

Data Structures (8A)

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Based on

ARM System-on-Chip Architecture, 2nd ed, Steve Furber

Introduction to ARM Cortex-M Microcontrollers
– Embedded Systems, Jonathan W. Valvano

Digital Design and Computer Architecture,
D. M. Harris and S. L. Harris

Computer Organization and Design ARM Edition:
The Hardware Software Interface
By David A. Patterson, John L. Hennessy

<https://thinkingeek.com/arm-assembler-raspberry-pi/>

Heap

1. **dynamically allocated** by the program
when it creates the data structure
2. used by the program to store information
3. **dynamically released** by the program
when the structure is no longer needed

Heap manager

```
pt = malloc(size);    // returns a pointer to a block of size bytes  
free(pt);            // deallocates the block at pt
```

simple version to be considered

```
pt = Heap_Allocate(); // returns a pointer to a block of fixed size bytes  
Heap_Release(pt);    // deallocates the block at pt
```

Heap

```
#define SIZE 4
#define NUM 5
#define NULL 0 // empty pointer
```

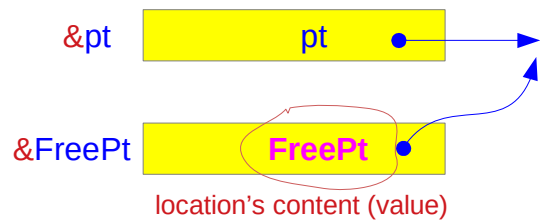
```
int32_t *FreePt;
int32_t Heap[SIZE*NUM];
```

SIZE	EQU	4
NUM	EQU	5
NULL	EQU	0
FreePT	SPACE	4
Heap	SPACE	SIZE*NUM*4

Pointer and array declarations – C and ARM assembly

C code

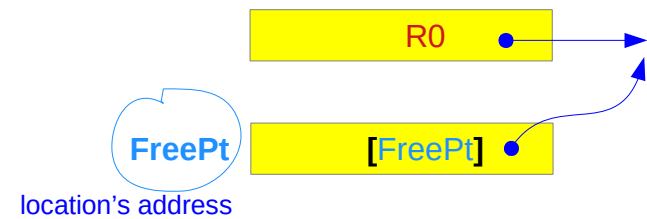
```
int32_t * pt;  
int32_t * FreePt;  
int32_t Heap[SIZE*NUM];
```



Heap	Heap[0]
Heap+1	Heap[1]
Heap+2	Heap[2]
Heap+3	Heap[3]
Heap+4	Heap[4]
Heap+5	Heap[5]

ARM assembly code

```
FreePt SPACE 4  
Heap SPACE SIZE*NUM*4
```



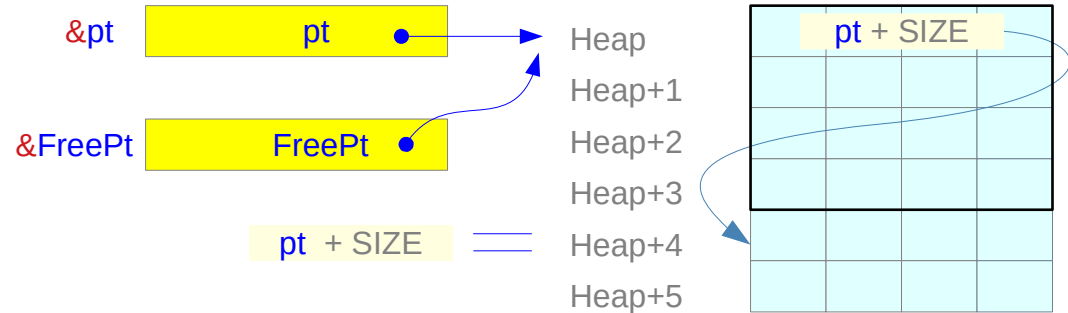
Heap	
Heap+1	
Heap+2	
Heap+3	
Heap+4	
Heap+5	

Heap_Init (1)

```
void Heap_Init(void) {  
    int    i  
    int32_t * pt;  
  
    pt = FreePt = &Heap[0];  
  
    for (i=1; i<NUM; i++) {  
        *pt = (int32_t) (pt + SIZE);  
        pt = pt + SIZE;  
    }  
  
    * (int32_t *) pt = NULL;  
}
```

