37 Extension: The Cut Operator

Realistic Prolog additionally provides an operator "!" (cut) which explicitly allows to prune the search space of backtracking.

Example:

$$
\begin{array}{lll}
\mathsf{branch}(X,Y) & \leftarrow & \mathsf{p}(X), !, \mathsf{q}_1(X,Y) \\
\mathsf{branch}(X,Y) & \leftarrow & \mathsf{q}_2(X,Y)
\end{array}
$$

Once the queries before the cut have succeeded, the choice is committed:

Backtracking will return only to backtrack points preceding the call to the left-hand side ...

The Basic Idea:

- We restore the oldBP from our current stack frame;
- We pop all stack frames on top of the local variables.

Accordingly, we translate the cut into the sequence:

```
prune
pushenv m
```

where m is the number of (still used) local variables of the clause.

Example:

Consider our example:

$$\begin{array}{lll} \mathsf{branch}(X, Y) & \leftarrow & \mathsf{p}(X), !, \mathsf{q}_1(X, Y) \\ \mathsf{branch}(X, Y) & \leftarrow & \mathsf{q}_2(X, Y) \end{array}$$

We obtain:

setbtp	A:	pushenv 2	C:	prune	lastmark	B:	pushenv 2
try A		mark C		pushenv 2	putref 1		putref 2
delbtp		putref 1			putref 2		putref 2
jump B		call $\mathsf{p}/1$			lastcall $\mathsf{q}_1/2$ 2		move 2 2
							jump $\mathsf{q}_2/2$

Example:

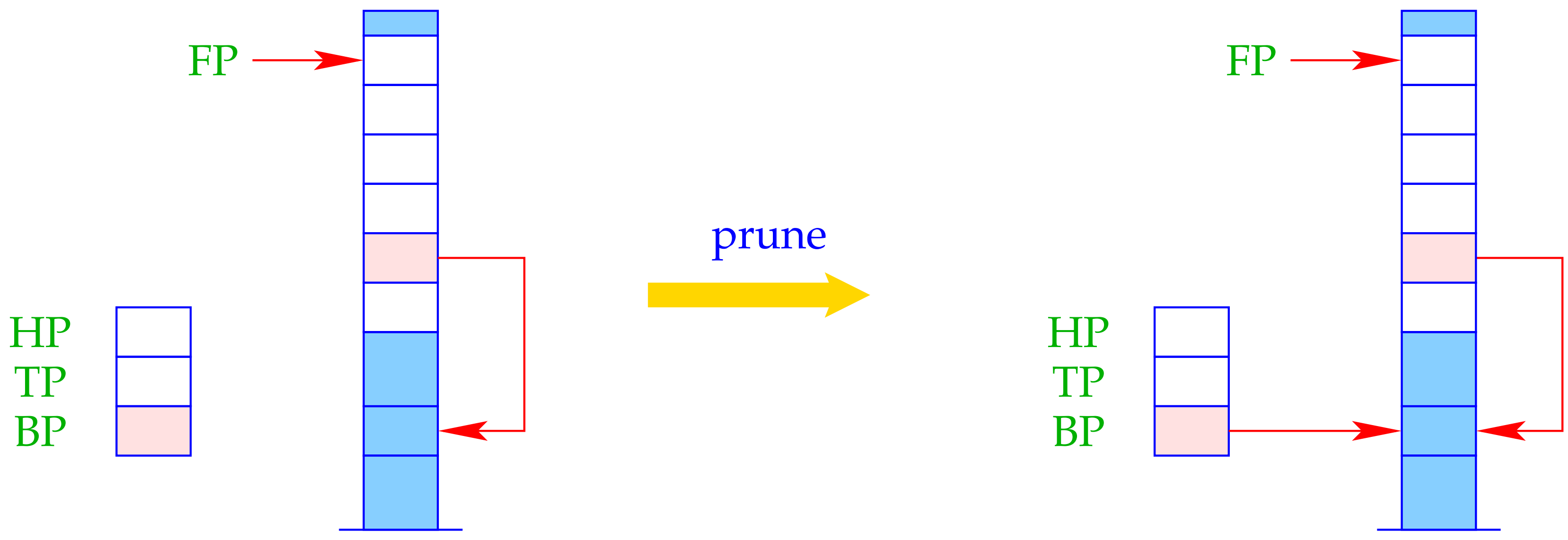
Consider our example:

$$
\begin{array}{lcl}
\mathsf{branch}(X, Y) & \leftarrow & \mathsf{p}(X), !, \mathsf{q}_1(X, Y) \\
\mathsf{branch}(X, Y) & \leftarrow & \mathsf{q}_2(X, Y)
\end{array}
$$

In fact, an optimized translation even yields here:

setbtp	A:	pushenv 2	C:	prune	putref 1	B:	pushenv 2
try A		mark C		pushenv 2	putref 2		putref 1
delbtp		putref 1			move 2 2		putref 2
jump B		call $\mathsf{p}/1$			jump $\mathsf{q}_1/2$		move 2 2
							jump $\mathsf{q}_2/2$

The new instruction prune simply restores the backtrack pointer:



BP = BPold;

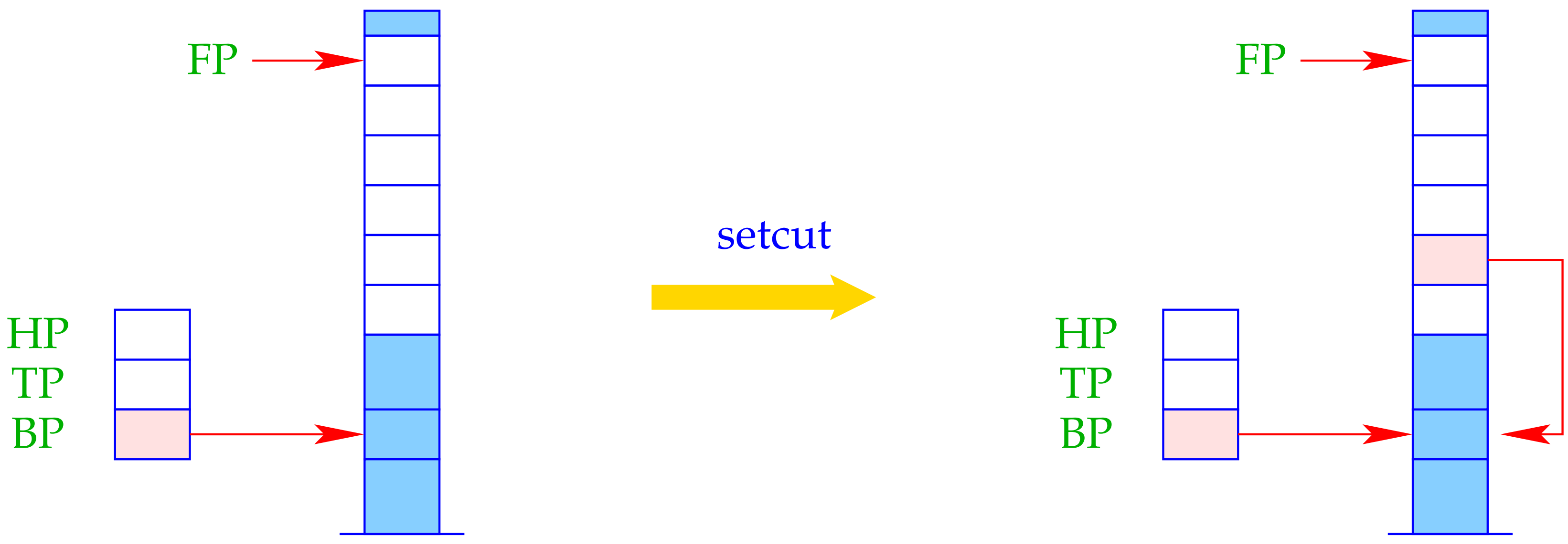
Problem:

If a clause is single, then (at least so far ;-) we have not stored the old BP inside the stack frame :-(

$$\Longrightarrow$$

For the cut to work also with single-clause predicates or try chains of length 1, we insert an extra instruction setcut before the clausal code (or the jump):

The instruction setcut just stores the current value of BP:



BPold = BP;

The Final Example: Negation by Failure

The predicate notP should succeed whenever p fails (and vice versa :-)

$$\mathsf{notP}(X) \leftarrow \mathsf{p}(X), !, \mathsf{fail}$$
$$\mathsf{notP}(X) \leftarrow$$

where the goal fail never succeeds. Then we obtain for notP :

setbtp	A:	pushenv 1	C:	prune	B:	pushenv 1
try A		mark C		pushenv 1		popenv
delbtp		putref 1		fail		
jump B		call p/1		popenv		

38 Garbage Collection

- Both during execution of a MaMa- as well as a WiM-programs, it may happen that some objects can no longer be reached through references.
- Obviously, they cannot affect the further program execution. Therefore, these objects are called garbage.
- Their storage space should be freed and reused for the creation of other objects.

Warning:

The WiM provides some kind of heap de-allocation. This, however, only frees the storage of failed alternatives !!!

Operation of a stop-and-copy-Collector:

- Division of the heap into two parts, the to-space and the from-space — which, after each collection flip their roles.
- Allocation with new in the current from-space.
- In case of memory exhaustion, call of the collector.

The Phases of the Collection:

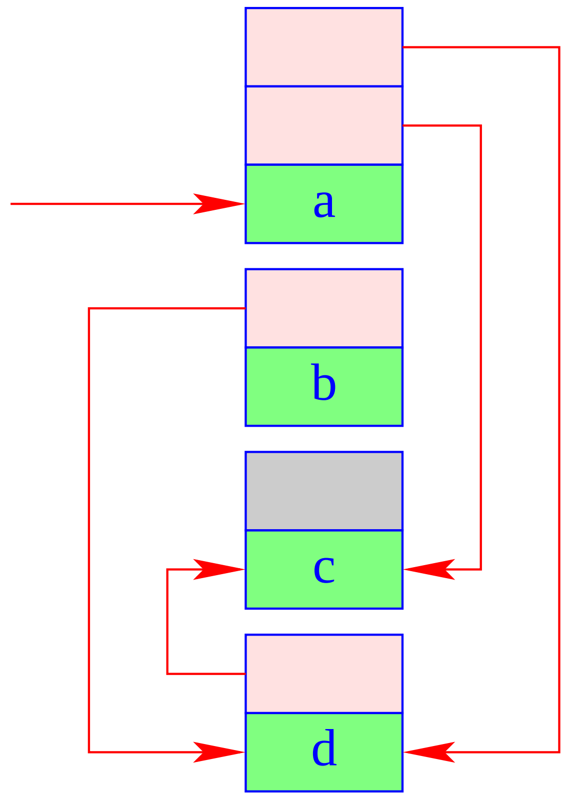
1. Marking of all reachable objects in the from-space.
2. Copying of all marked objects into the to-space.
3. Correction of references.
4. Exchange of from-space and to-space.

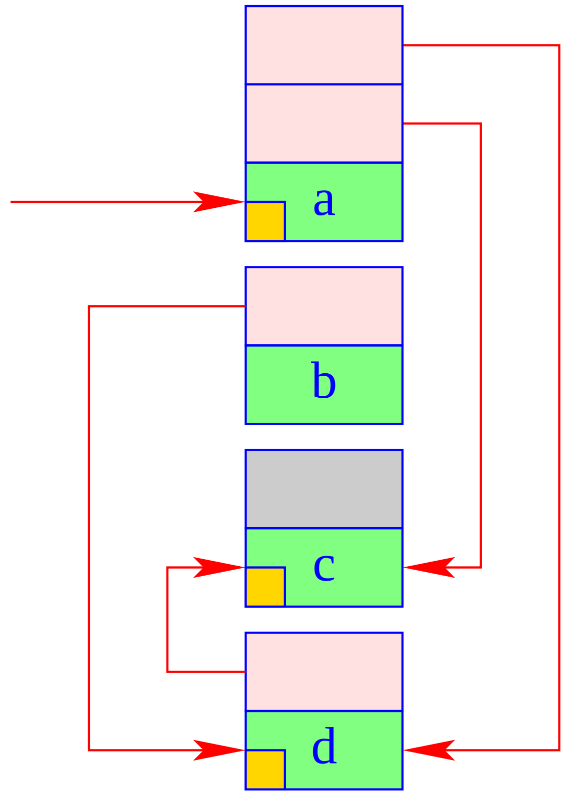
(1) Mark: Detection of live objects:

- all references in the stack point to live objects;
- every reference of a live object points to a live object.

