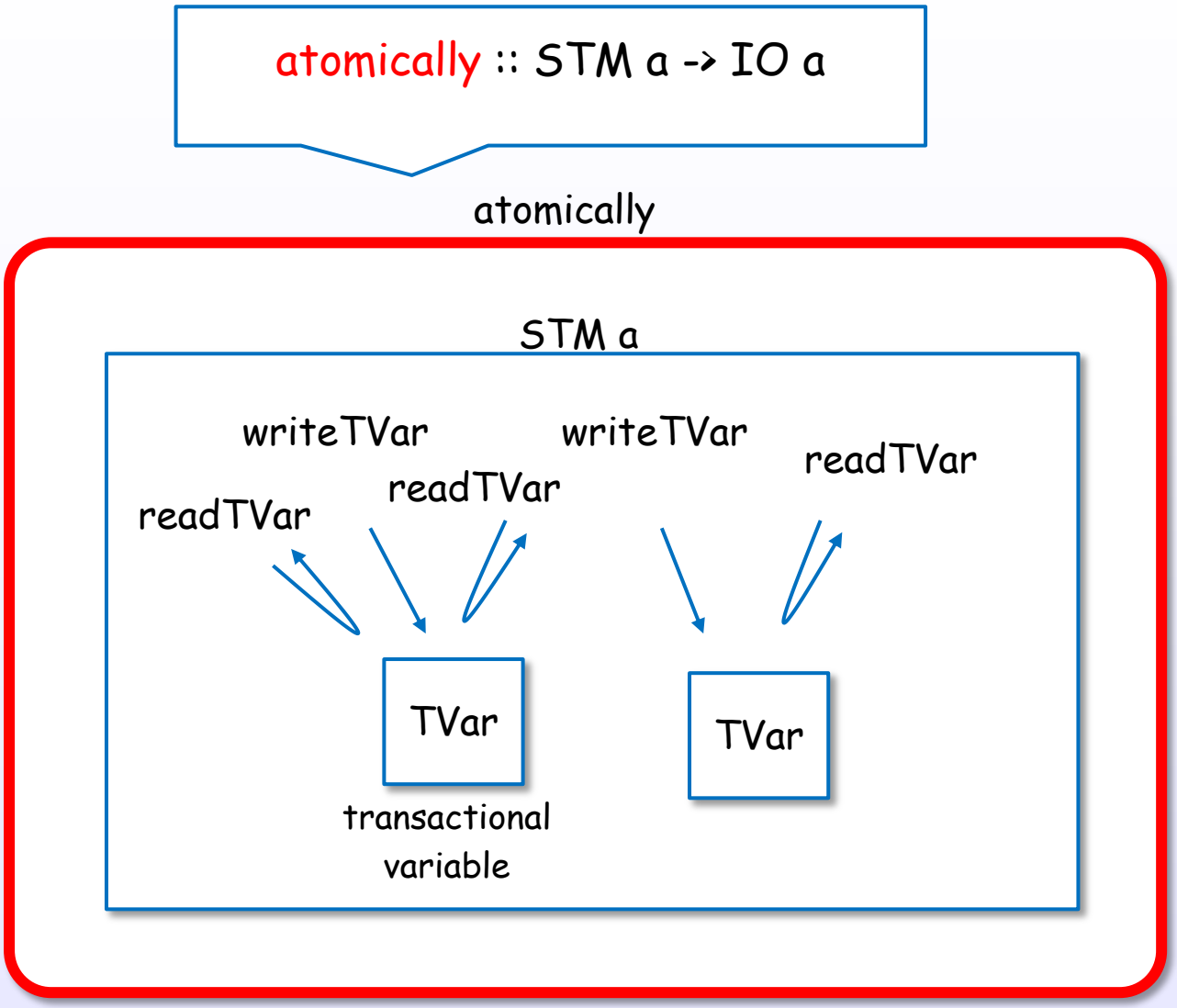
takeMVar (full case)



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

Software transactional memory

Create a atomic block by atomically

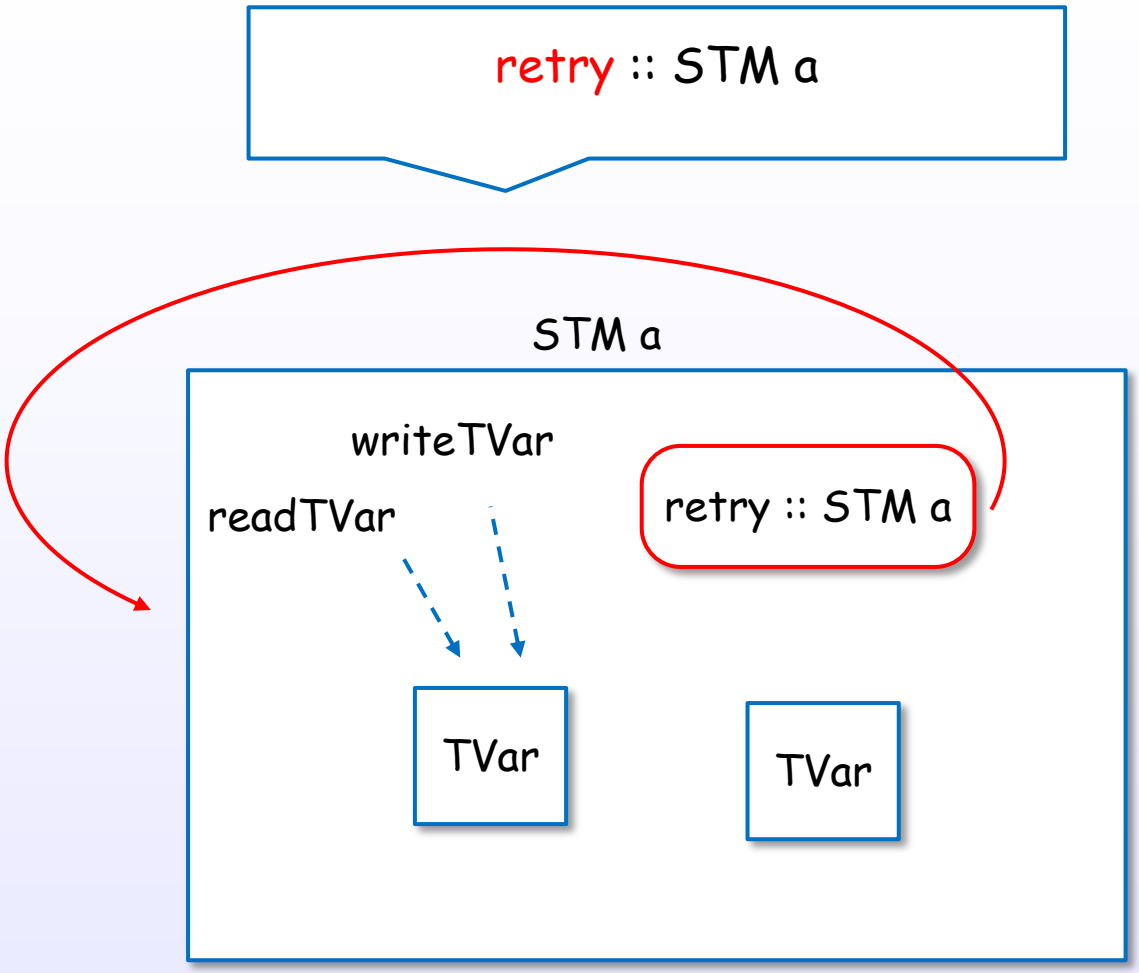


Create and evaluate a composable "atomic block"