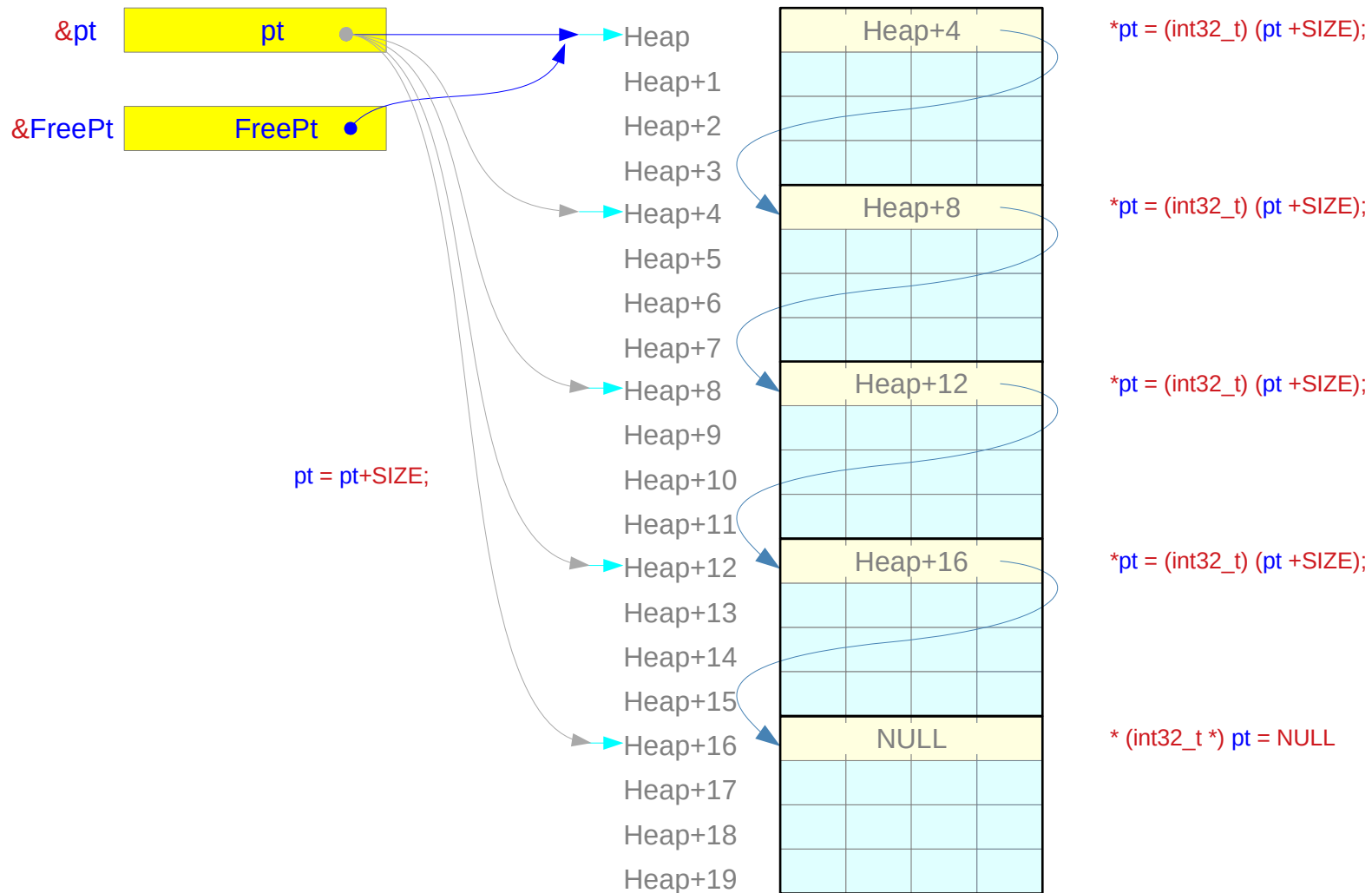
```
#define    SIZE 4  
#define    NUM 5  
#define    NULL 0    // empty pointer
```

```
int32_t    *FreePt;  
int32_t    Heap[SIZE*NUM];
```