$\Longrightarrow$

Graph Reachability


a
b
c
d

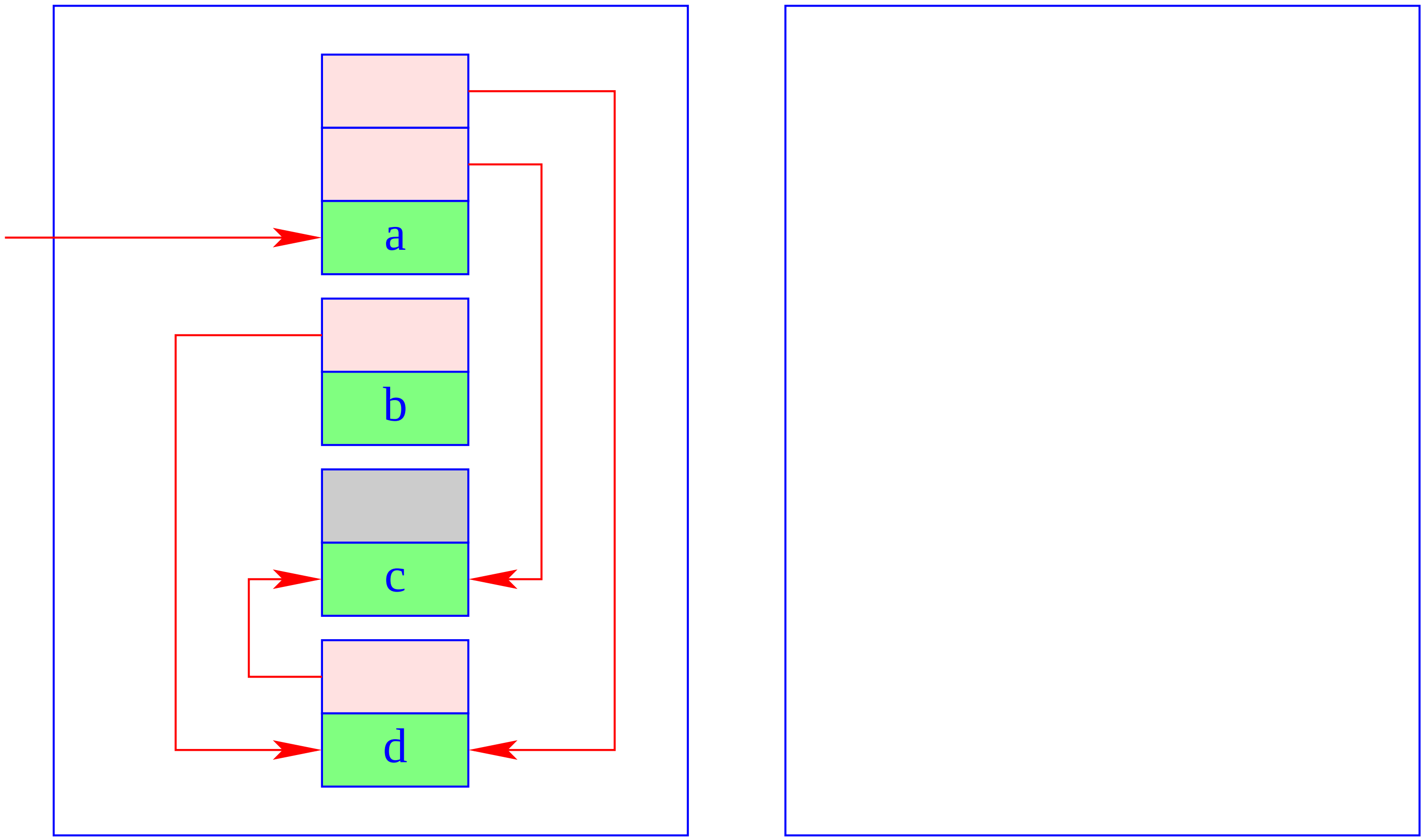

a
b
c
d

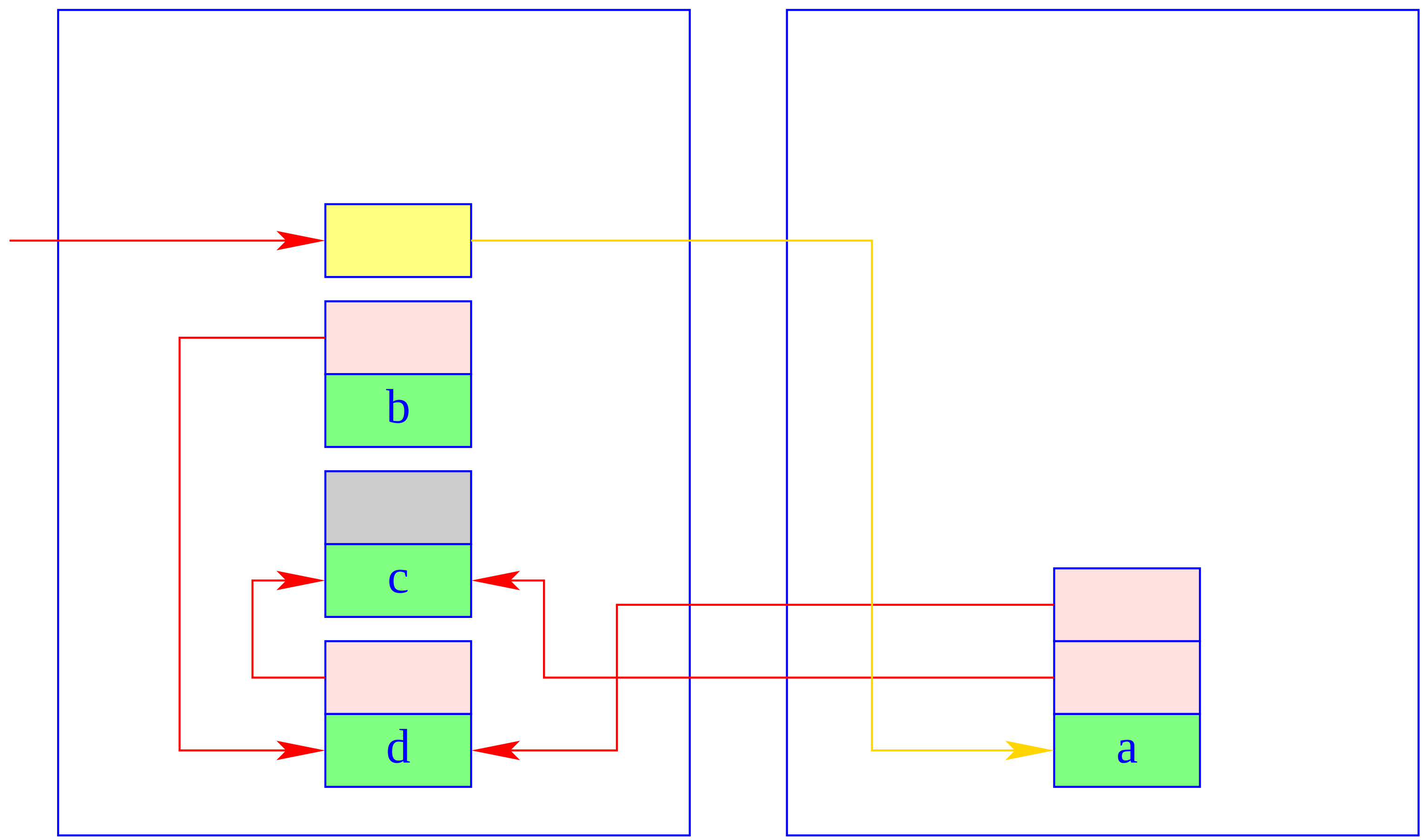
(2) Copy: Copying of all live objects from the current from-space into the current to-space. This means for every detected object:

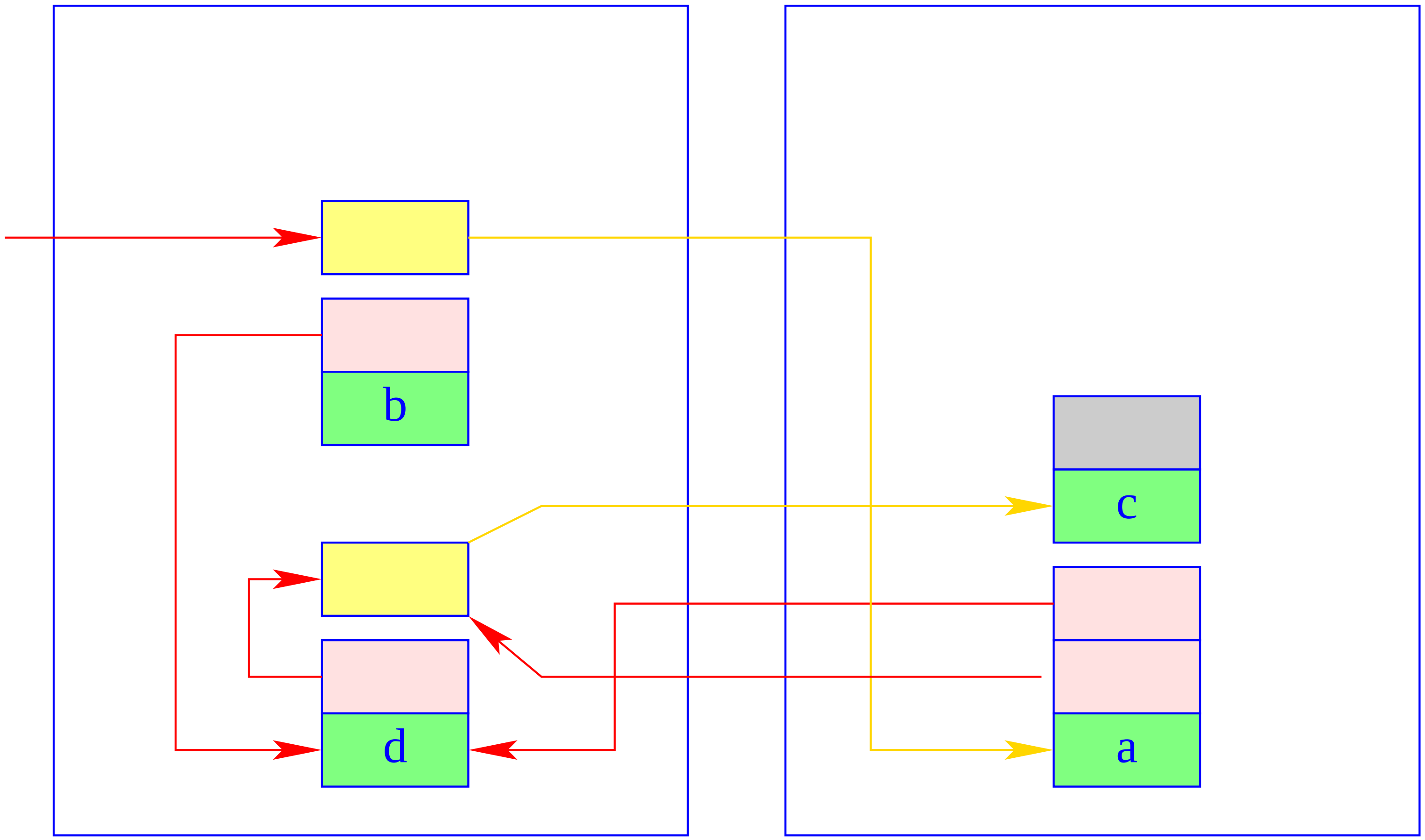
- Copying the object;
- Storing a forward reference to the new place at the old place :-)

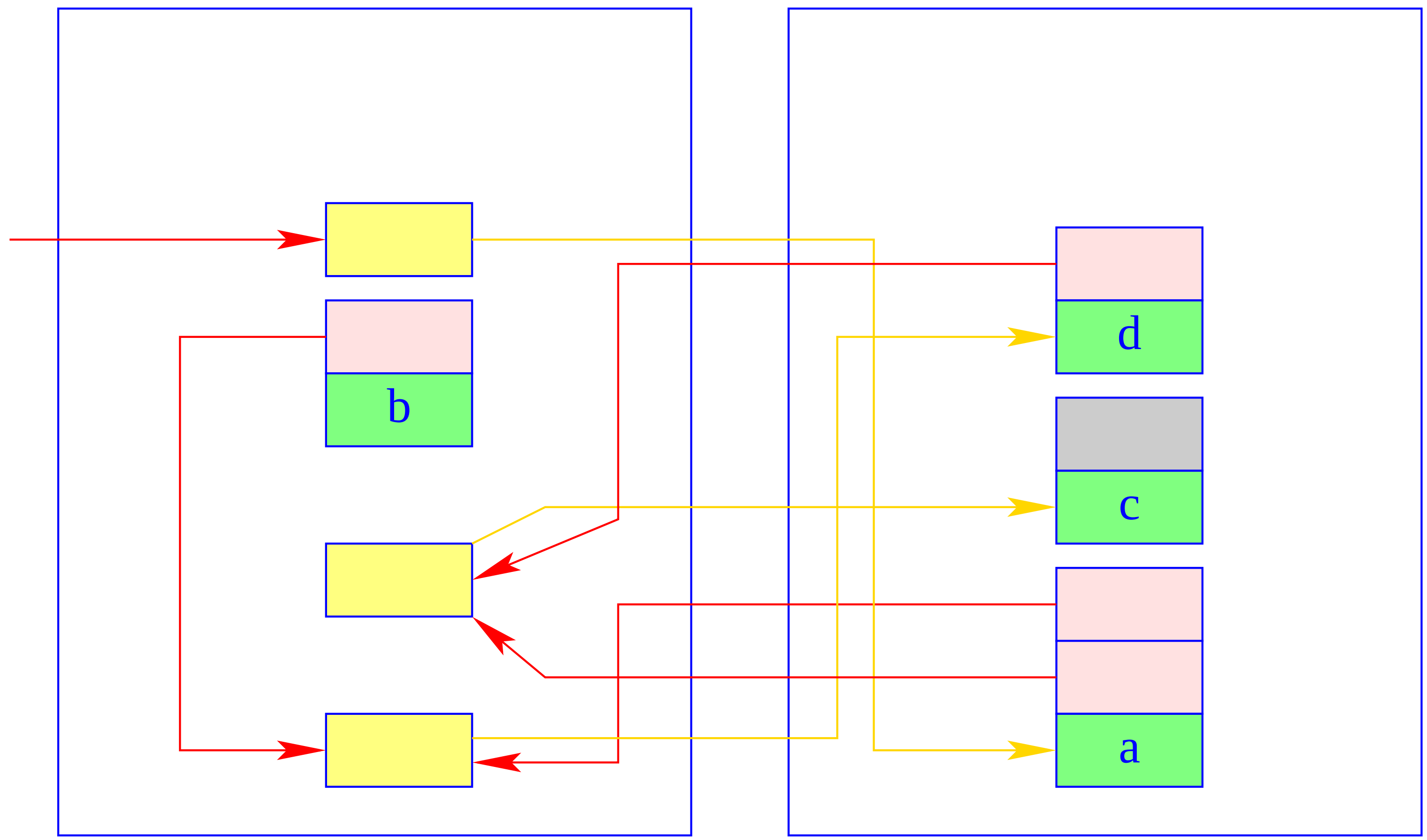
$$\Longrightarrow$$

all references of the copied objects point to the forward references in the from-space.