Atomic block = All or Nothing

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

Rollback and blocking control by retry

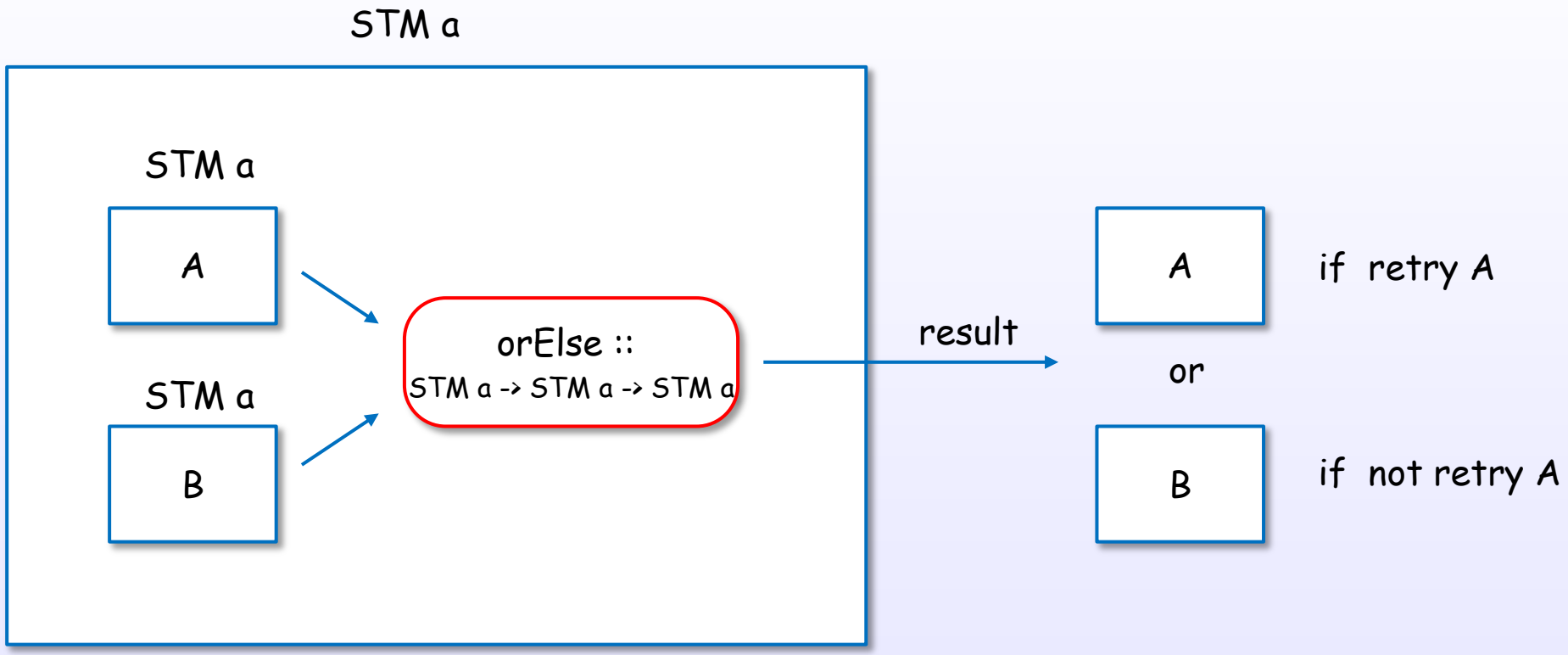


Discard, blocking and try again

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

Compose OR case by orElse

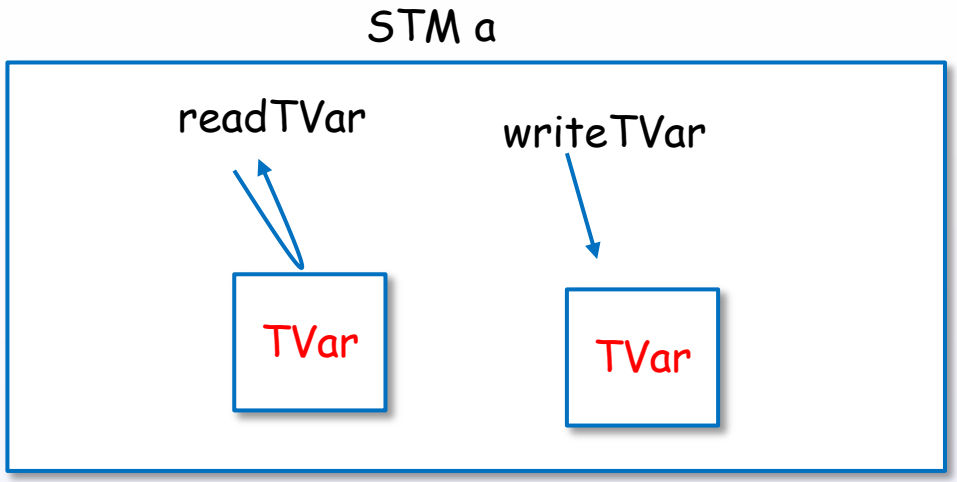
orElse :: STM a -> STM a -> STM a

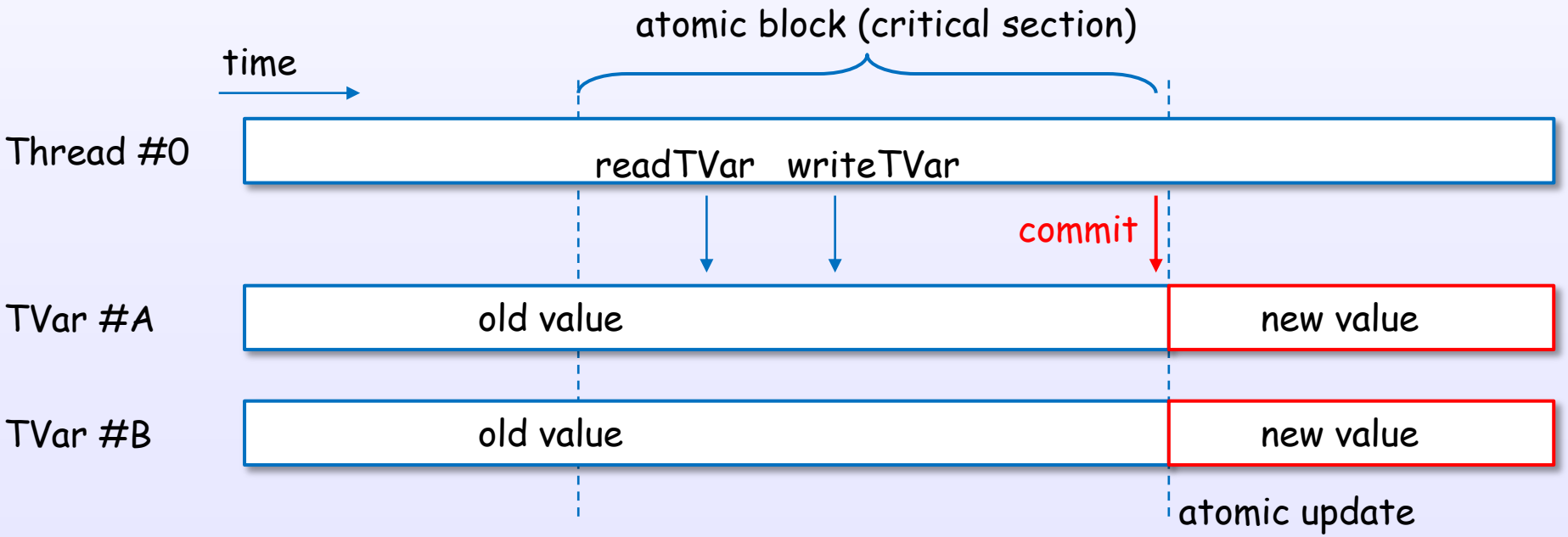


A or B or Nothing

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

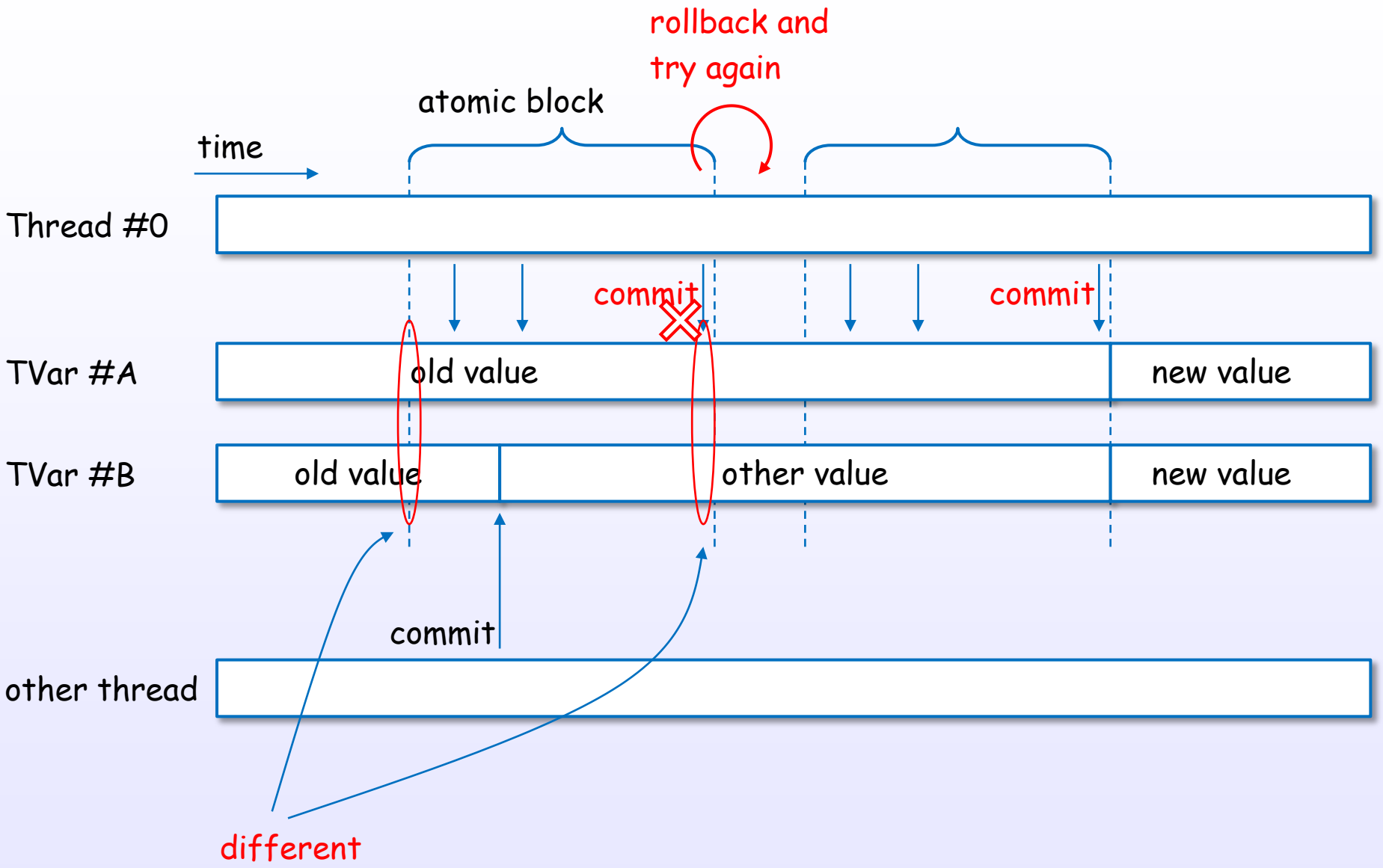
STM, TVar example (normal case)





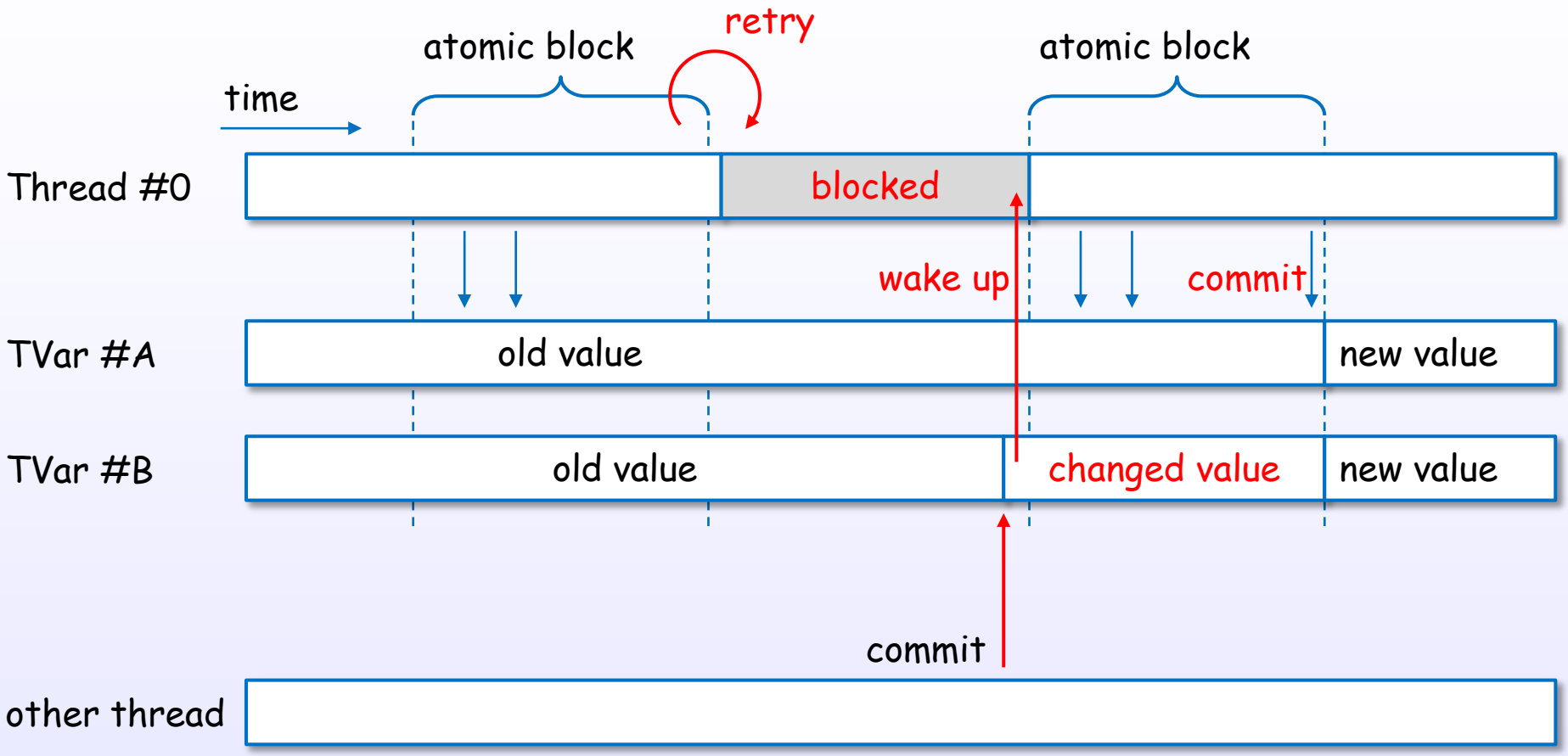
References : [17], [19], [20], [C18], [S12], [S28]