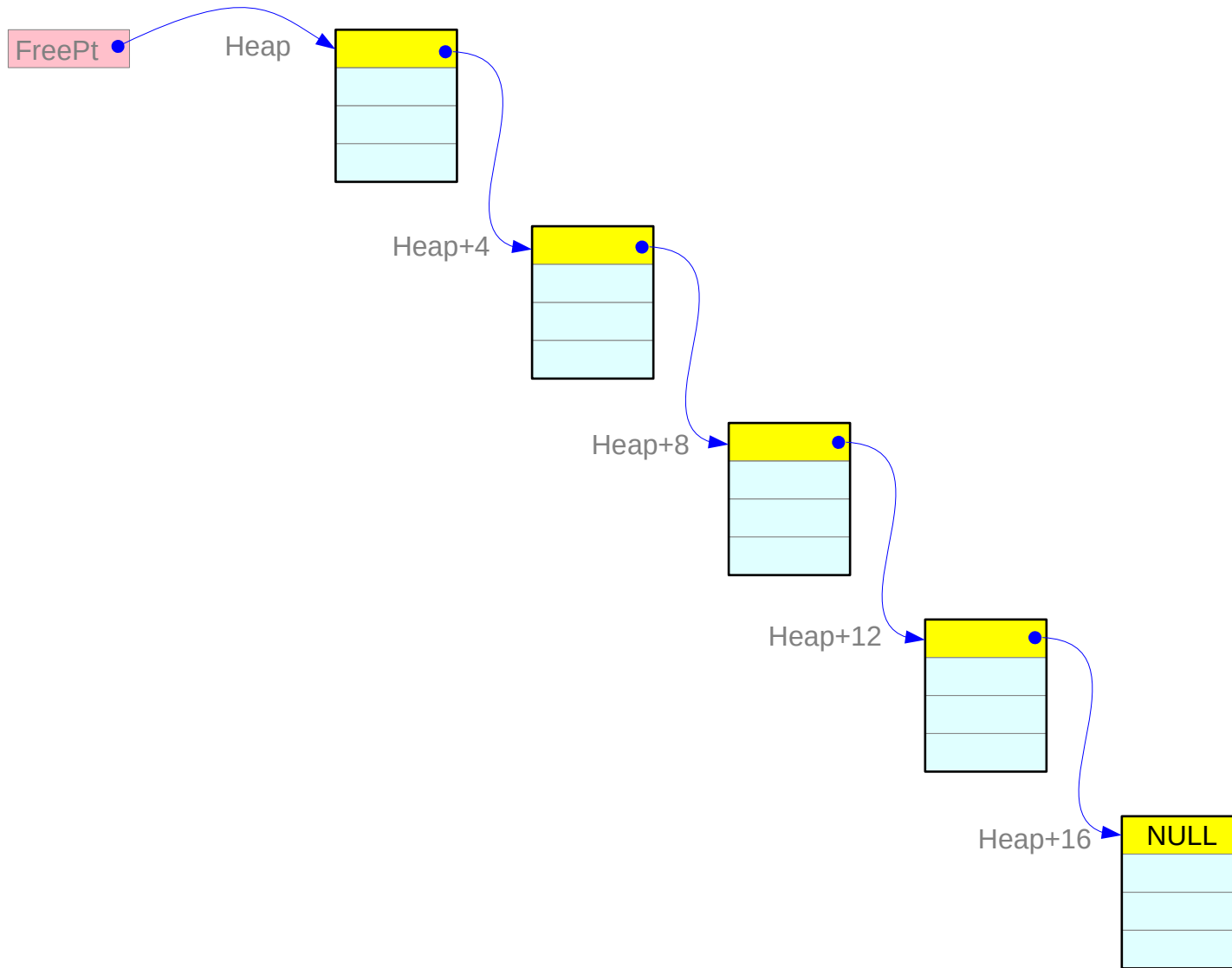
```
int32_t * pt;  
int32_t * FreePt;
```


Heap_Init (2)



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Heap_Init (3)



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Heap_Init (1)

```
Heap_Init    LDR    R0, =Heap           ; pt           ; R0 ← &Heap
             LDR    R1, =FreePt        ;             ; R1 ← FreePt
             STR    R0, [R1]          ; *FreePT = Heap ; [FreePt] ← Heap
             MOV    R2, #SIZE         ; R2 ← #4
             MOV    R3, #NUM-1        ; R3 ← #3
imLoop       ADD    R1, R0, R2, LSL #2 ; pt + SIZE    ; R1 ← R0 + R2*4
             STR    R1, [R0]          ; *pt = pt + SIZE ; [R0] ← R0 + R2*4
             MOV    R0, R1            ; pt = pt + SIZE ; R0 ← R1
             SUBS   R3, R3, #1         ; R3 ← R3 - 1
             BNE    imLoop
             MOV    R1, #NULL         ; R1 ← #0
             STR    R1, [R0]          ; last ptr is NULL ; [R0] ← NULL
             BX     LR
```

Heap_Init (2)

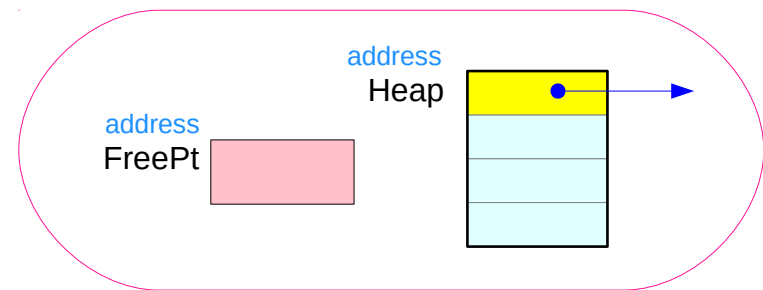
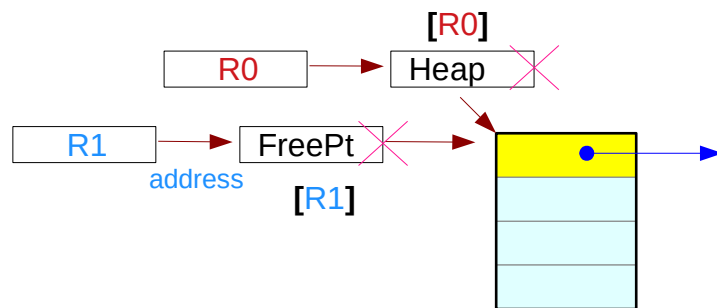
```

Heap_Init    LDR    R0, =Heap      ; pt      ; R0 ← Heap
             LDR    R1, =FreePt   ;         ; R1 ← FreePt
             STR    R0, [R1]      ; *FreePt = Heap ; [FreePt] ← Heap
    
```