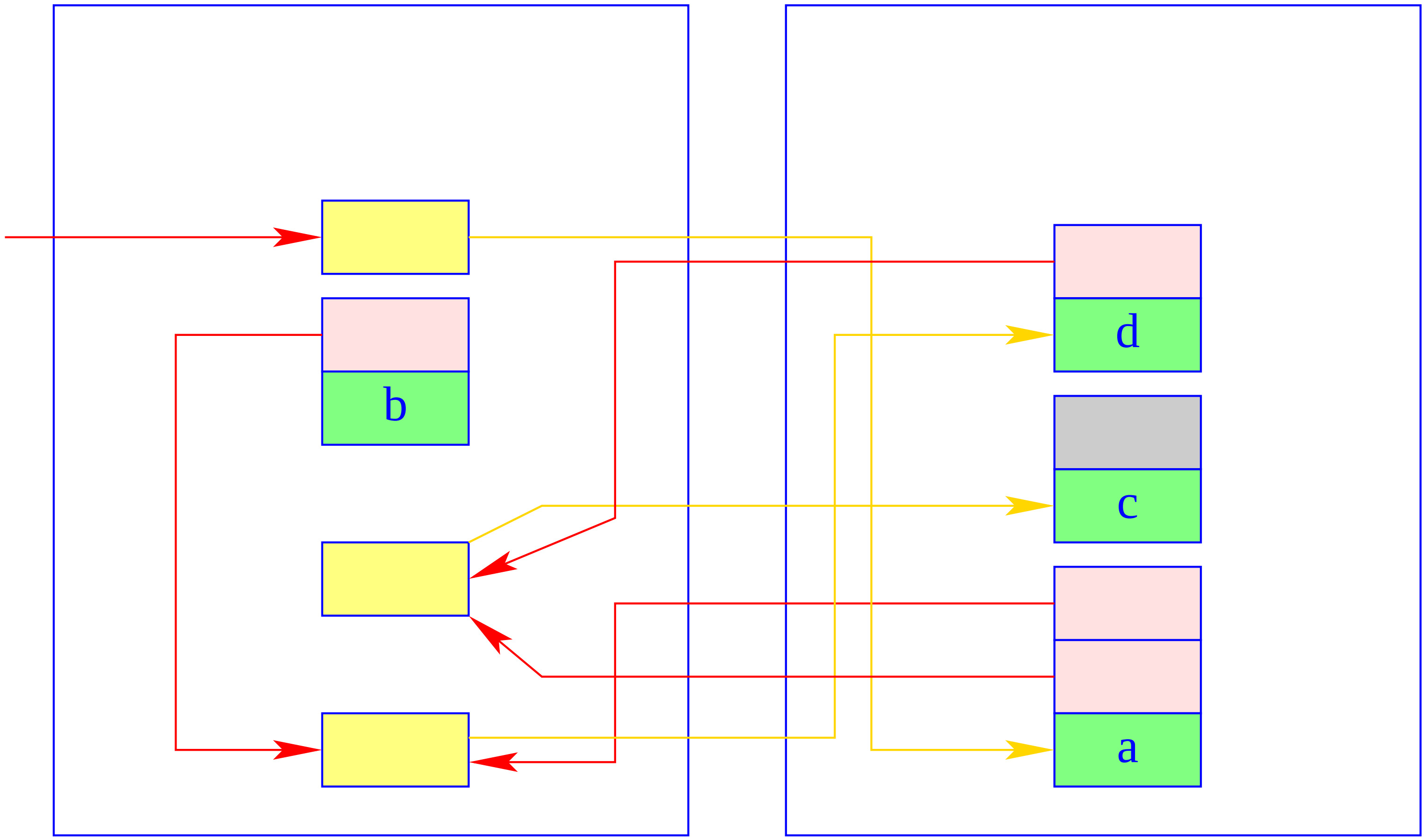

a
b
c
d

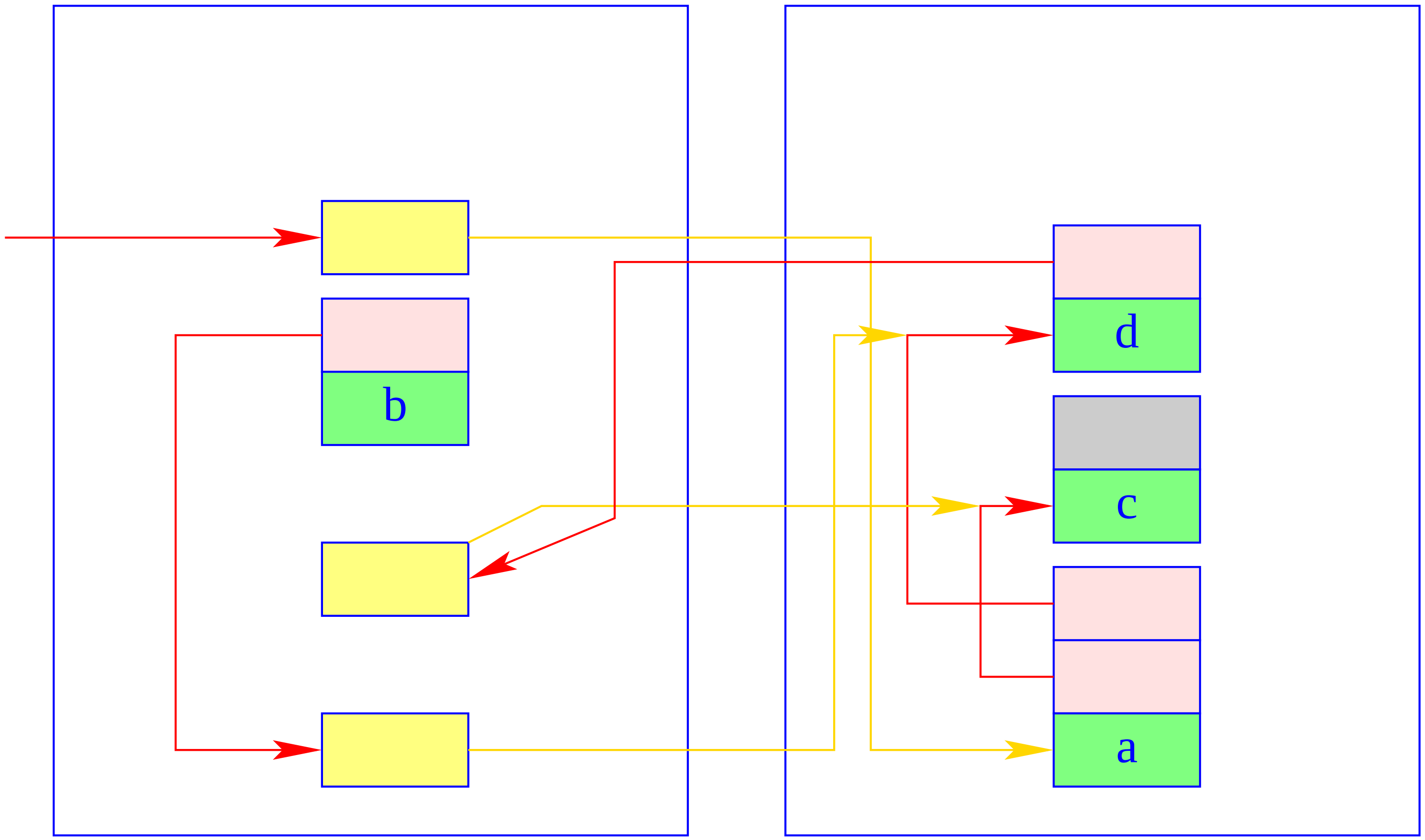

b
c
d
a

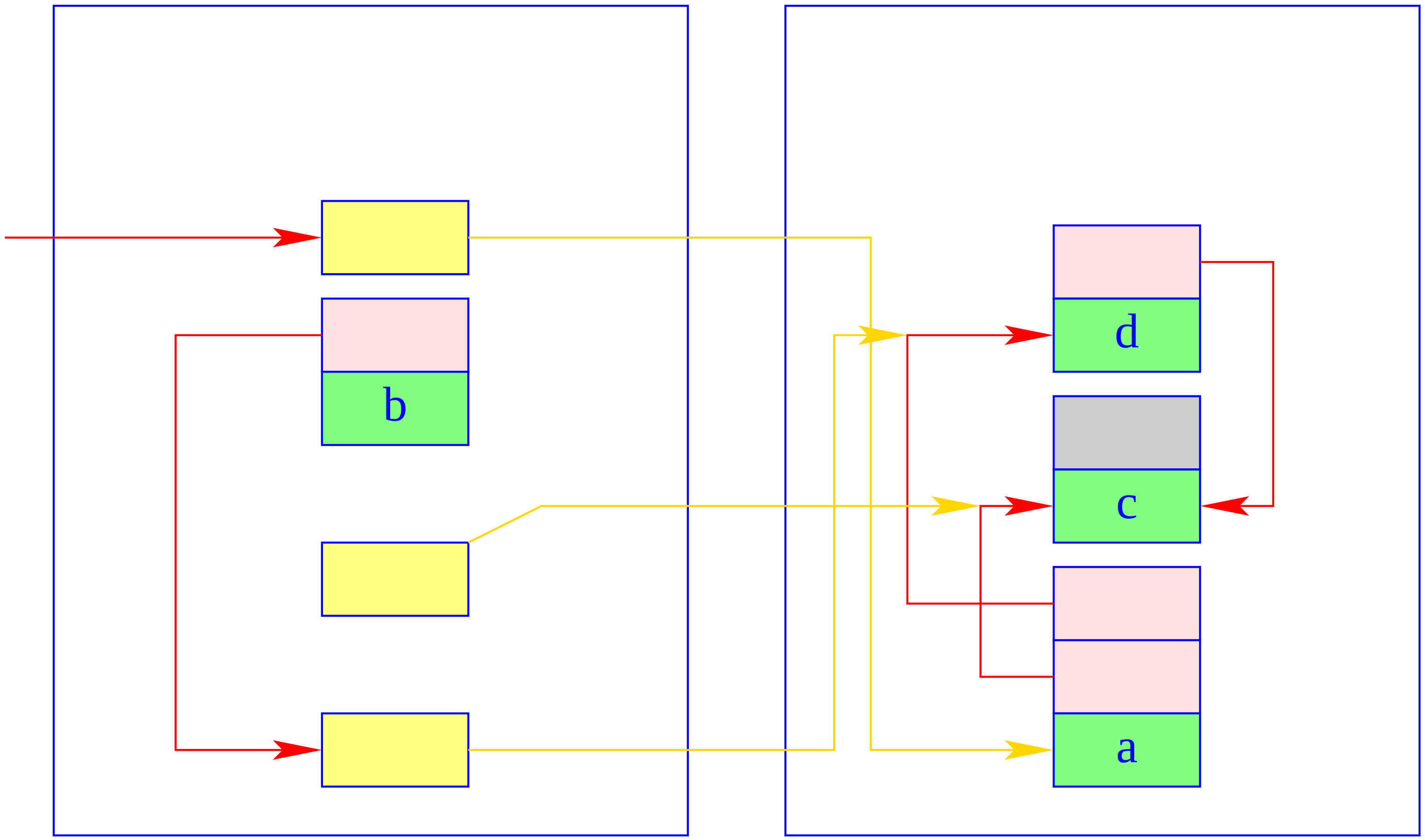

b
c
d
a

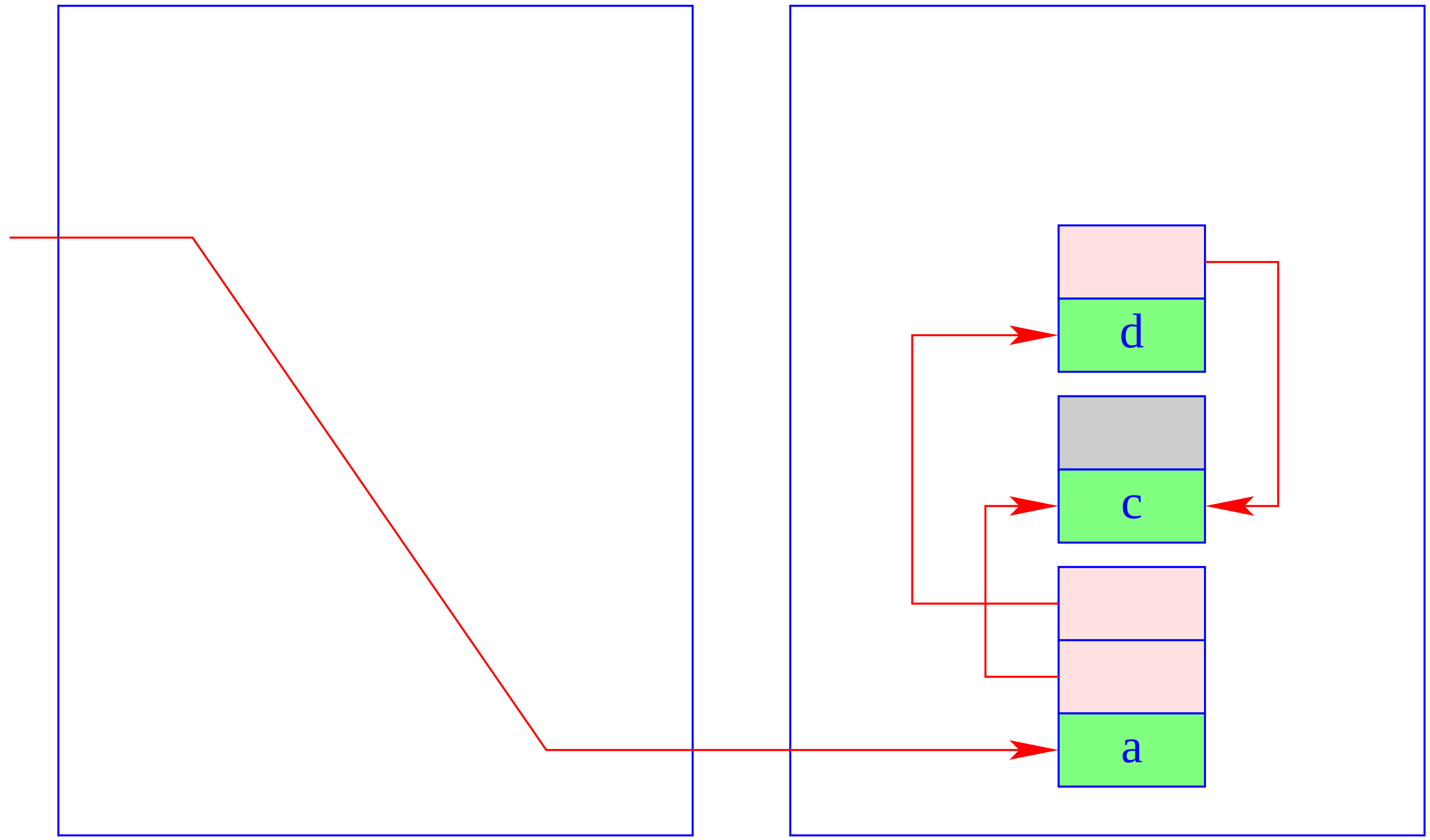

d
b
c
a