STM, TVar example (conflict case)



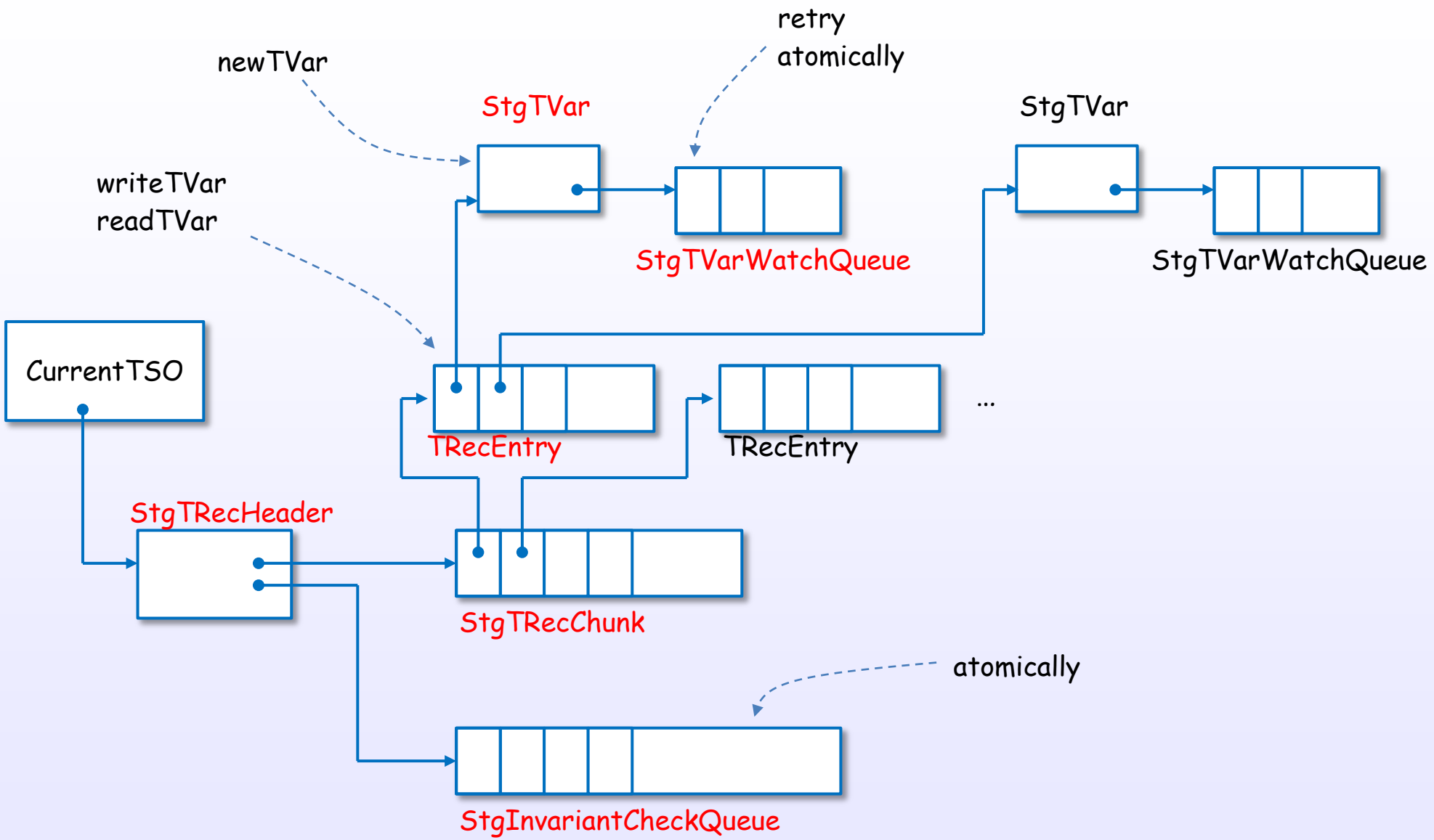
References : [17], [19], [20], [C18], [S12], [S28]

retry example



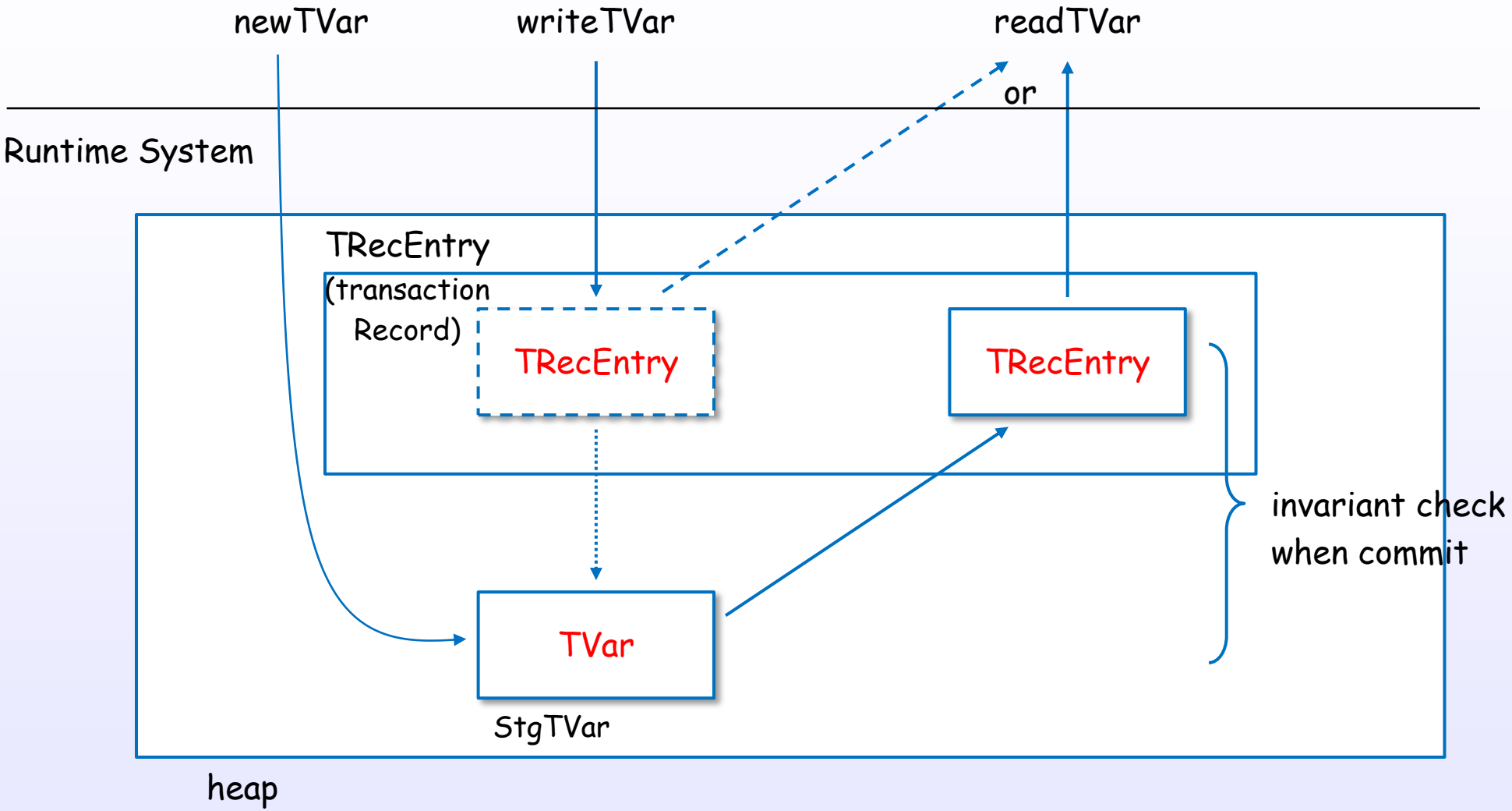
References : [17], [19], [20], [C18], [S12], [S28]

STM, TVar data structure



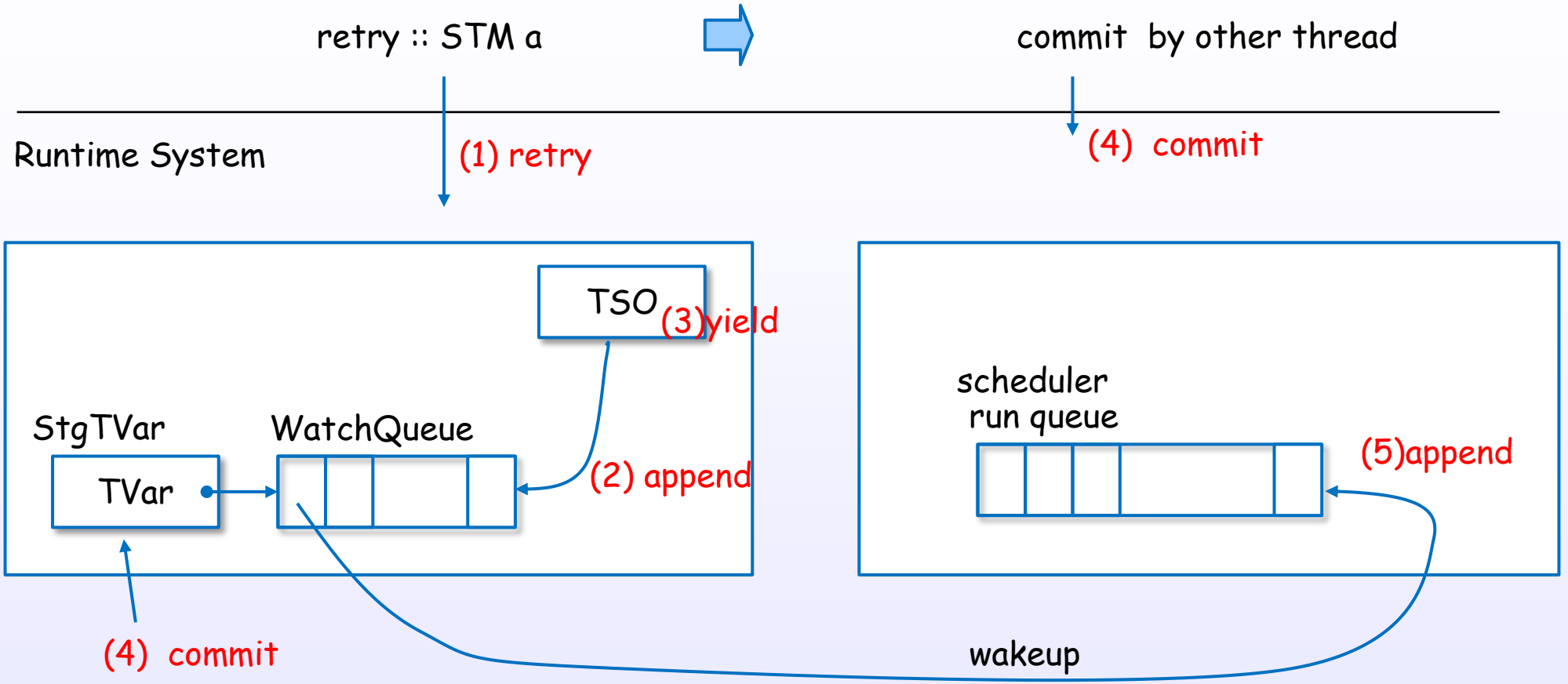
References : [17], [19], [20], [C18], [S12], [S28]