~~LDR R0, =Heap ; R0 ← &Heap
 LDR R1, =FreePt ; R1 ← &FreePt~~

~~[R0] ≡ Heap
 [R1] ≡ FreePt~~

▼ Heap, FreePt : all address labels of memory locations

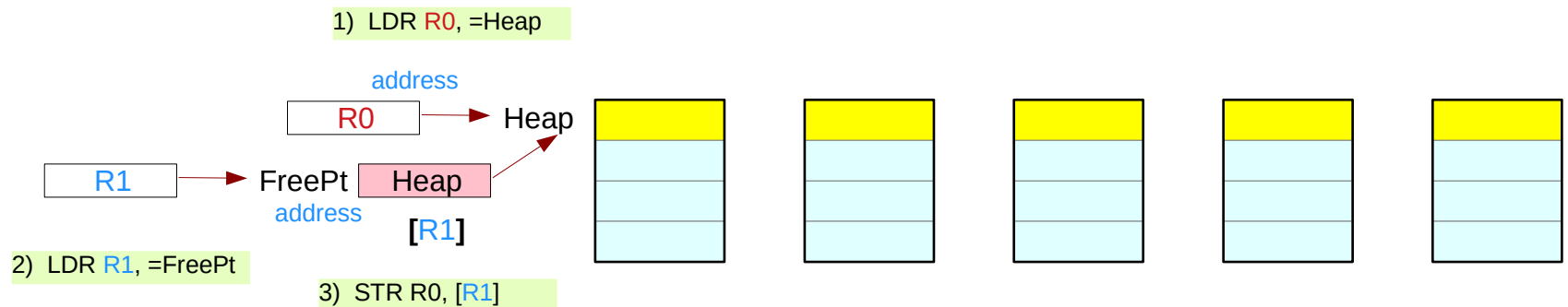


Heap_Init (3)

```
Heap_Init    LDR    R0, =Heap    ; pt          ; R0 ← Heap
             LDR    R1, =FreePt  ;             ; R1 ← FreePt
             STR    R0, [R1]     ; *FreePt = Heap ; [FreePt] ← Heap
```

```
LDR R0, =Heap    ; R0 ← Heap
LDR R1, =FreePt  ; R1 ← FreePt
```

```
R0 ≡ Heap      address
R1 ≡ FreePt    address
```