(3) Traversing of the to-space in order to correct the references.

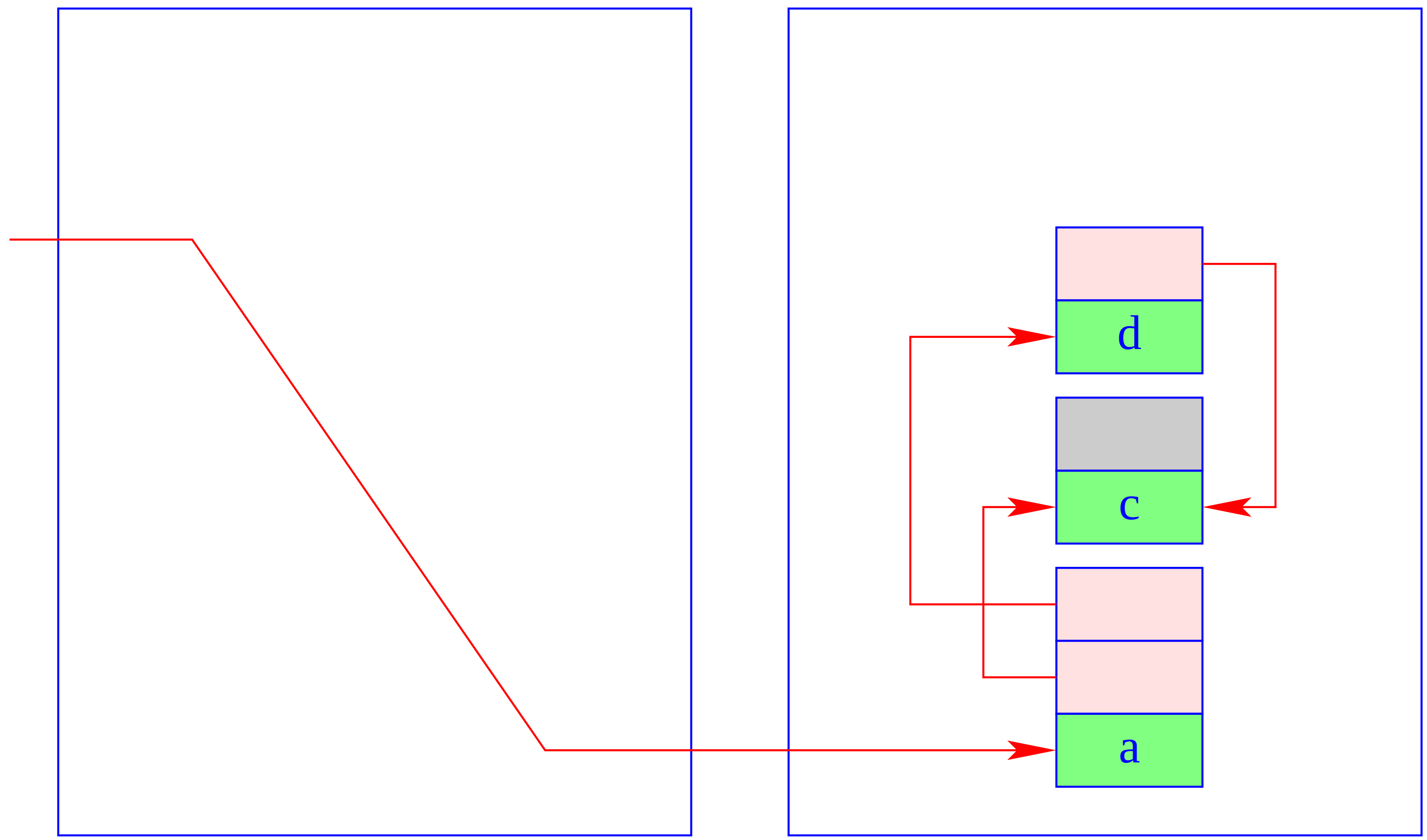


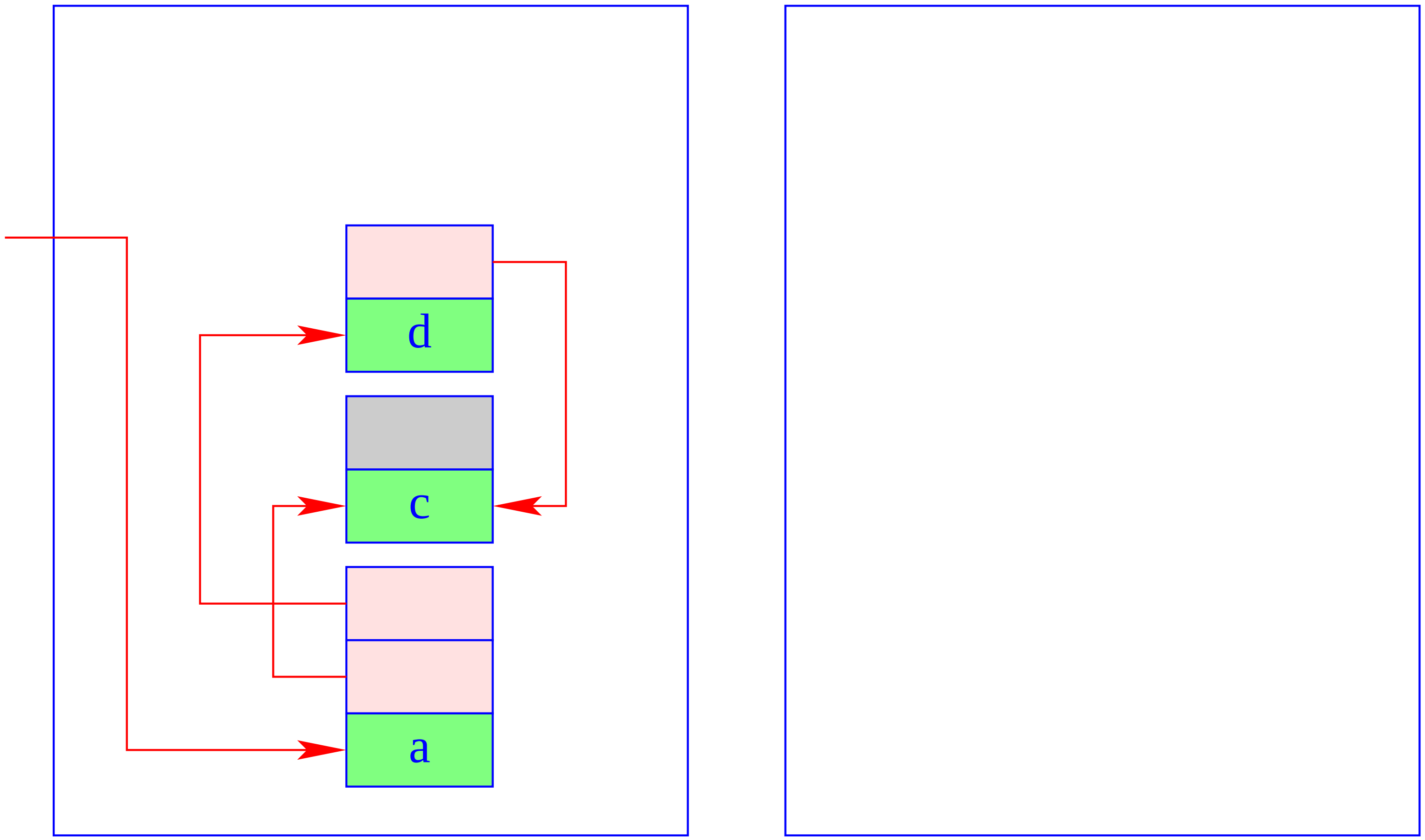

d
b
c
a


b
d
c
a


d
c
a

(4) Exchange of to-space and from-space.