newTVar, writeTVar, readTVar



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

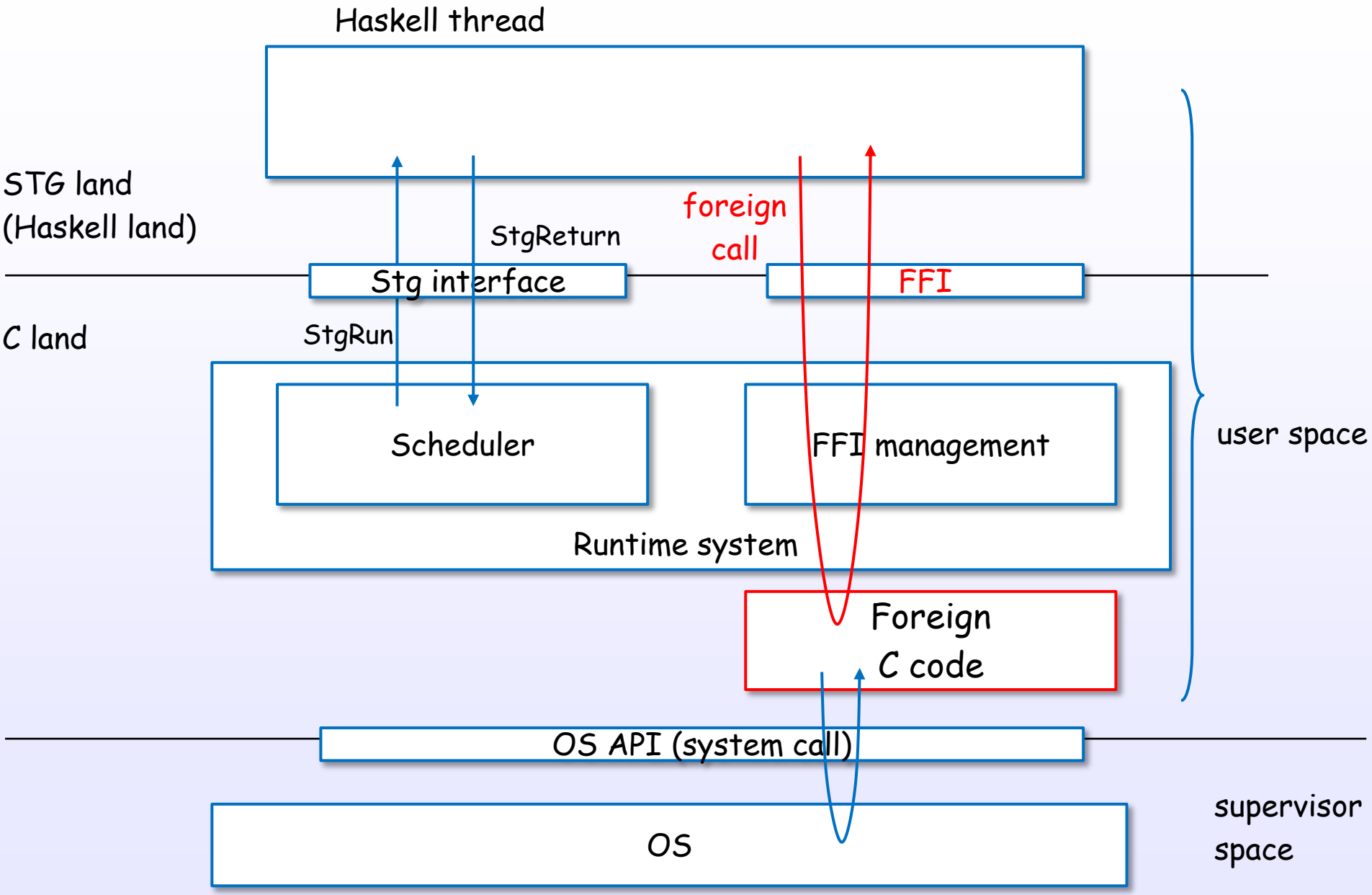
block by retry, wake up by commit



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

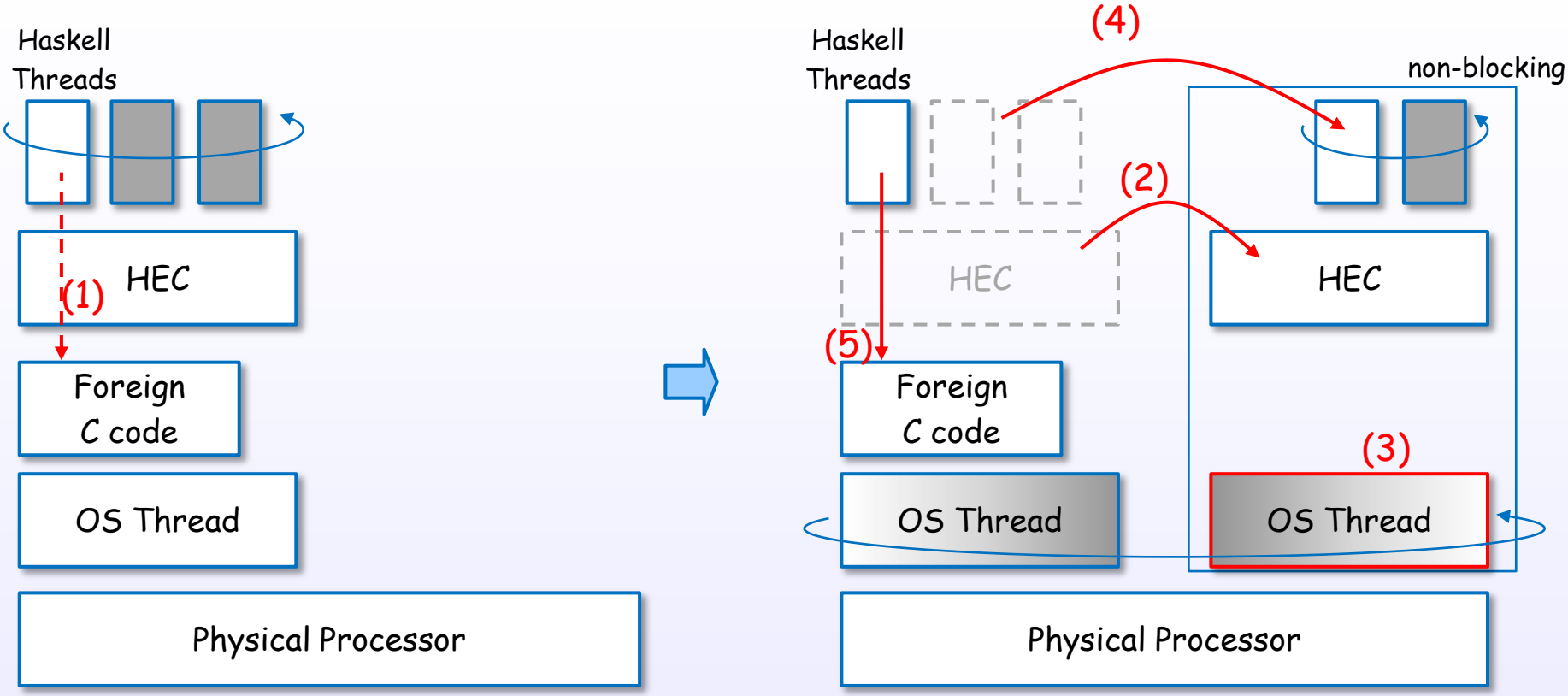
FFI

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]

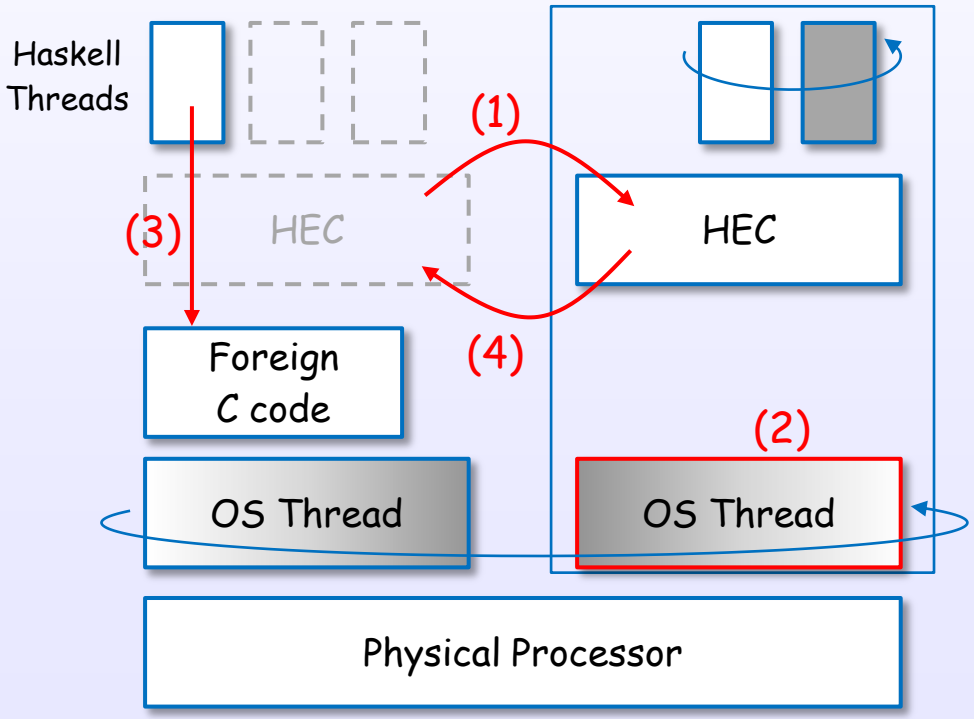
A safe foreign call (code)