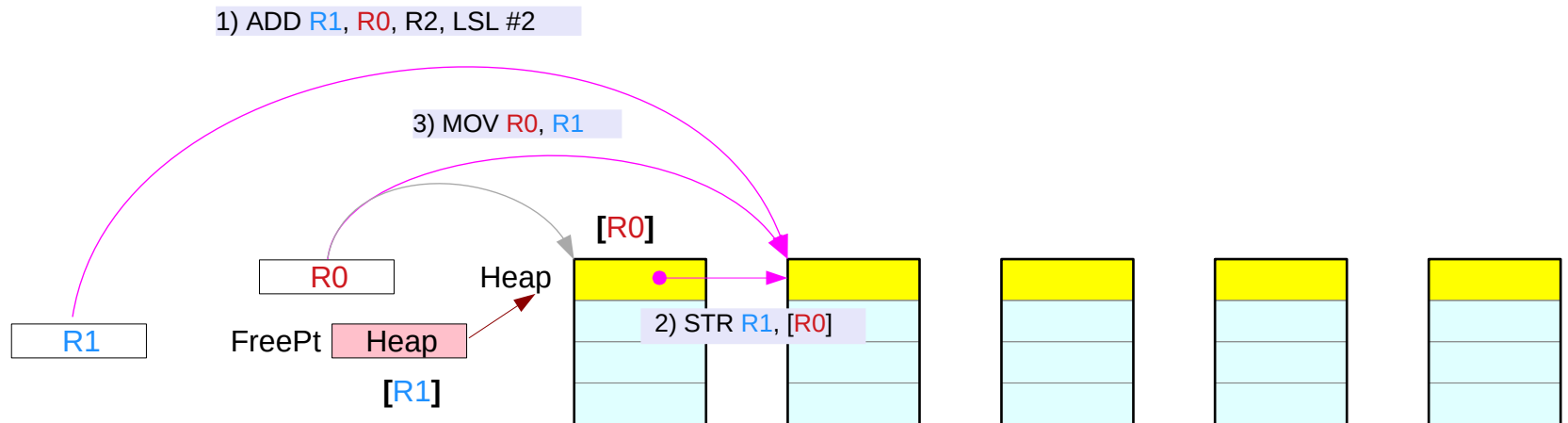


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Heap_Init (4)

```
imLoop    MOV     R2, #SIZE           ; R2 ← #4
          MOV     R3, #NUM-1       ; R3 ← #3
          ADD     R1, R0, R2, LSL #2 ; pt + SIZE ; R1 ← R0 + R2*4
          STR     R1, [R0]         ; *pt = pt + SIZE ; [R0] ← R0 + R2*4
          MOV     R0, R1          ; pt = pt + SIZE ; R0 ← R0 + R2*4
```

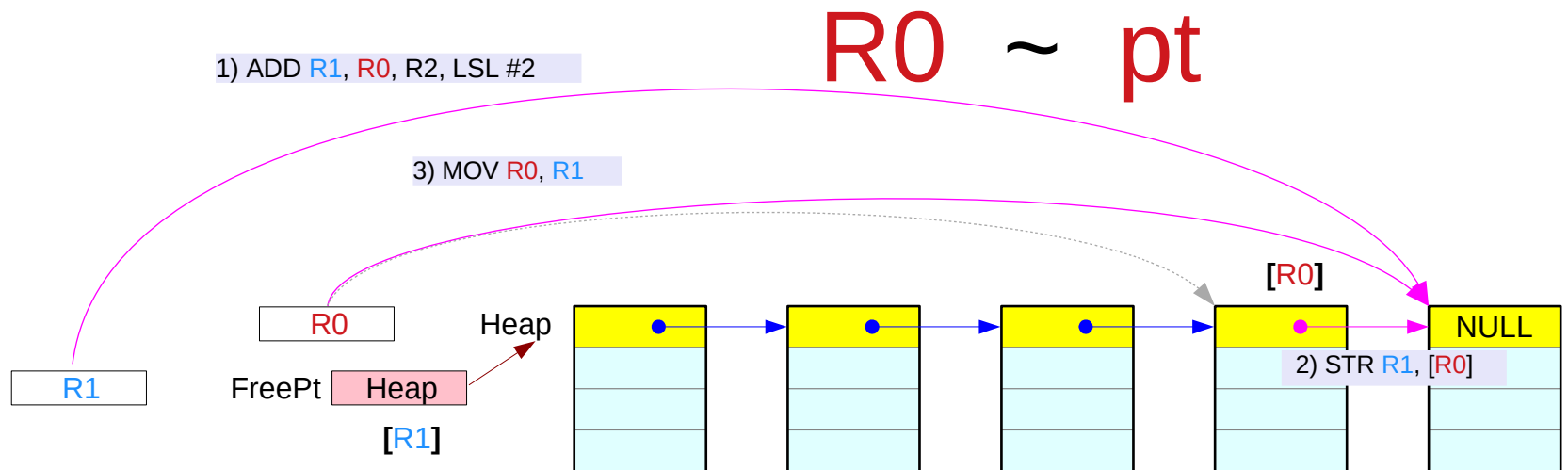
R0 ~ pt



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Heap_Init (5)

```
imLoop    ADD    R1, R0, R2, LSL #2    ; pt + SIZE    ; R1 ← R0 + R2*4
          STR    R1, [R0]              ; *pt = pt + SIZE ; [R0] ← R0 + R2*4
          MOV    R0, R1                ; pt = pt + SIZE  ; R0 ← R0 + R2*4
          SUBS   R3, R3, #1            ; R3 ← R3 - 1
          BNE    imLoop
          MOV    R1, #NULL              ; R1 ← #0
          STR    R1, [R0]              ; last ptr is NULL ; [R0] ← NULL
```