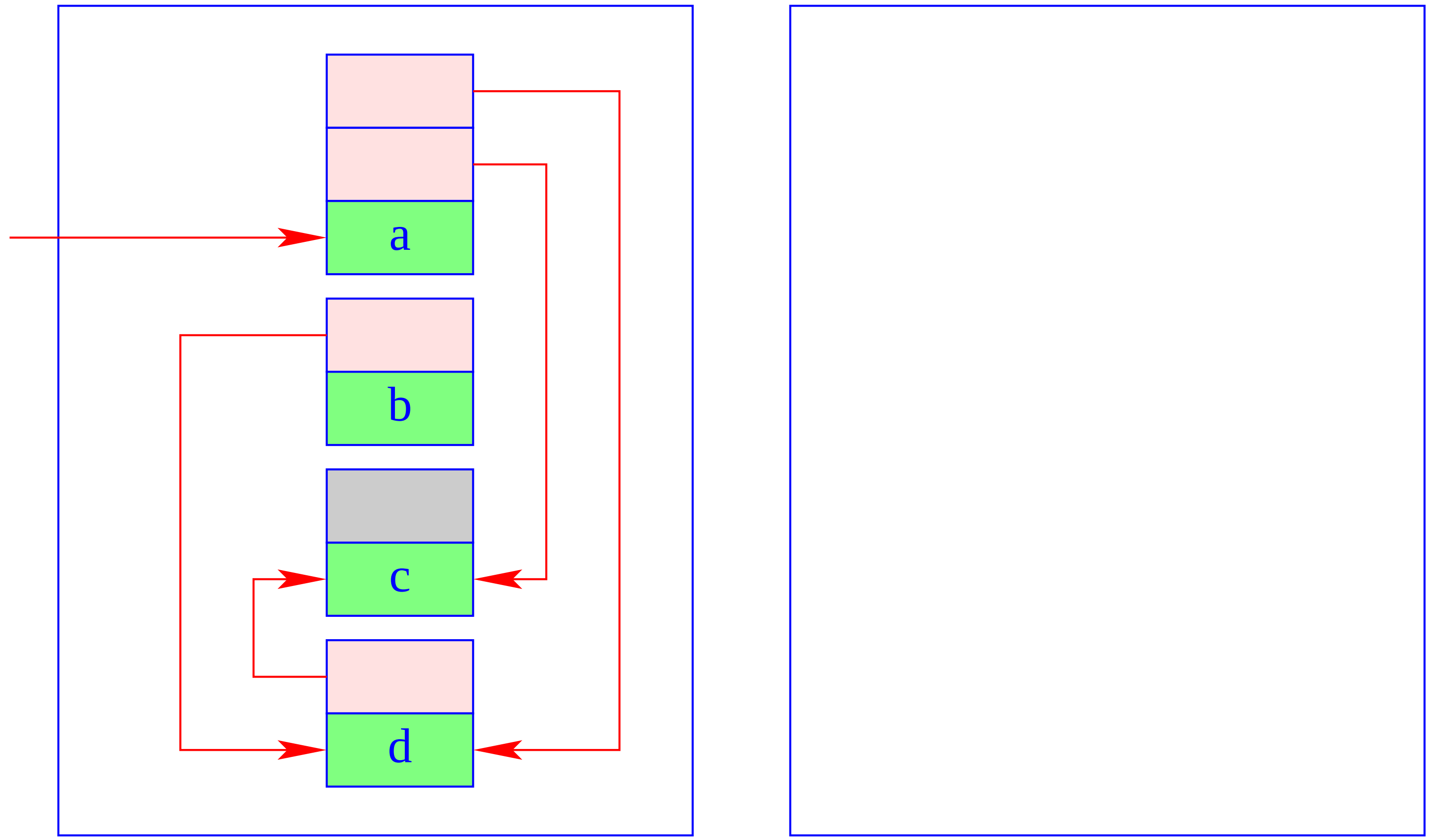

d
c
a

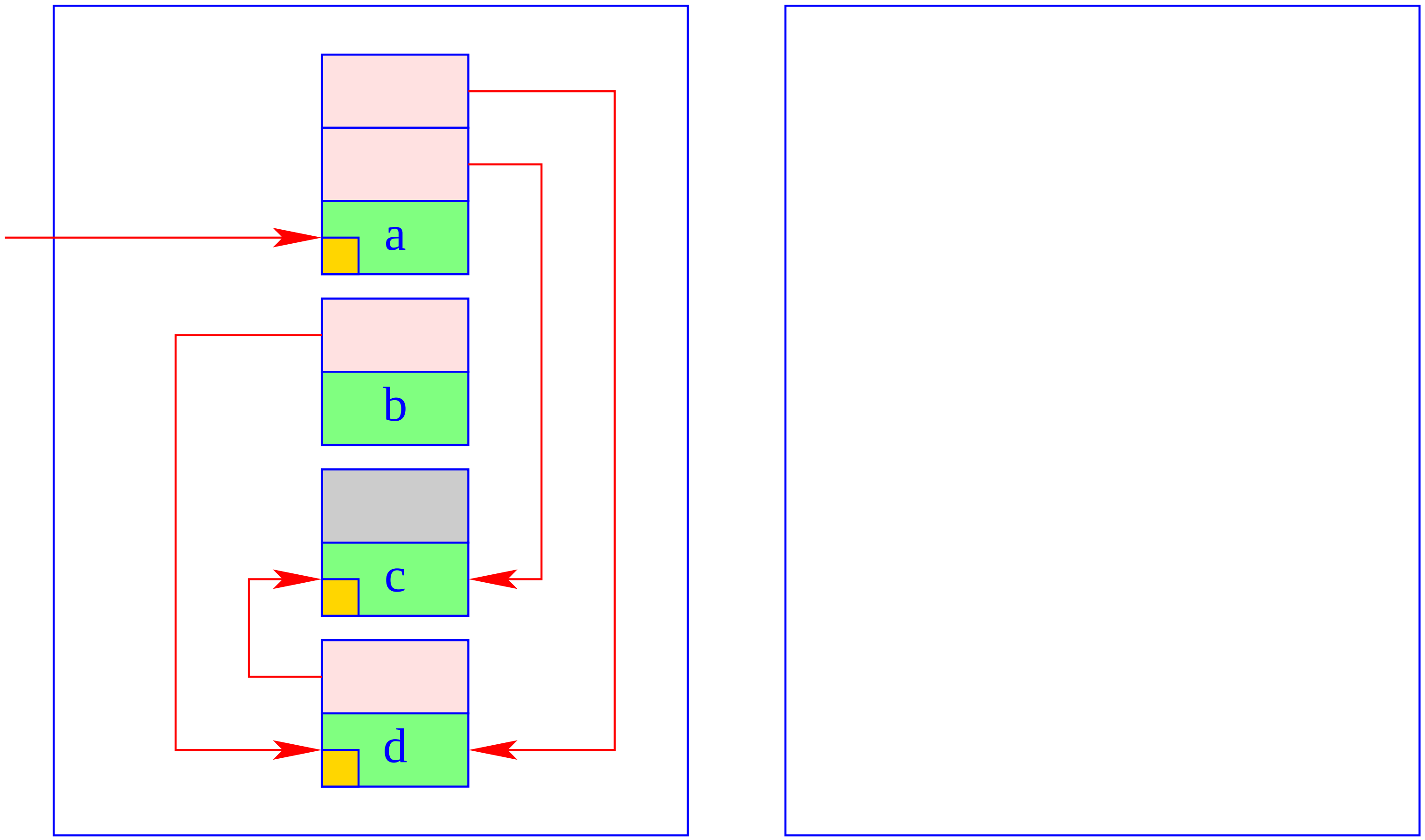
Warning:

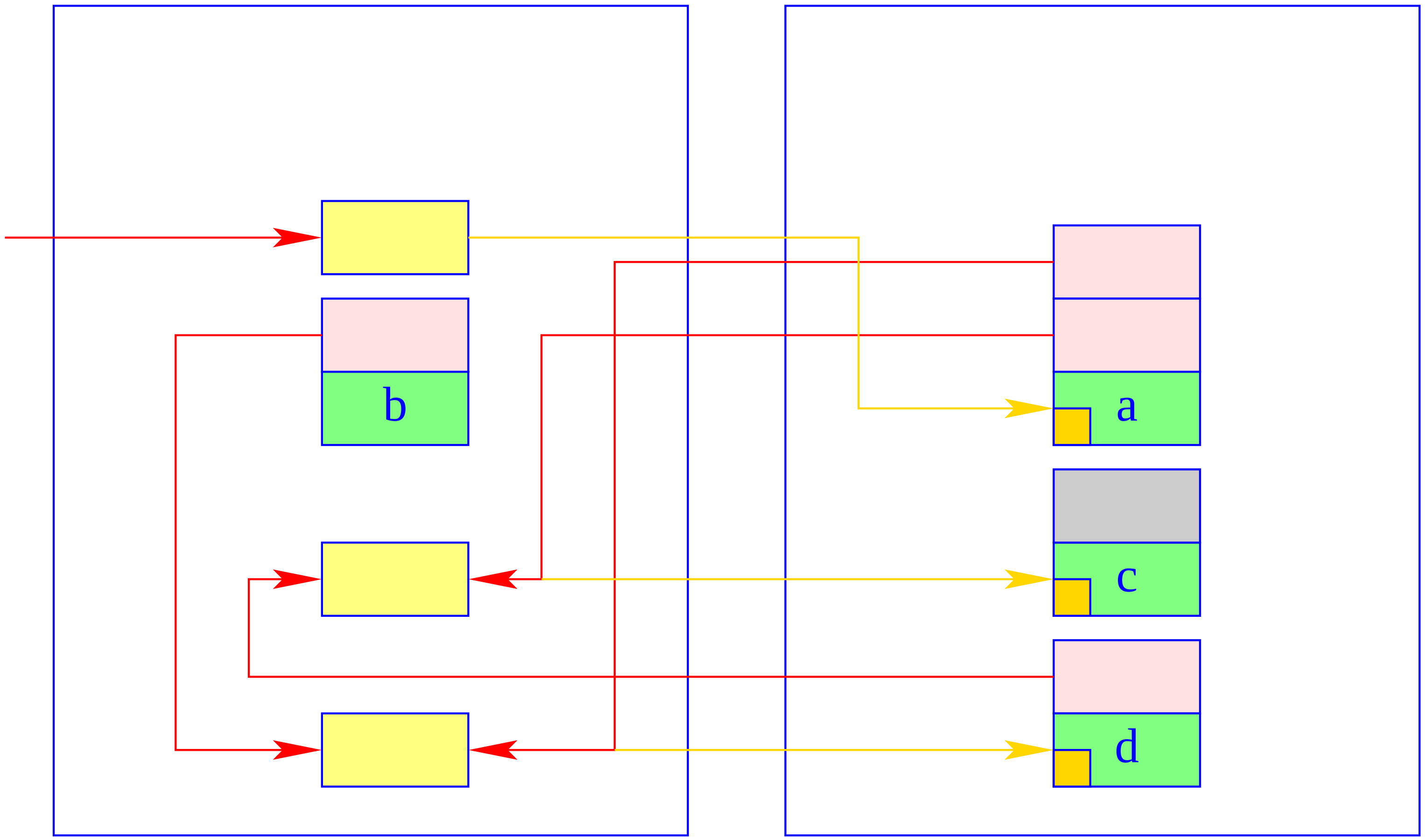
The garbage collection of the WiM must harmonize with backtracking.

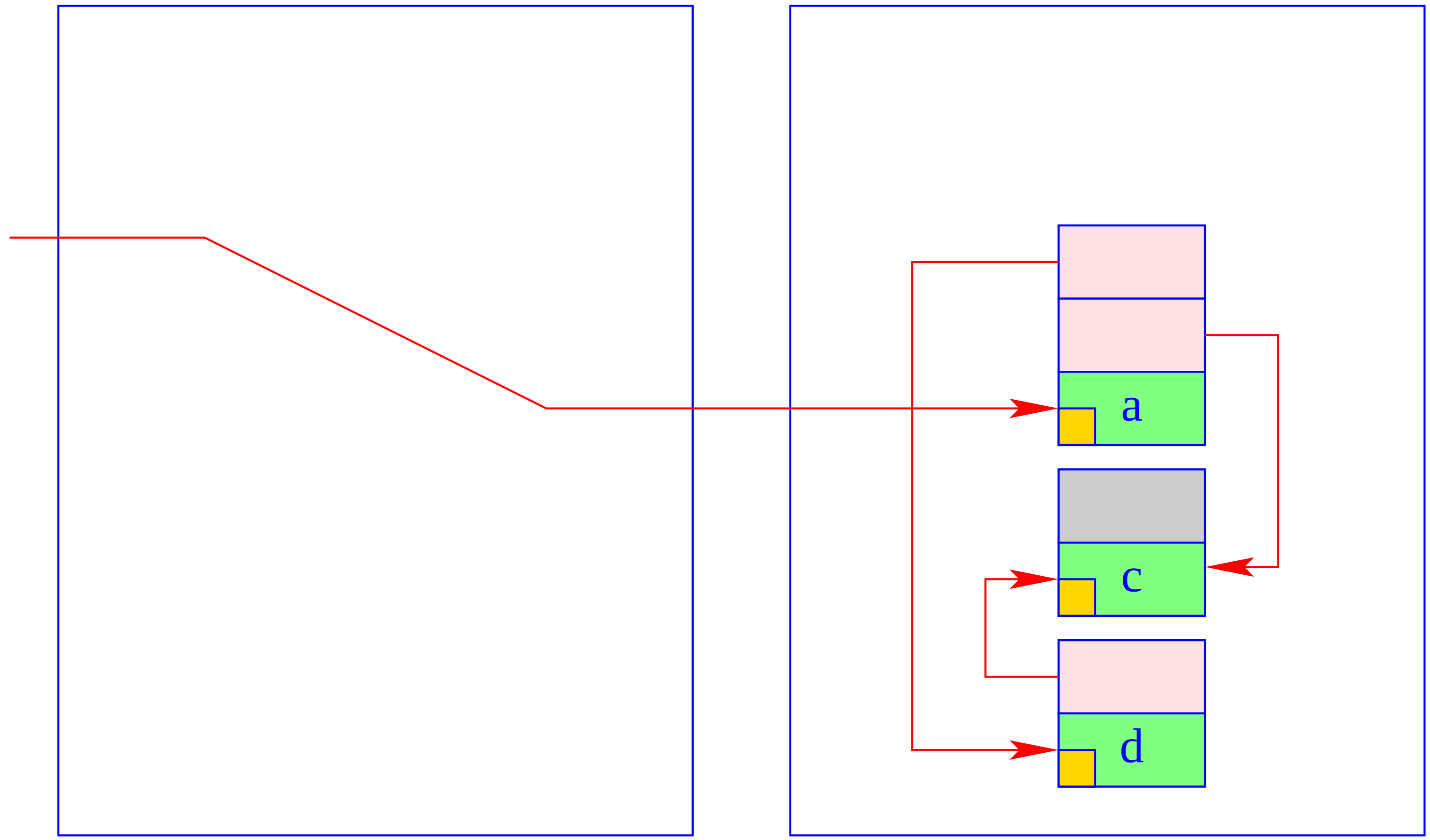
This means:

- The relative position of heap objects must not change during copying :-!!
- The heap references in the trail must be updated to the new positions.
- If heap objects are collected which have been created before the last backtrack point, then also the heap pointers in the stack must be updated.


a
b
c
d


a
b
c
d


b
a
c
d


a
c
d

Threads

39 The Language ThreadedC

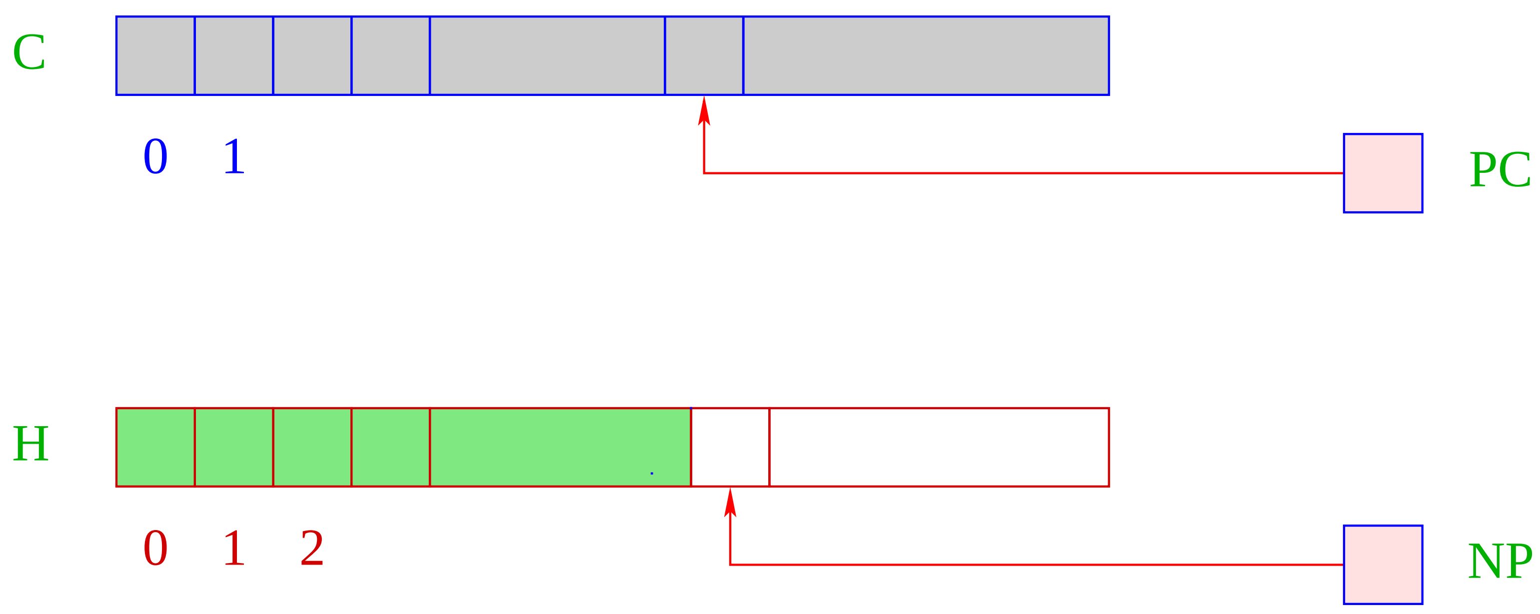
We extend C by a simple thread concept. In particular, we provide functions for:

- generating new threads: create();
- terminating a thread: exit();
- waiting for termination of a thread: join();
- mutual exclusion: lock(), unlock(); ...