Haskell Threads

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

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

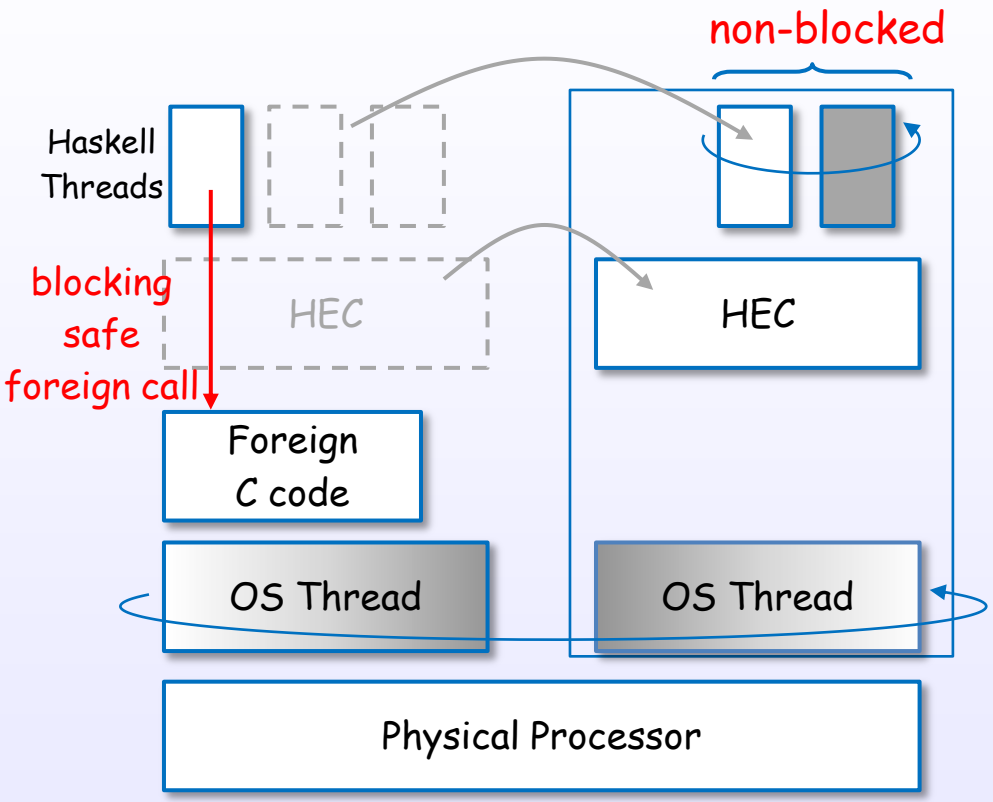
```
waitForReturnCapability    ... (4)
```



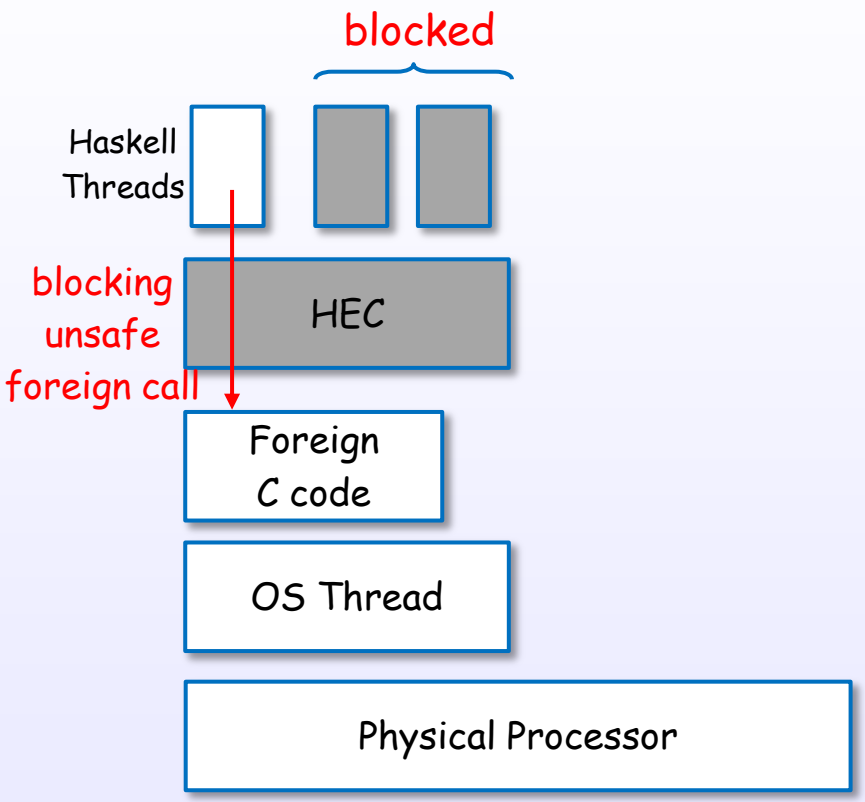
References : [6], [11], [20], [S39], [S38], [S37], [S36], [S40]