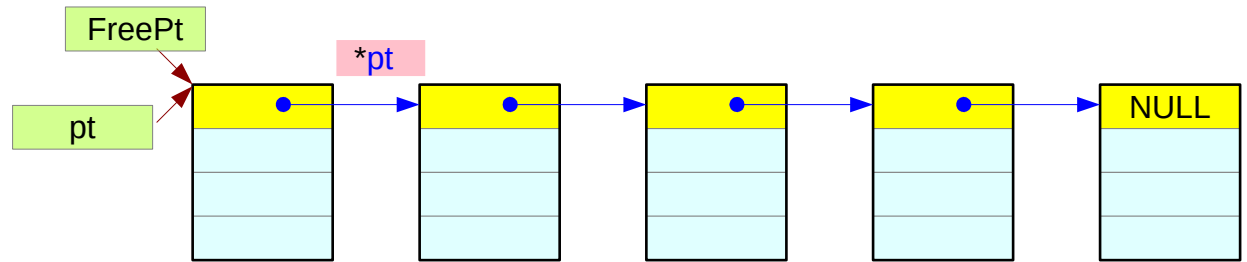


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Heap_Allocate

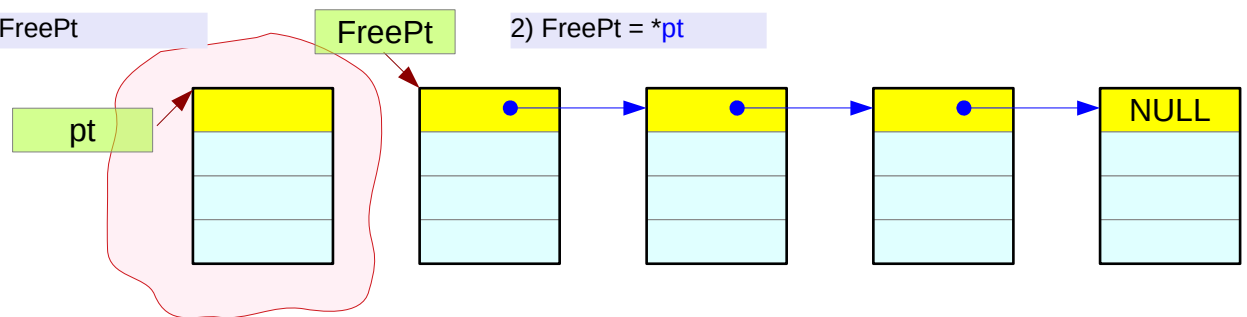
```
int32_t *Heap_Allocate(void) {  
    int32_t * pt;
```

```
    pt = FreePt;  
    if (pt != NULL) {  
        FreePt = (int32_t *) *pt;  
    }  
    return(pt);  
}
```



1) pt = FreePt

2) FreePt = *pt



```
int32_t *FreePt;  
int32_t Heap[SIZE*NUM];
```

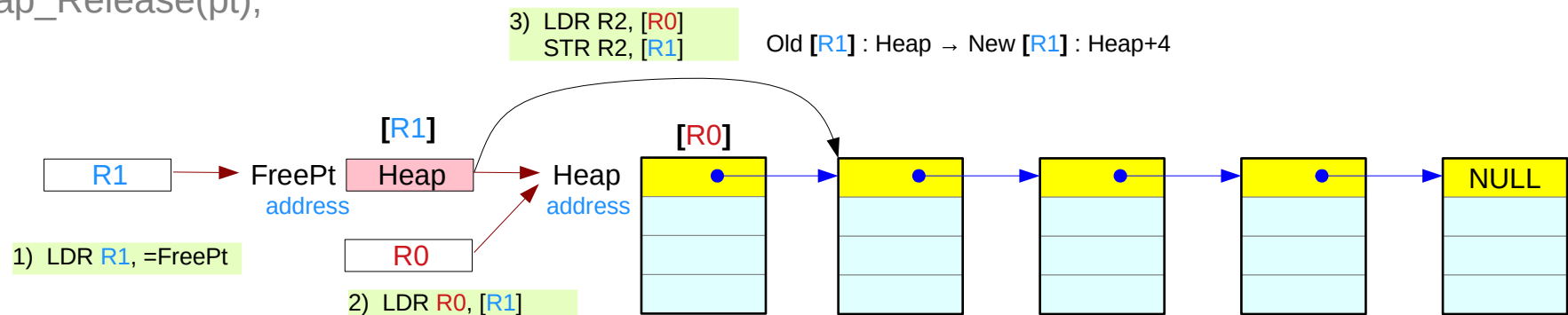
```
void Heap_Init(void) {  
    ...  
    int32_t * pt;  
    ...  
    pt = FreePt = &Heap[0];  
    ...  
}
```