In order to enable a parallel program execution, we extend the abstract machine (what else? :-)

40 Storage Organization

All threads share the same common code store and heap:

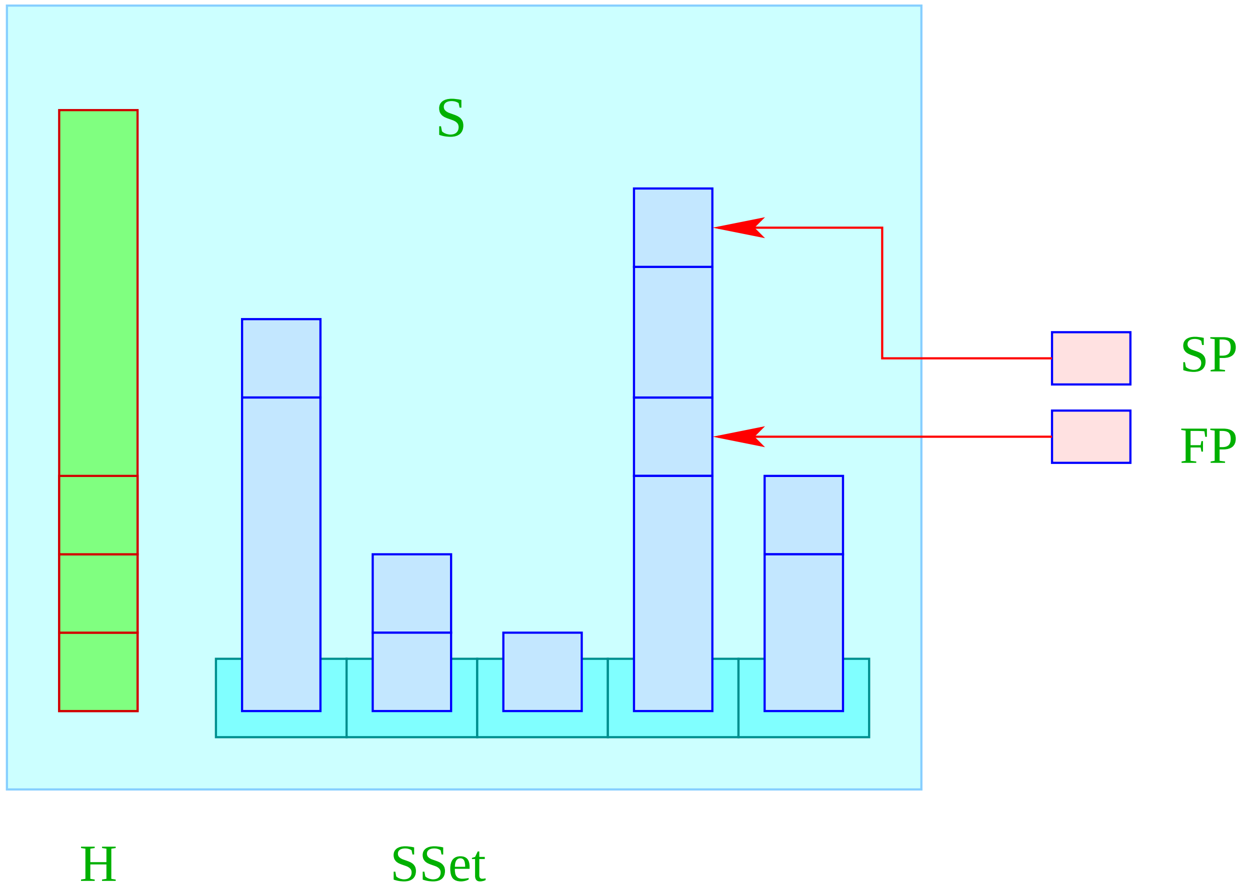


... similar to the CMa, we have:

C	=	Code Store – contains the CMa program; every cell contains one instruction;
PC	=	Program-Counter – points to the next executable instruction;
H	=	Heap – every cell may contain a base value or an address; the globals are stored at the bottom;
NP	=	New-Pointer – points to the first free cell.

For a simplification, we assume that the heap is stored in a separate segment.
The function malloc() then fails whenever NP exceeds the topmost border.

Every thread on the other hand needs its own stack:



In constrast to the CMa, we have:

SSet	=	Set of Stacks – contains the stacks of the threads;
		every cell may contain a base value of an address;
S	=	common address space for heap and the stacks;
SP	=	Stack-Pointer – points to the current topmost ocupied stack cell;
FP	=	Frame-Pointer – points to the current stack frame.

Warning:

- If all references pointed into the heap, we could use separate address spaces for each stack.

  Besides SP and FP, we would have to record the number of the current stack :-)

- In the case of C, though, we must assume that all storage reagions live within the same address space — only at different locations :-)

  SP Und FP then uniquely identify storage locations.

- For simplicity, we omit the extreme-pointer EP.

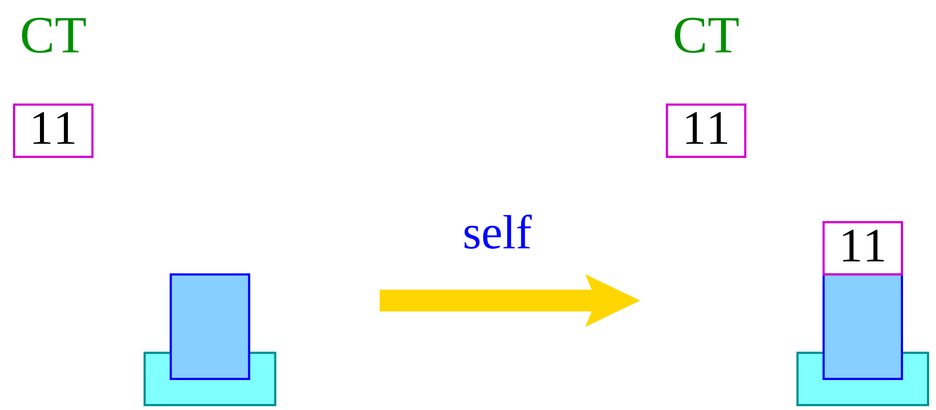
41 The Ready-Queue

Idea:

- Every thread has a unique number tid.
- A table TTab allows to determine for every tid the corresponding thread.
- At every point in time, there can be several executable threads, but only one running thread (per processor :-)
- the tid of the currently running thread is cept in the register CT (Current Thread).
- The function: **tid self ()** returns the tid of the current thread. Accordingly:

$$\text{code}_R \; \textbf{self} \; () \; \rho \quad = \quad \text{self}$$

... where the instruction self pushes the content of the register CT onto the (current) stack:

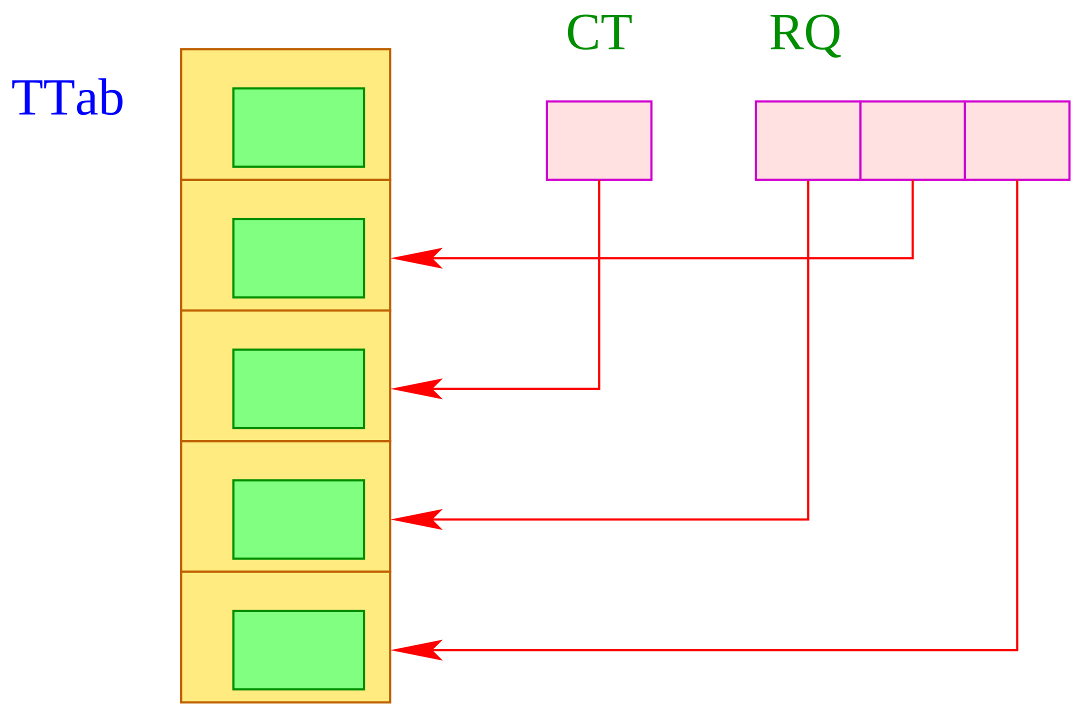


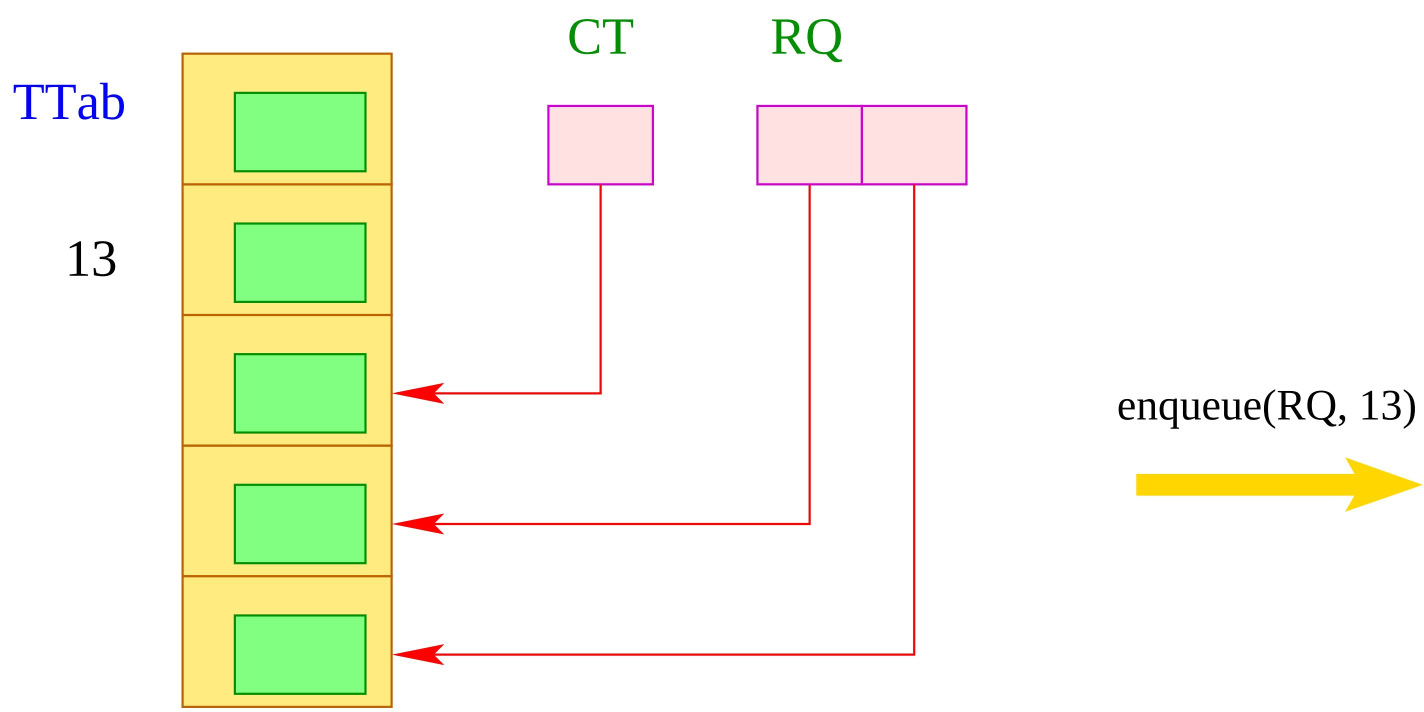
$$S[SP{+}{+}] = CT;$$

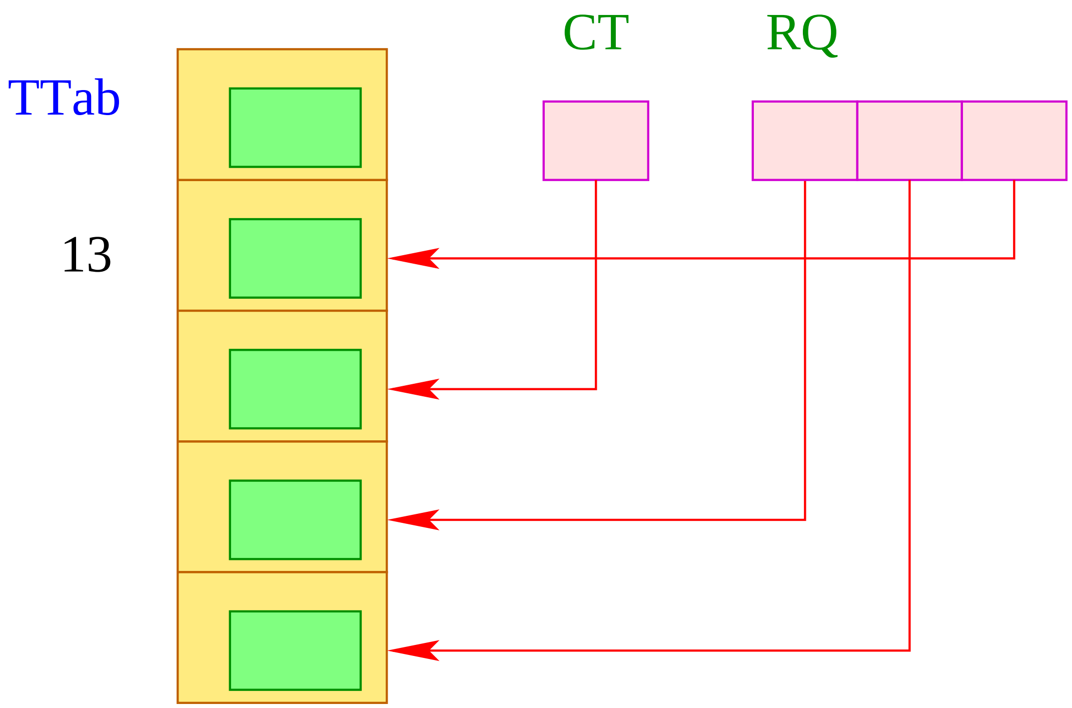
- The remaining executable threads (more precisely, their tid's) are maintained in the queue RQ (Ready-Queue).
- For queues, we need the functions:

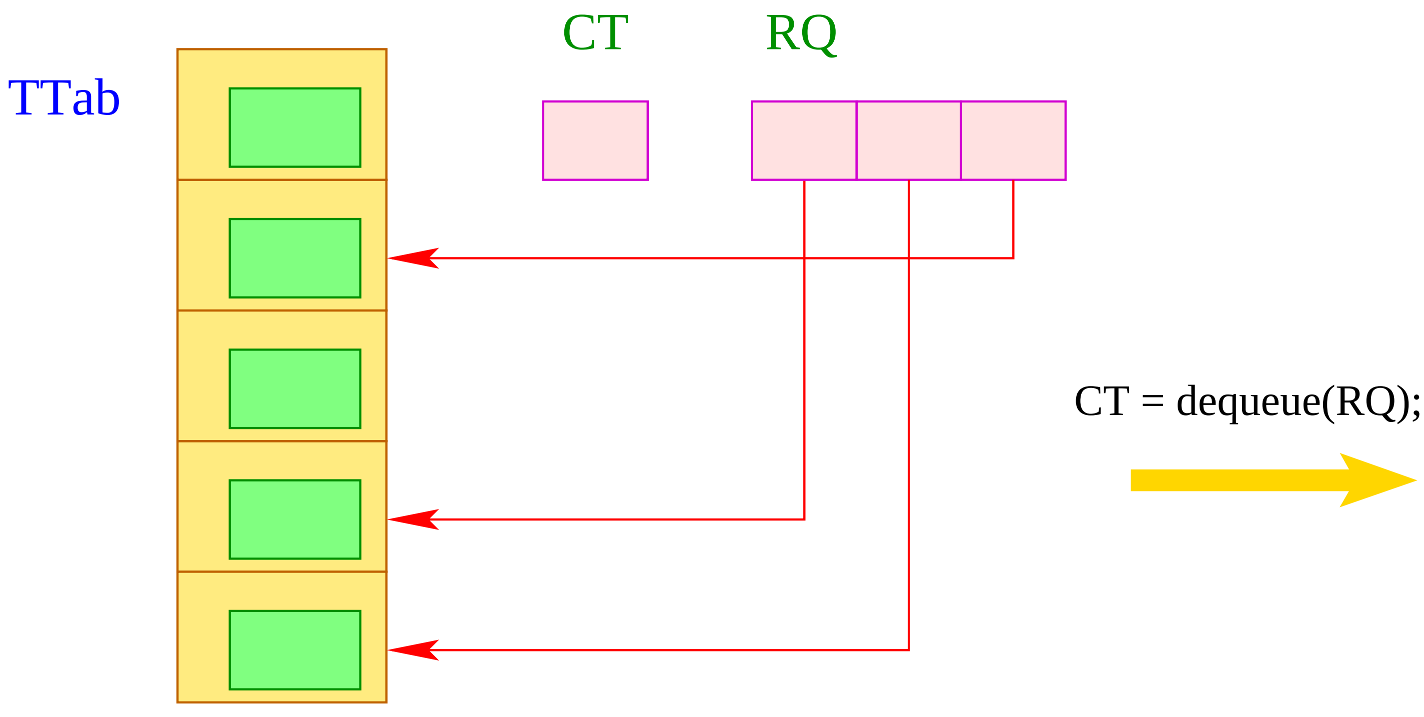
```
void enqueue (queue q, tid t),
tid dequeue (queue q)
```

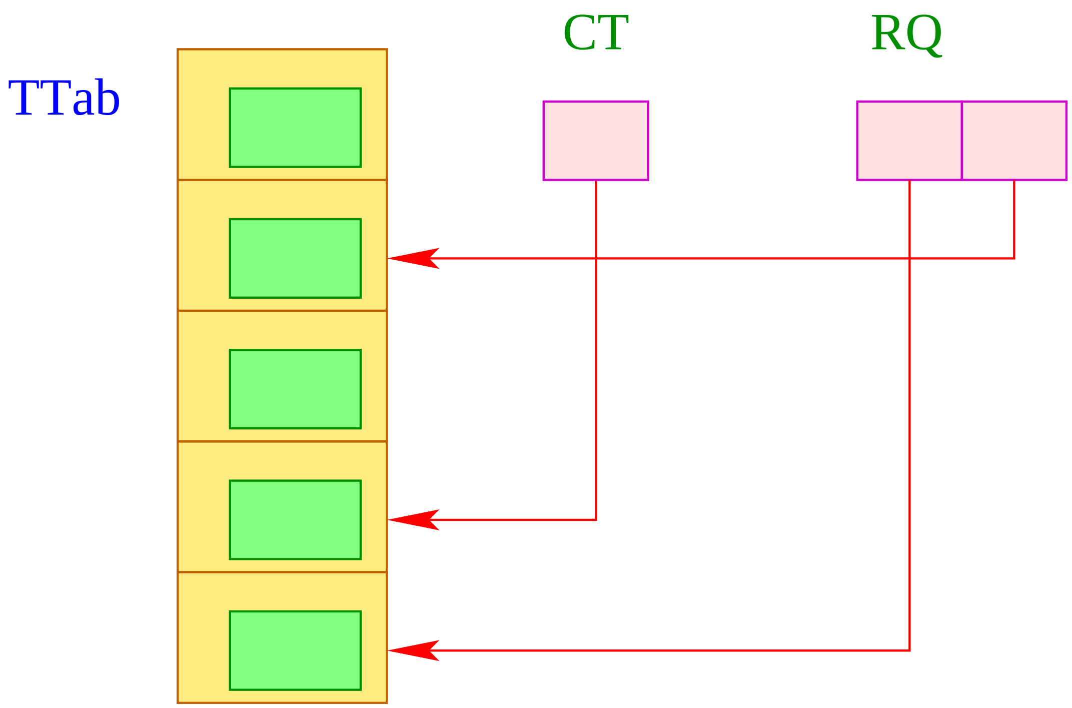
which insert a tid into a queue and return the first one, respectively ...


TTab
CT
RQ


TTab
13
CT
RQ
enqueue(RQ, 13)

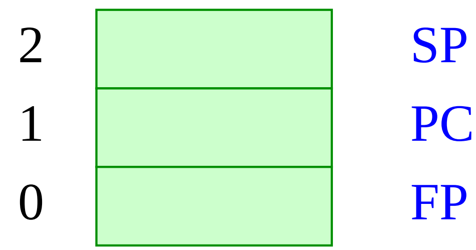

CT
RQ
TTab
13


TTab
CT
RQ
CT = dequeue(RQ);


TTab
CT
RQ

If a call to dequeue () failed, it returns a value $< \ 0$:-)

The thread table must contain for every thread, all information which is needed for its execution. In particular it consists of the registers PC, SP und FP:



Interrupting the current thread therefore requires to save these registers:

```
void save () {
     TTab[CT][0] = FP;
     TTab[CT][1] = PC;
     TTab[CT][2] = SP;
     }
```

Analogously, we restore these registers by calling the function:

```
void restore () {
     FP = TTab[CT][0];
     PC = TTab[CT][1];
     SP = TTab[CT][2];
     }
```

Thus, we can realize an instruction yield which causes a thread-switch:

```
tid ct = dequeue ( RQ );
if (ct ≥ 0) {
     save (); enqueue ( RQ, CT );
     CT = ct;
     restore ();
     }
```

Only if the ready-queue is non-empty, the current thread is replaced :-)

42 Switching between Threads

Problem:

We want to give each executable thread a fair chance to be completed.

$\Longrightarrow$

- Every thread must former or later be scheduled for running.
- Every thread must former or later be interrupted.

Possible Strategies:

- Thread switch only at explicit calls to a function `yield()` :-(
- Thread switch after **every** instruction $\Longrightarrow$ too expensive :-(
- Thread switch after a **fixed number** of steps $\Longrightarrow$ we must install a counter and execute **yield** at dynamically chosen points :-(

We insert thread switches at selected program points ...

- at the beginning of function bodies;
- before every jump whose target does not exceed the current PC ...

$\Longrightarrow$ rare :-))

The modified scheme for loops $s \equiv \textbf{while}\ (e)\ s$ then yields:

$$
\begin{array}{lllll}
\text{code}\ s\ \rho & = & \text{A}: & \text{code}_\text{R}\ e\ \rho \\
 & & & \text{jumpz B} \\
 & & & \text{code}\ s\ \rho \\
 & & & \text{yield} \\
 & & & \text{jump A} \\
 & & \text{B}: & \dots
\end{array}
$$

Note:

- **If-then-else**-Statements do not necessarily contain thread switches.
- **do-while**-Loops require a thread switch at the end of the condition.
- Every loop should contain (at least) one thread switch :-)
- Loop-Unroling reduces the number of thread switches.
- At the translation of **switch**-statements, we created a jump table behind the code for the alternatives. Nonetheless, we can avoid thread switches here.
- At freely programmed uses of jumpi as well as jumpz we should also insert thread switches before the jump (or at the jump target).
- If we want to reduce the number of executed thread switches even further, we could switch threads, e.g., only at every 100th call of yield ...

43 Generating New Threads

We assume that the expression: $s \equiv \textbf{create}\,(e_0, e_1)$ first evaluates the expressions e_i to the values f, a and then creates a new thread which computes $f\,(a)$.

If thread creation fails, s returns the value -1.

Otherwise, s returns the new thread's tid.