a safe and an unsafe foreign call

a safe foreign call



an unsafe foreign call

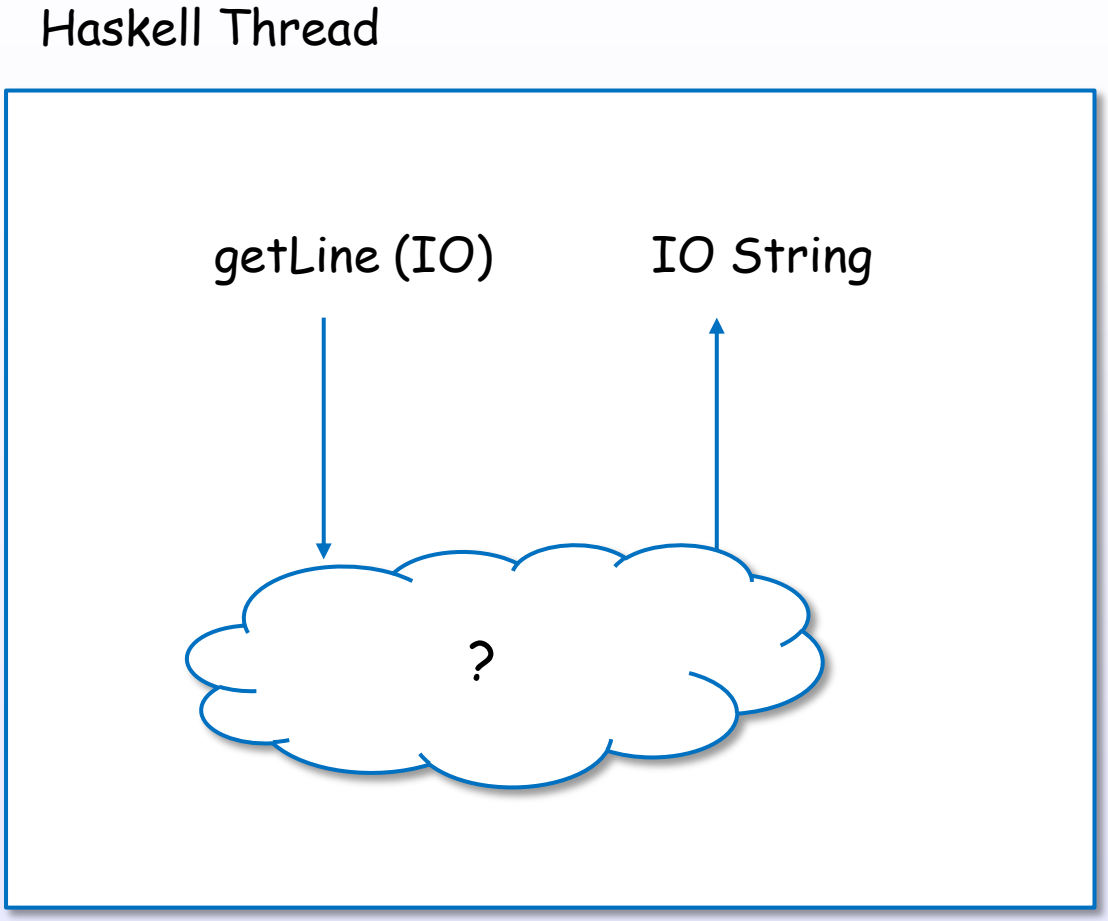


faster,
but blocking to the other Haskell threads

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

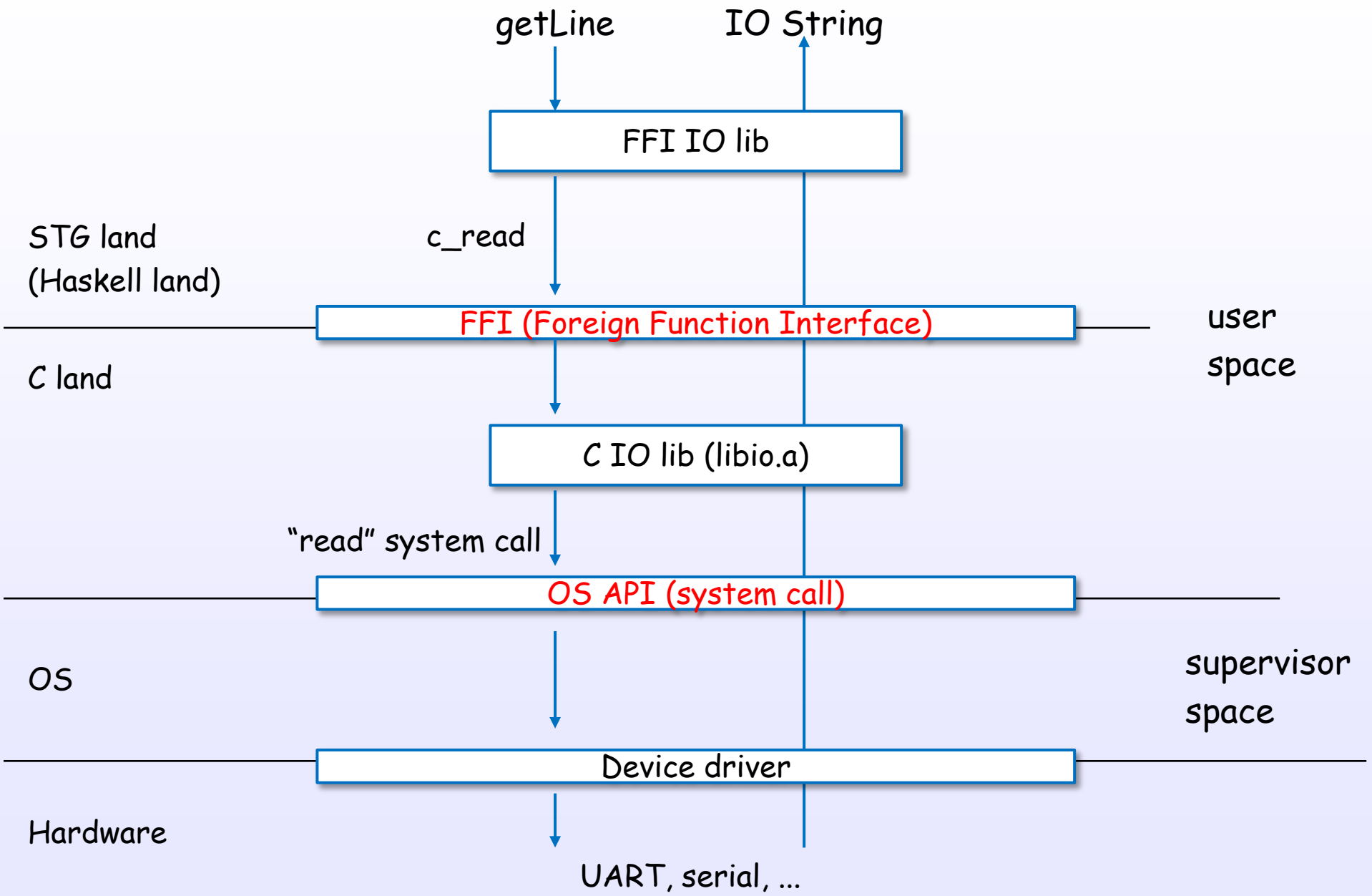
IO and FFI

IO



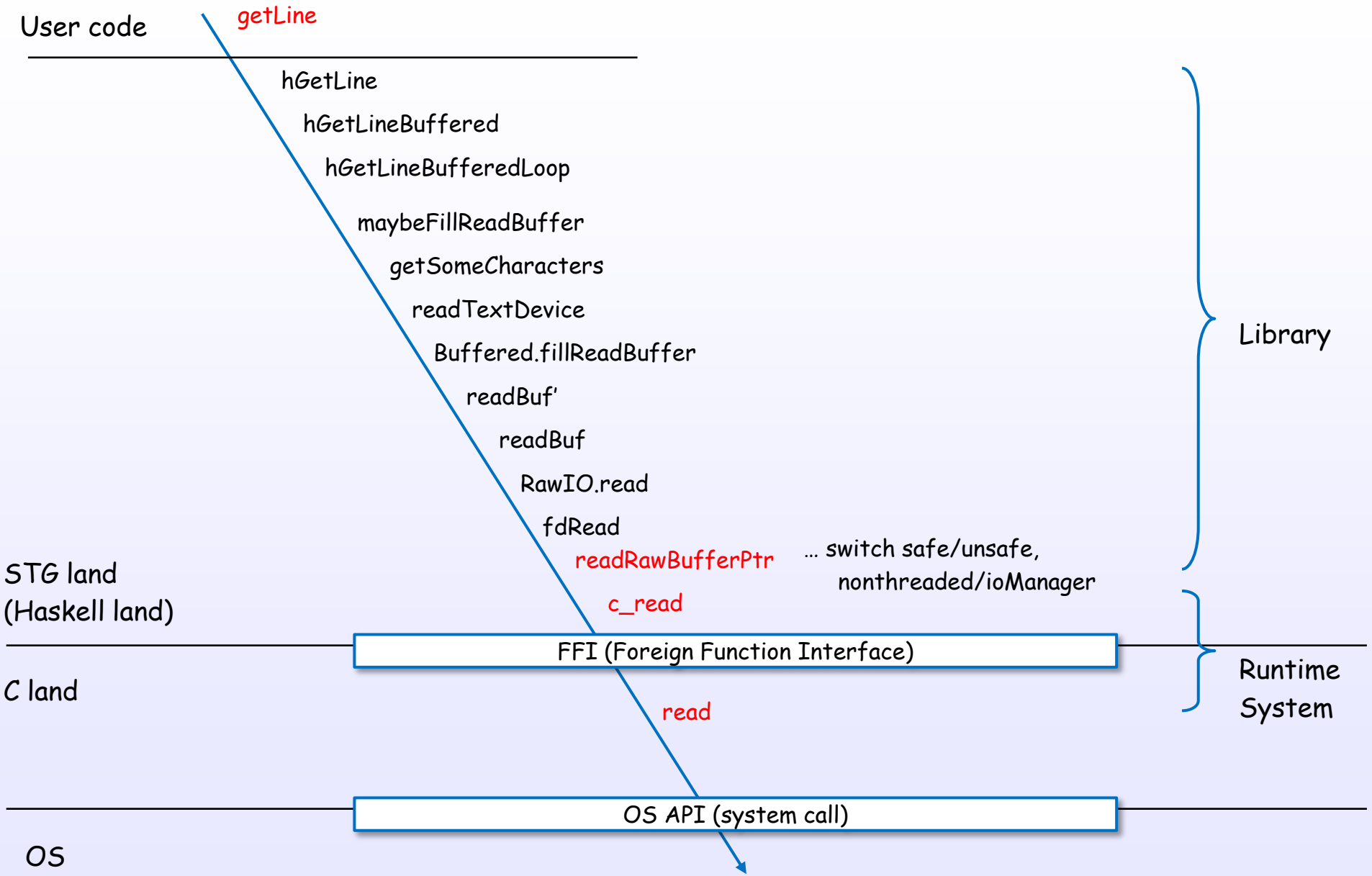
References : [6], [11]

IO example: getLine



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

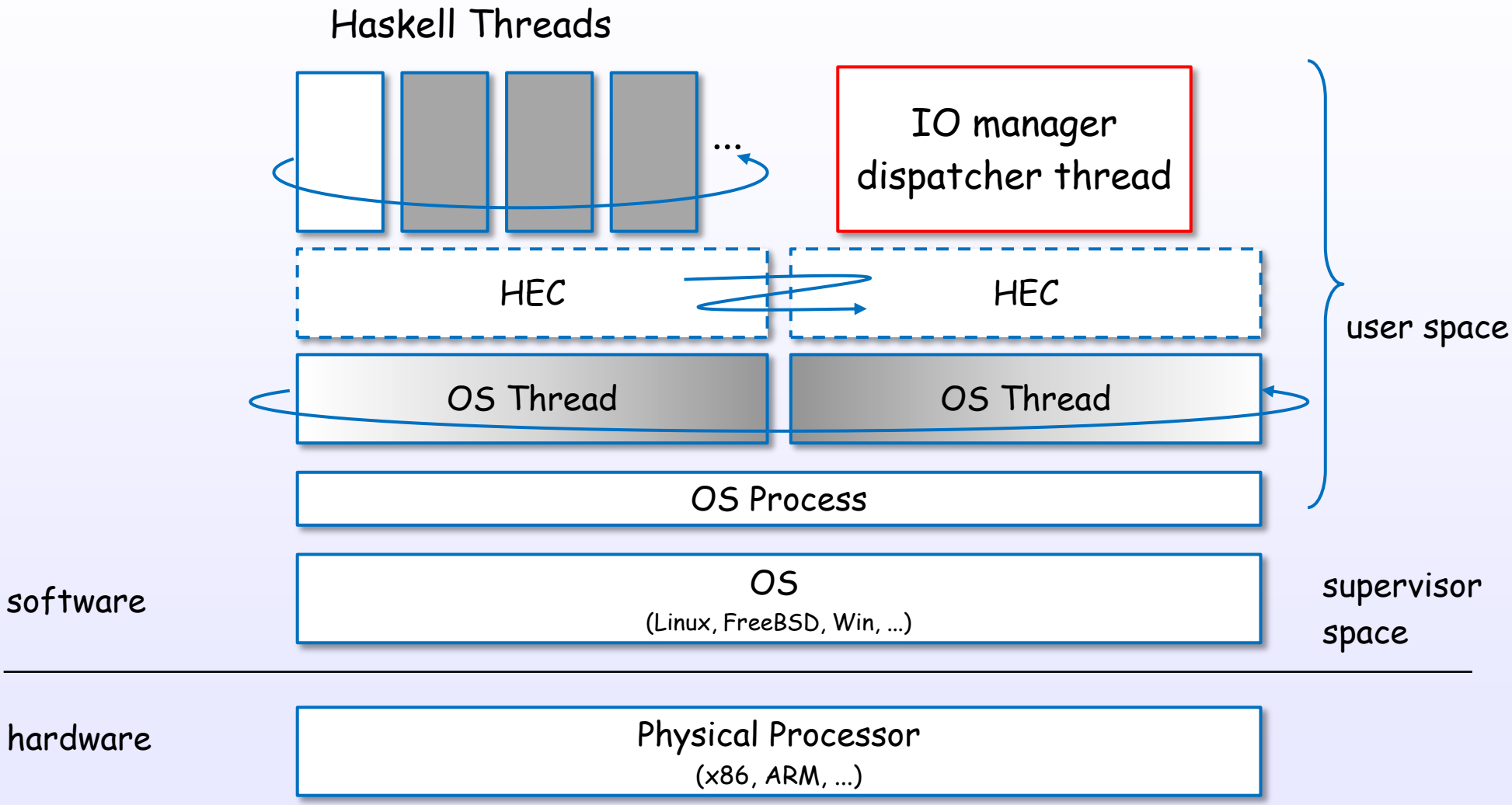
IO example: getLine (code)



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

IO manager

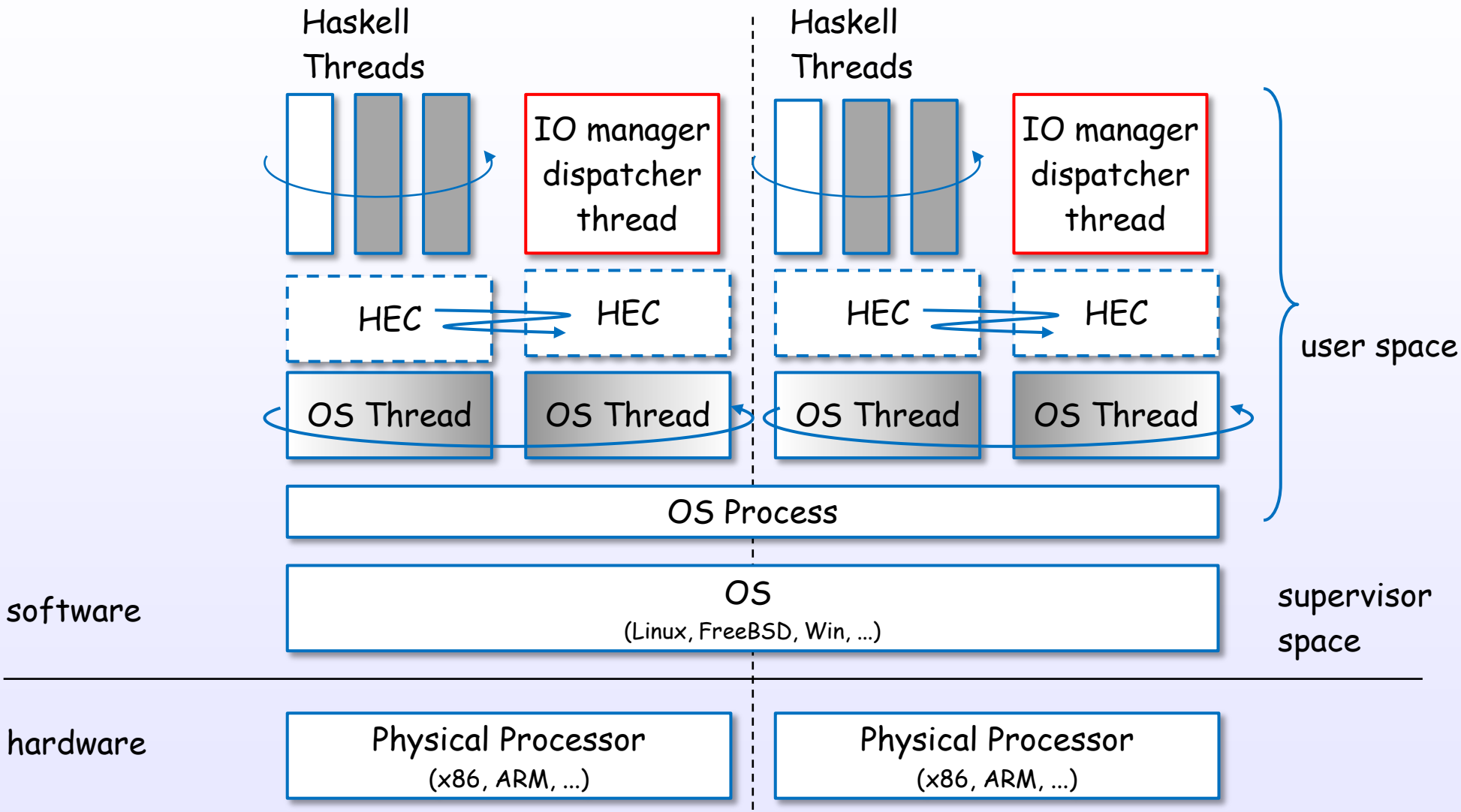
IO manager (single core)