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Heap_Allocate

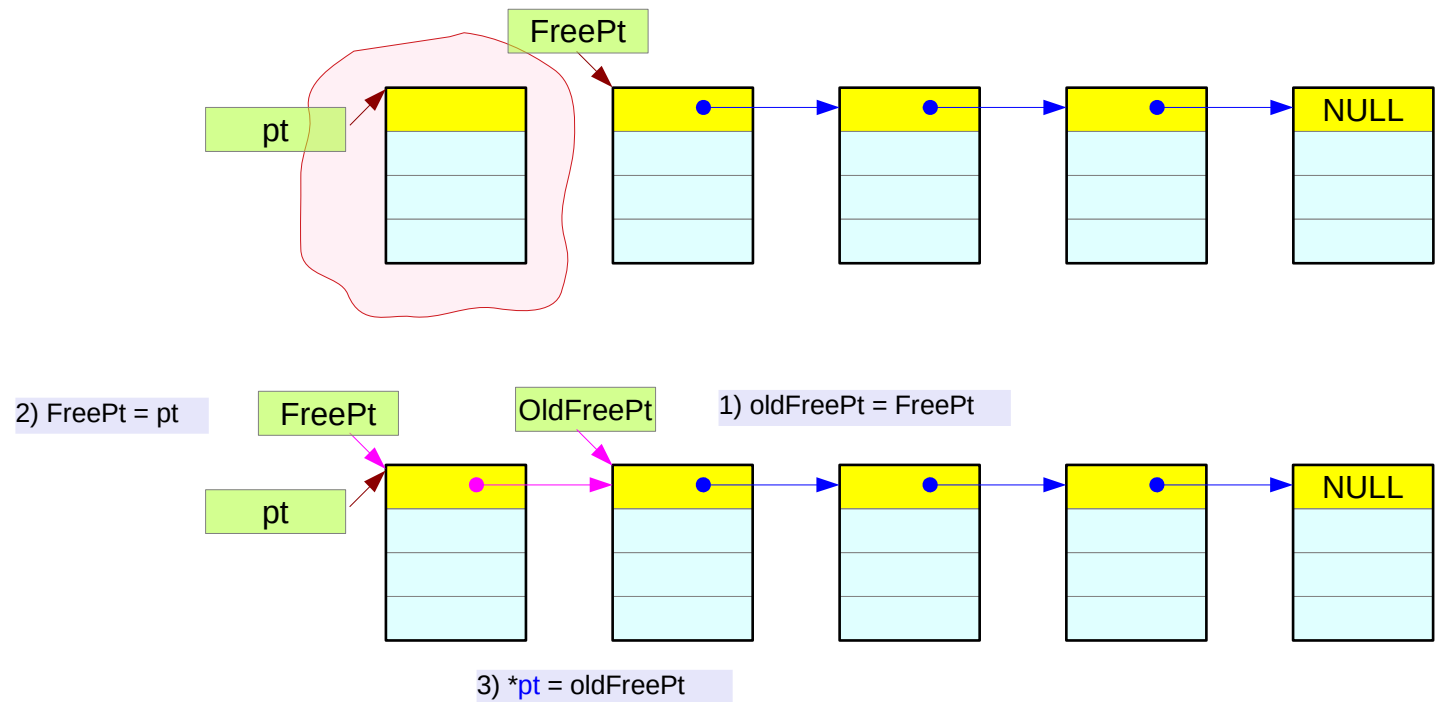
Heap_Allocate			; R0 points to new block
LDR	R1, =FreePt		; R1 = FreePt ; R1 ← &FreePt
LDR	R0, [R1]		; R0 = [FreePt] ; R0 ← [R1]
CMP	R0, #NULL		; if (pt != NULL)
LDR	R2, [R0]		; link next ; R2 ← [R0]
STR	R2, [R1]		; FreePt = *pt ; [R1] ← R2
Adone	BX	LR	

```
pt = Heap_Allocate();
Heap_Release(pt);
```



Heap_Release

```
int32_t *Heap_Release(int32_t *pt) {  
    int32_t * oldFreePt;  
  
    oldFreePt = FreePt;  
    FreePt = pt;  
    *pt = (int32_t) oldFreePt;  
}
```



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Heap_Release

Heap_Release:

```
LDR    R1, =FreePt
```

```
LDR    R2, [R1]
```

```
STR    R0, [R1]
```

```
STR    R2, [R0]
```