Tasks of the Generated Code:

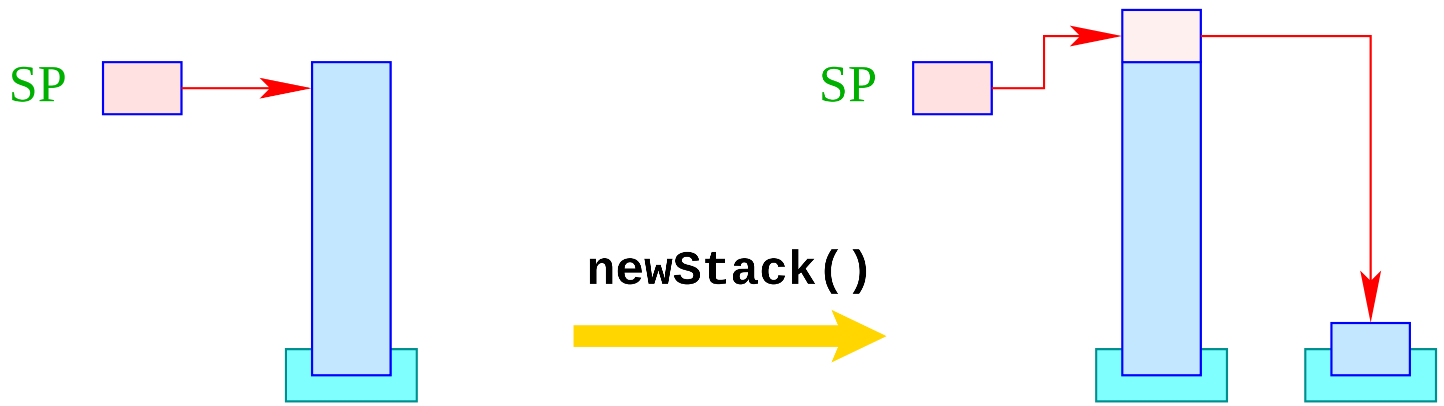
- Evaluation of the e_i;
- Allocation of a new run-time stack together with a stack frame for the evaluation of $f\,(a)$;
- Generation of a new tid;
- Allocation of a new entry in the TTab;
- Insertion of the new tid into the ready-queue.

The translation of s then is quite simple:

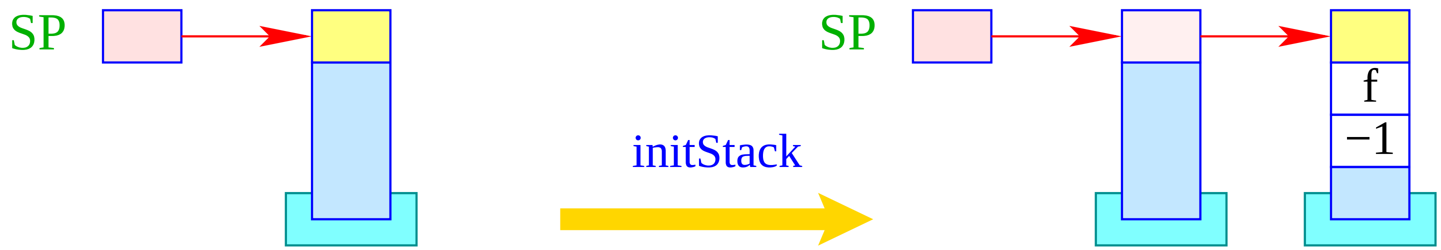
$$\begin{array}{lll} \mathrm{code_R}\ s\ \rho & = & \mathrm{code_R}\ e_0\ \rho \\ & & \mathrm{code_R}\ e_1\ \rho \\ & & \mathrm{initStack} \\ & & \mathrm{initThread} \end{array}$$

where we assume the argument value occupies 1 cell :-)

For the implementation of initStack we need a run-time function newStack() which returns a pointer onto the first element of a new stack:



If the creation of a new stack fails, the value 0 is returned.




```
newStack();
if (S[SP]) {
        S[S[SP]+1] = -1;
        S[S[SP]+2] = f;
        S[S[SP]+3] = S[SP-1];
        S[SP-1] = S[SP]; SP--
    }
else S[SP = SP - 2] = -1;
```

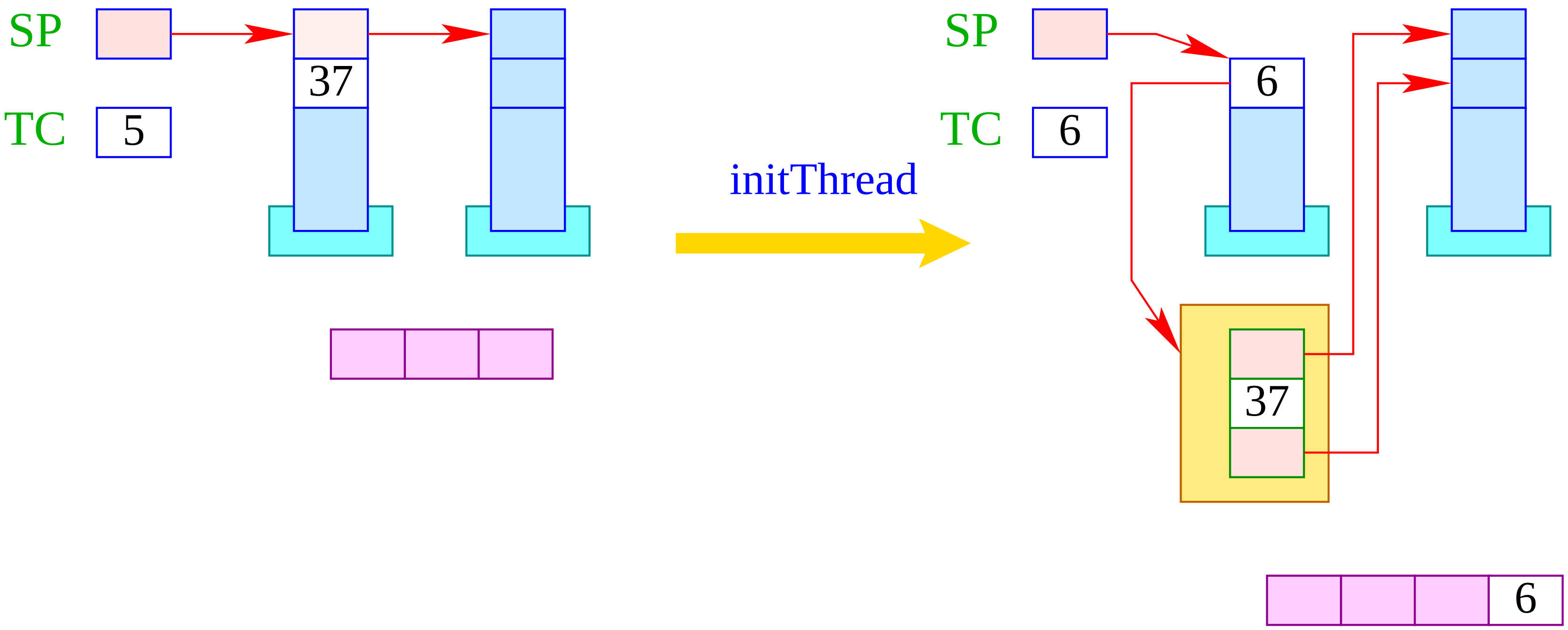
Note:

- The continuation address f points to the (fixed) code for the termination of threads.
- Inside the stack frame, we no longer allocate space for the EP $\Longrightarrow$ the return value has relative address -2.
- The bottom stack frame can be identified through FPold = -1 :-)

In order to create new thread ids, we introduce a new register TC (Thread Count).

Initially, TC has the value 0 (corresponds to the tid of the initial thread).

Before thread creation, TC is incremented by 1.


SP
TC
5
37
initThread
SP
TC
6
6
37
6

```
if (S[SP] ≥ 0) {
    tid = ++TCount;
    TTab[tid][0] = S[SP]-1;
    TTab[tid][1] = S[SP-1];
    TTab[tid][2] = S[SP];
    S[--SP] = tid;
    enqueue( RQ, tid );
}
```

44 Terminating Threads

Termination of a thread (usually :-) returns a value. There are two (regular) ways to terminate a thread:

1. The initial function call has terminated. Then the return value is the return value of the call.

2. The thread executes the statement **exit** (e); Then the return value equals the value of e.

Warning:

- We want to return the return value in the bottom stack cell.

- **exit** may occur arbitrarily deeply nested inside a recursion. Then we de-allocate all stack frames ...

- ... and jump to the terminal treatment of threads at address f .

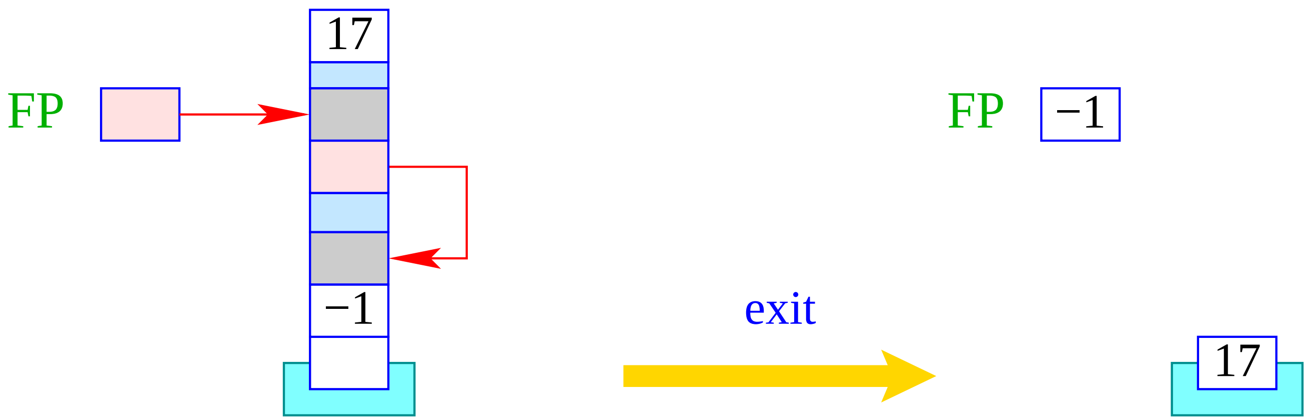
Therefore, we translate:

$$\begin{array}{lll} \text{code } \textbf{exit } (e);\ \rho & = & \text{code}_R\ e\ \rho \\ & & \text{exit} \\ & & \text{term} \\ & & \text{next} \end{array}$$

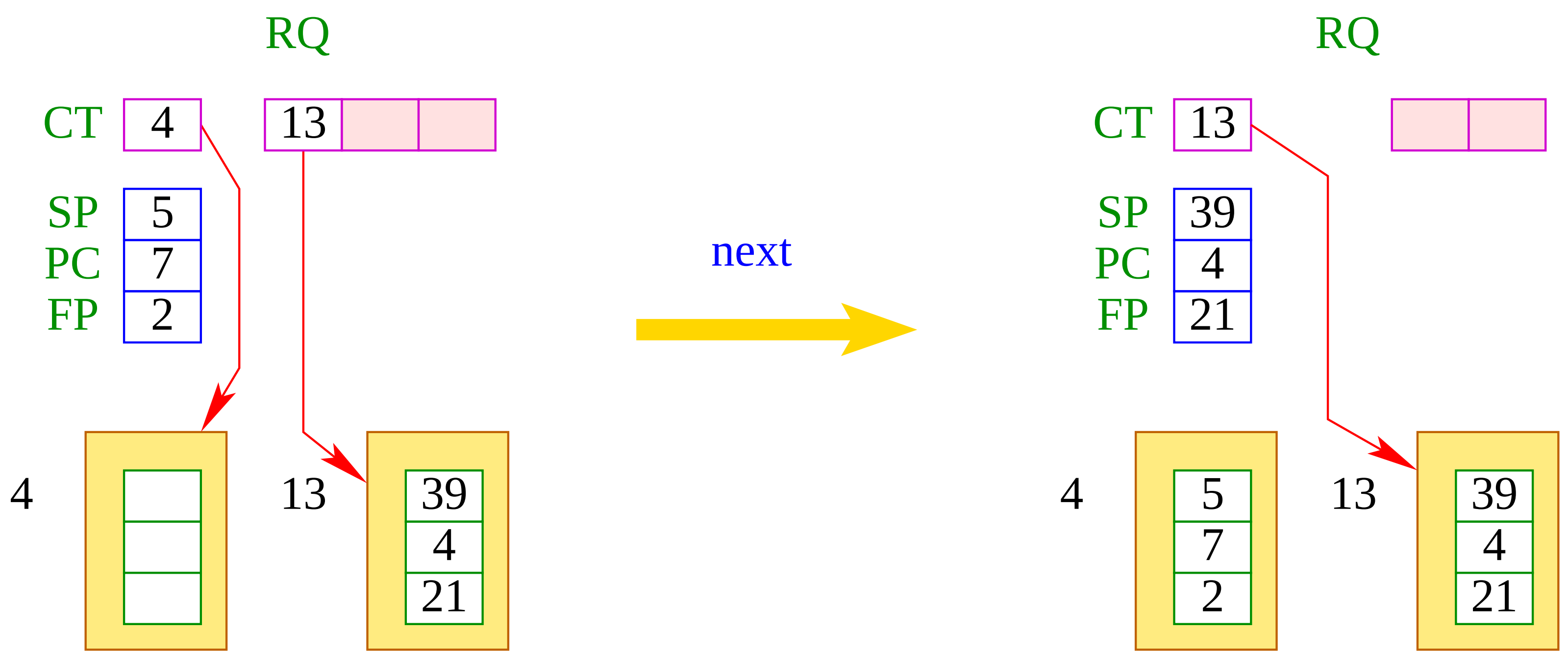
The instruction term is explained later :-)

The instruction exit successively pops all stack frames:

```
result = S[SP];
while (FP ≠ –1) {
        SP = FP–2;
        FP = S[FP–1];
        }
S[SP] = result;
```


17
FP
−1
exit
FP
−1
17

The instruction next activates the next executable thread:
in contrast to yield the current thread is not inserted into RQ .



Ist die Schlange RQ leer, wird zusätzlich If the queue RQ is empty, we additionally terminate the whole program:

```
if (0 > ct = dequeue( RQ ))    halt;
else {
        save ();
        CT = ct;
        restore ();
    }
```