*Threaded option case (ghc -threaded)

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

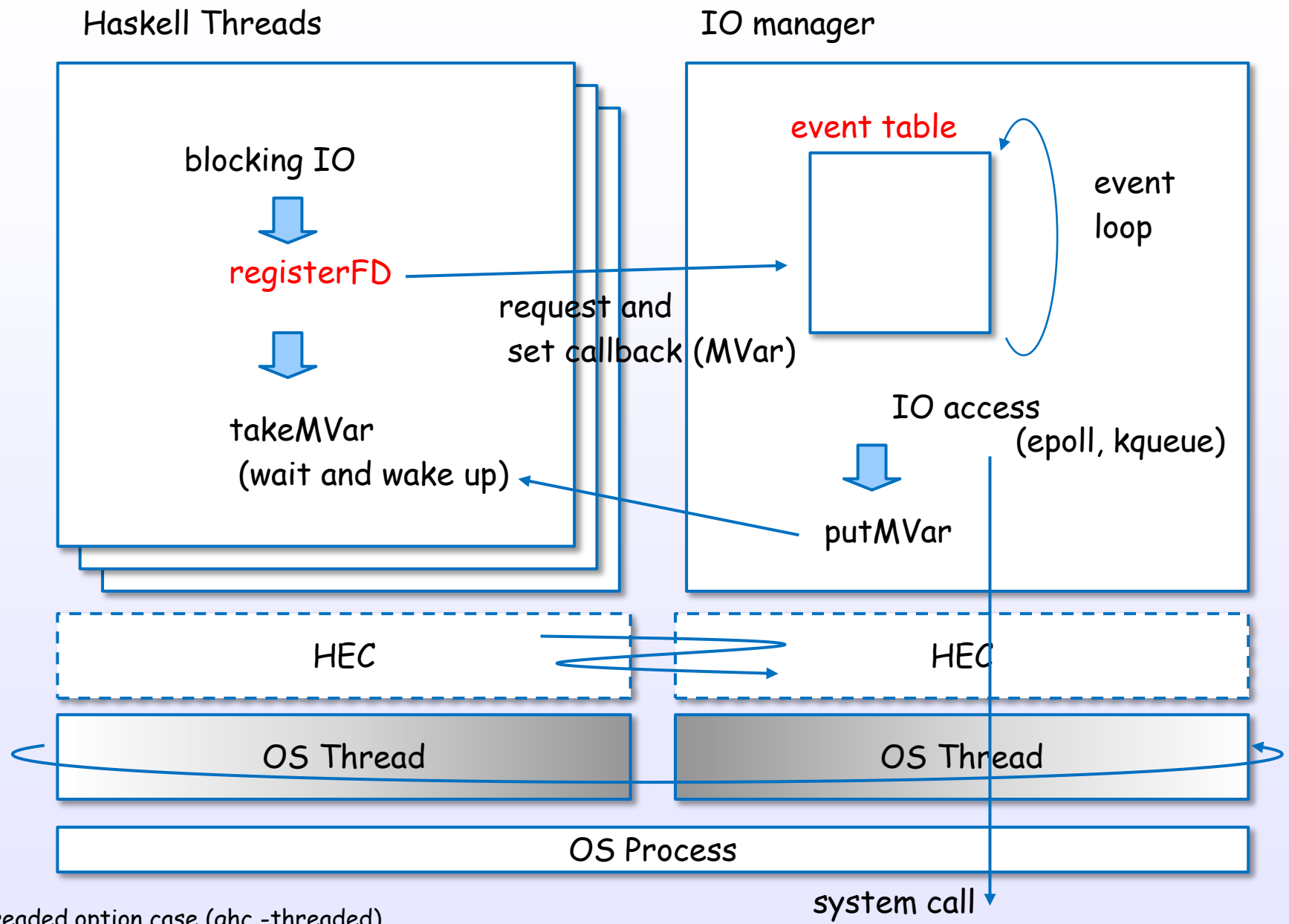
IO manager (multi core)



*Threaded option case (ghc -threaded)

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

IO manager

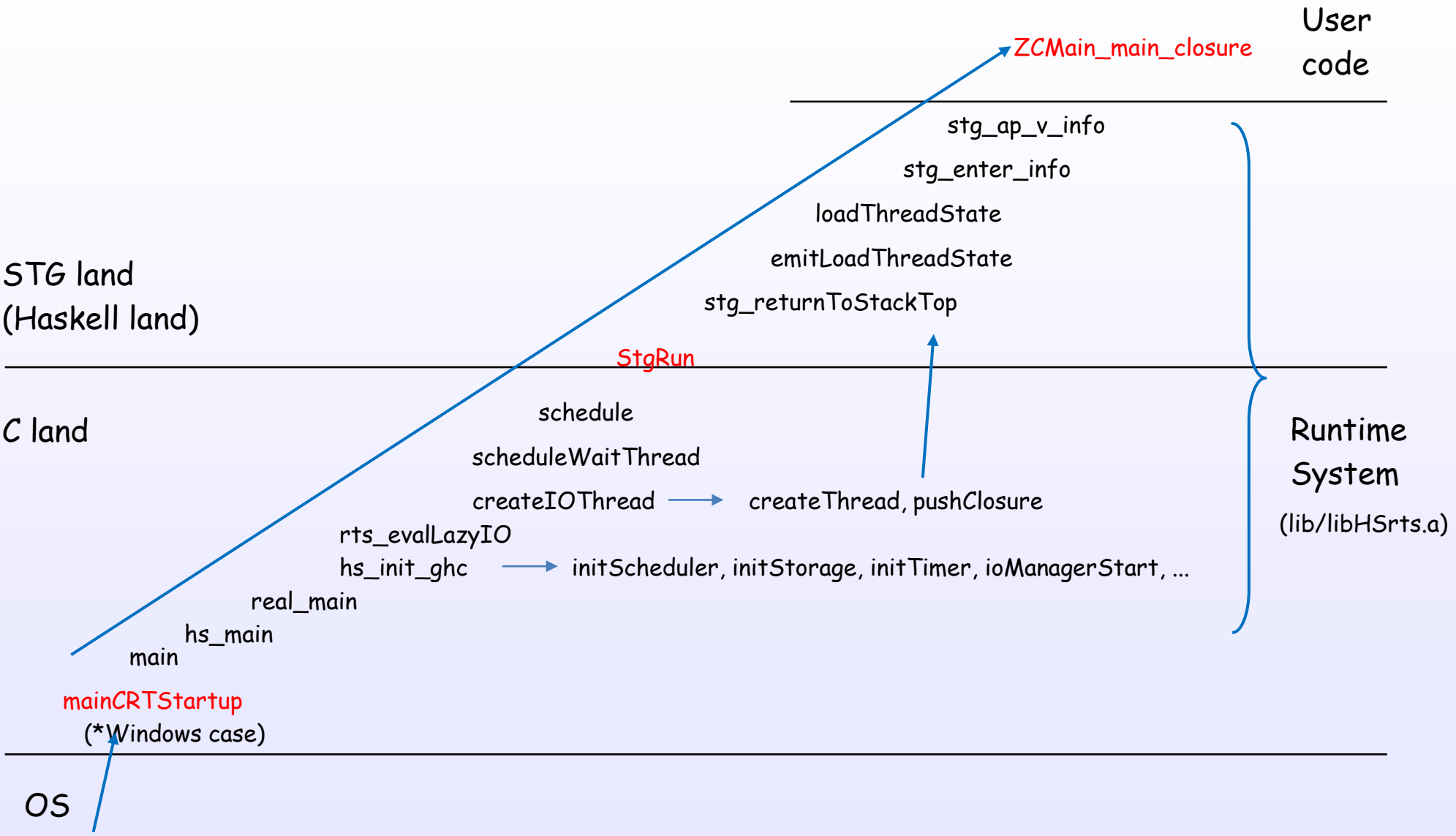


*Threaded option case (ghc -threaded)

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

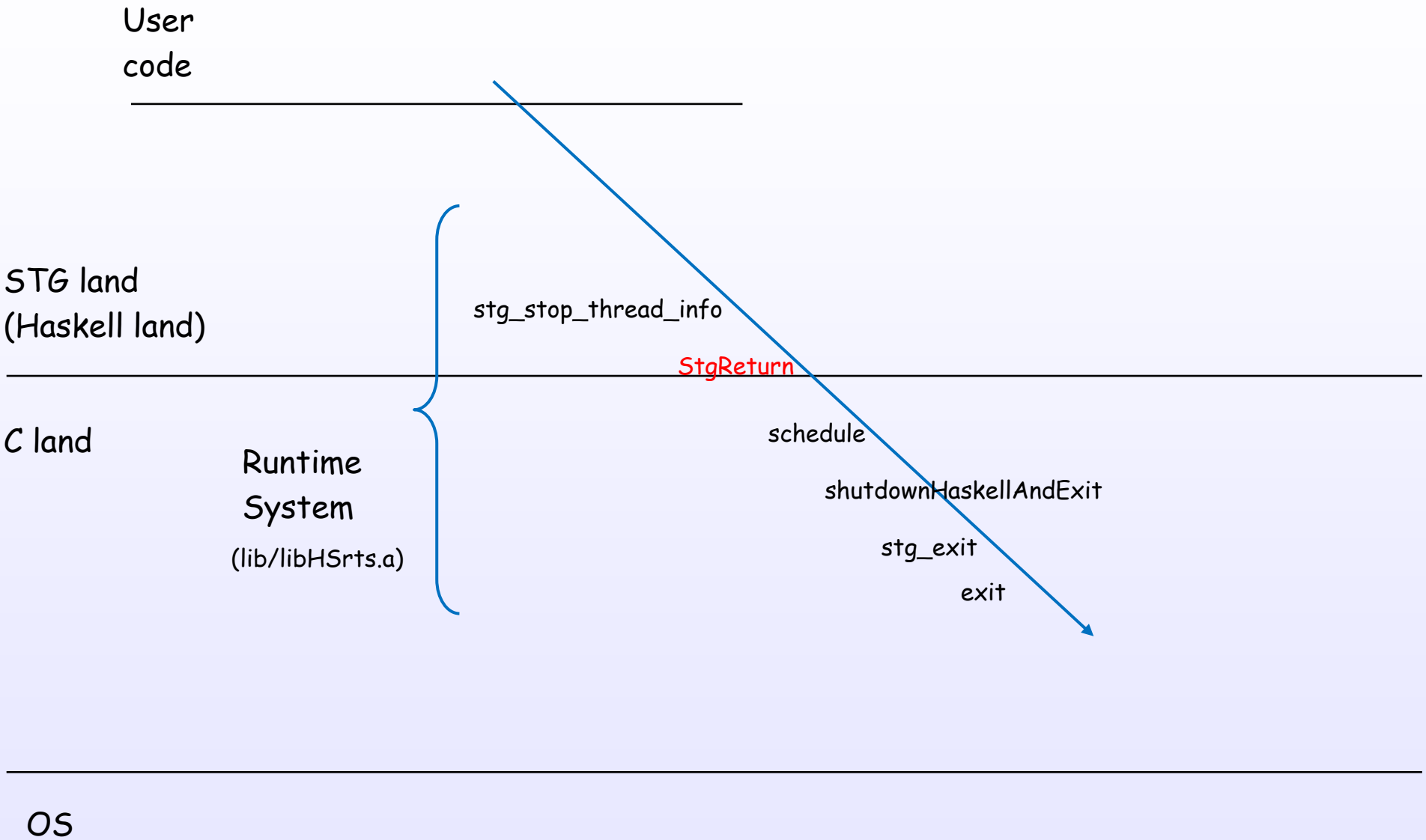
Bootstrap

Bootstrap sequence



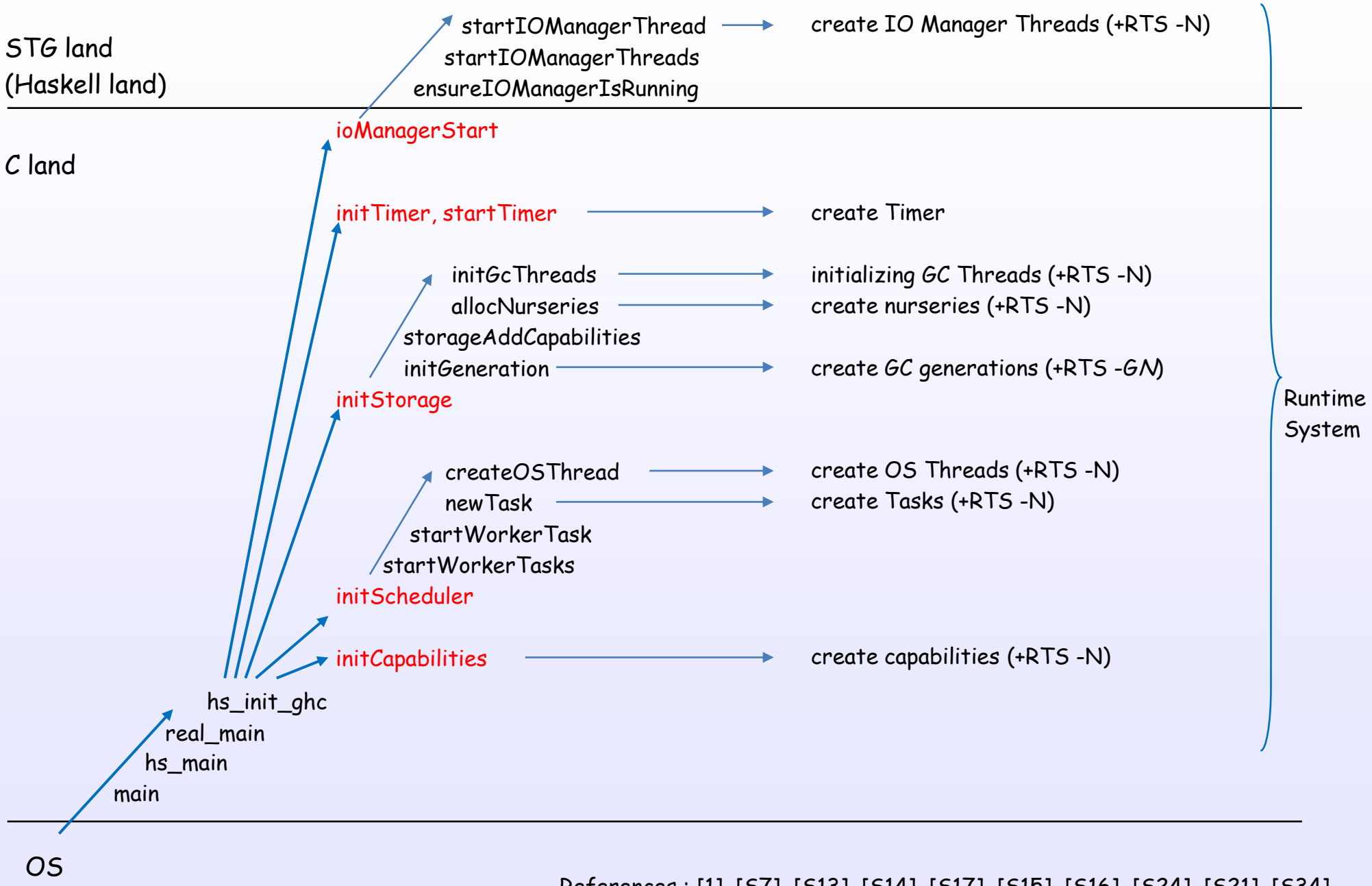
References : [S7], [S13], [S14], [S17], [S18], [S19], [S9], [S10], [S21], [S41]

Exit sequence



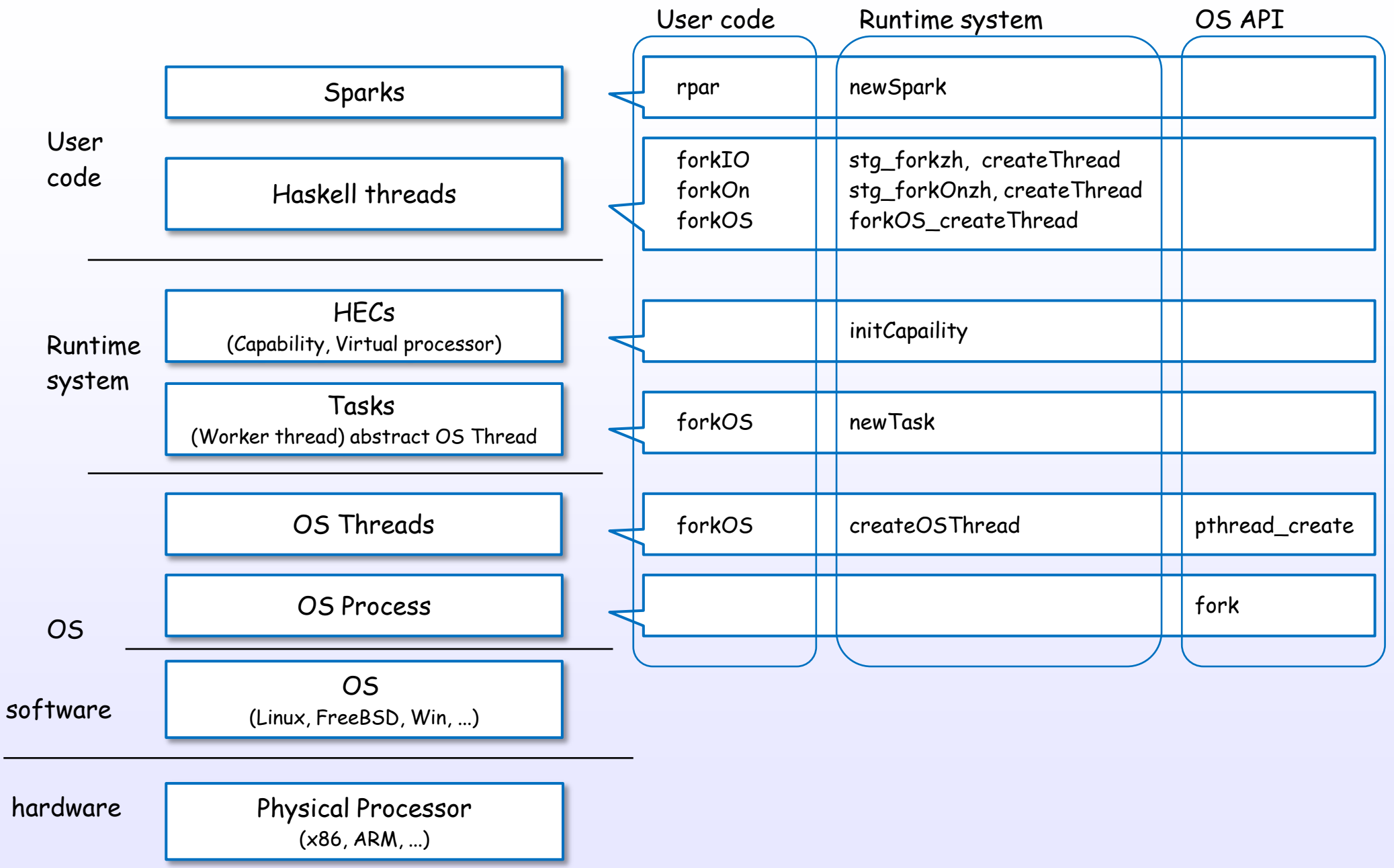
References : [S19], [S18], [S17]

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]

References

References

[1] The Glorious Glasgow Haskell Compilation System User's Guide
https://downloads.haskell.org/~ghc/latest/docs/html/users_guide/index.html

[2] Implementing lazy functional languages on stock hardware: the Spineless Tagless G-machine Version 2.5
http://research.microsoft.com/en-us/um/people/simonpj/Papers/spineless-tagless-gmachine.ps.gz

[3] Making a Fast Curry Push/Enter vs Eval/Apply for Higher-order Languages
http://research.microsoft.com/en-us/um/people/simonpj/papers/eval-apply/

[4] Faster Laziness Using Dynamic Pointer Tagging
http://research.microsoft.com/en-us/um/people/simonpj/papers/ptr-tag/ptr-tagging.pdf

[5] Runtime Support for Multicore Haskell
http://research.microsoft.com/en-us/um/people/simonpj/papers/parallel/multicore-ghc.pdf

[6] Extending the Haskell Foreign Function Interface with Concurrency
http://community.haskell.org/~simonmar/papers/conc-ffi.pdf

[7] Mio: A High-Performance Multicore IO Manager for GHC
http://haskell.cs.yale.edu/wp-content/uploads/2013/08/hask035-voellmy.pdf

[8] The GHC Runtime System
web.mit.edu/~ezyang/Public/jfp-ghc-rts.pdf

[9] The GHC Runtime System
http://www.scs.stanford.edu/14sp-cs240h/slides/ghc-rts.pdf

[10] Evaluation on the Haskell Heap
http://blog.ezyang.com/2011/04/evaluation-on-the-haskell-heap/

References

[11] IO evaluates the Haskell Heap
http://blog.ezyang.com/2011/04/io-evaluates-the-haskell-heap/

[12] Understanding the Stack
http://www.well-typed.com/blog/94/

[13] Understanding the RealWorld
http://www.well-typed.com/blog/95/

[14] The GHC scheduler
http://blog.ezyang.com/2013/01/the-ghc-scheduler/

[15] GHC's Garbage Collector
http://www.mm-net.org.uk/workshop190404/GHC's_Garbage_Collector.ppt

[16] Concurrent Haskell
http://www.haskell.org/ghc/docs/papers/concurrent-haskell.ps.gz

[17] Beautiful Concurrency
https://www.fpcomplete.com/school/advanced-haskell/beautiful-concurrency

[18] Anatomy of an MVar operation
http://blog.ezyang.com/2013/05/anatomy-of-an-mvar-operation/

[19] Parallel and Concurrent Programming in Haskell
http://community.haskell.org/~simonmar/pcph/

[20] Real World Haskell
http://book.realworldhaskell.org/

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
[C19] https://ghc.haskell.org/trac/ghc/wiki/Commentary/Libraries

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.lhs
[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