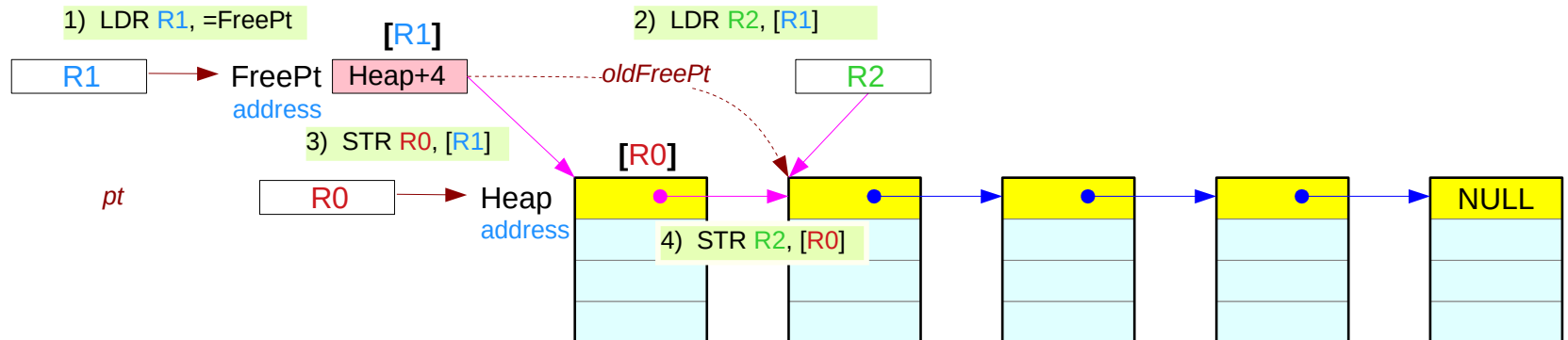
```
BX     LR
```

; R0 : block being released pt

; R2 : oldFreePt

; FreePt = pt

; *pt=oldFreePt



Fifo

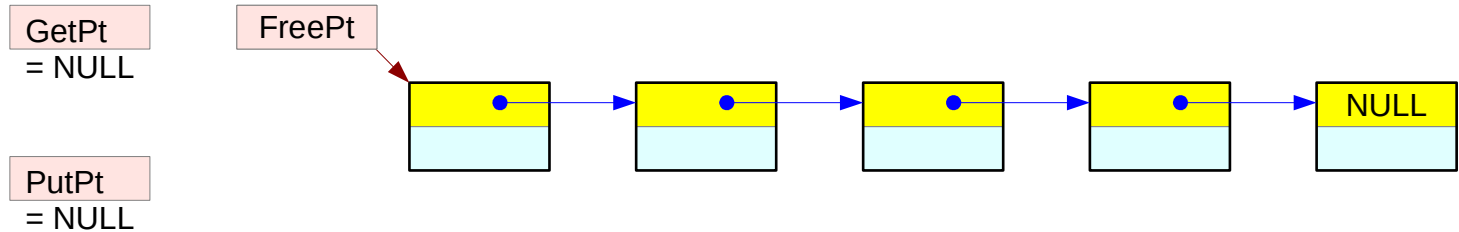
```
struct Node {  
    struct Node *Next;  
    int32_t Data;  
};  
typedef struct Node NodeType;
```

```
NodeType *PutPt; // place to put  
NodeType *GetPt; // place to get
```

```
; put in RAM  
NEXT EQU 0 ; next  
Data EQU 4 ; 32-bit data for node  
  
GetPt SPACE 4 ; pointer to oldest node  
PutPt SPACE 4 ; pointer to newest node
```

```
void Fifo_Init(void) {
    GetPt = NULL;
    PutPt = NULL;
    Heap_Init();
}
```

// Empty when null



In Heap_Init

```
#define SIZE 2
#define NUM 5
#define NULL 0 // empty pointer

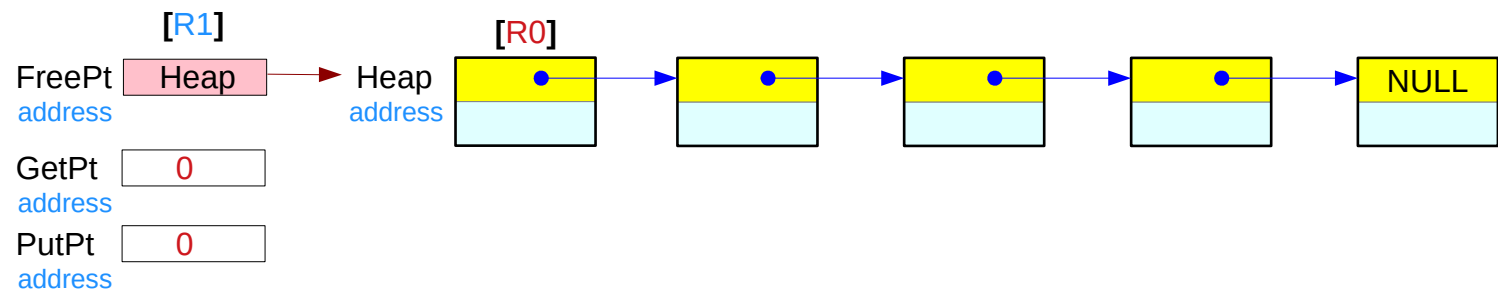
int32_t *FreePt;
int32_t Heap[SIZE*NUM];

SIZE EQU 2
NUM EQU 5
NULL EQU 0
FreePT SPACE 4
Heap SPACE SIZE*NUM*4
```

```

Fifo_Init:    PUSH    {R4, LR}
              MOV     R1, #NULL;
              LDR     R0, =GetPt          ; R0 ← GetPt
              STR     R1, [R0]           ; GetPt = NULL ; [GetPt] ← NULL
              LDR     R0, =PutPt         ; R0 ← PutPt
              STR     R1, [R0]           ; PutPt = NULL ; [PutPt] ← NULL
              BL     Heap_Init
              POP     {R4, PC}
    
```

3) LDR R2, [R0]
STR R2, [R1] Old [R1] : Heap → New [R1] : Heap+4



```
int Fifo_Put(int32_t theData) {
    NodeType *pt;           // Empty when null

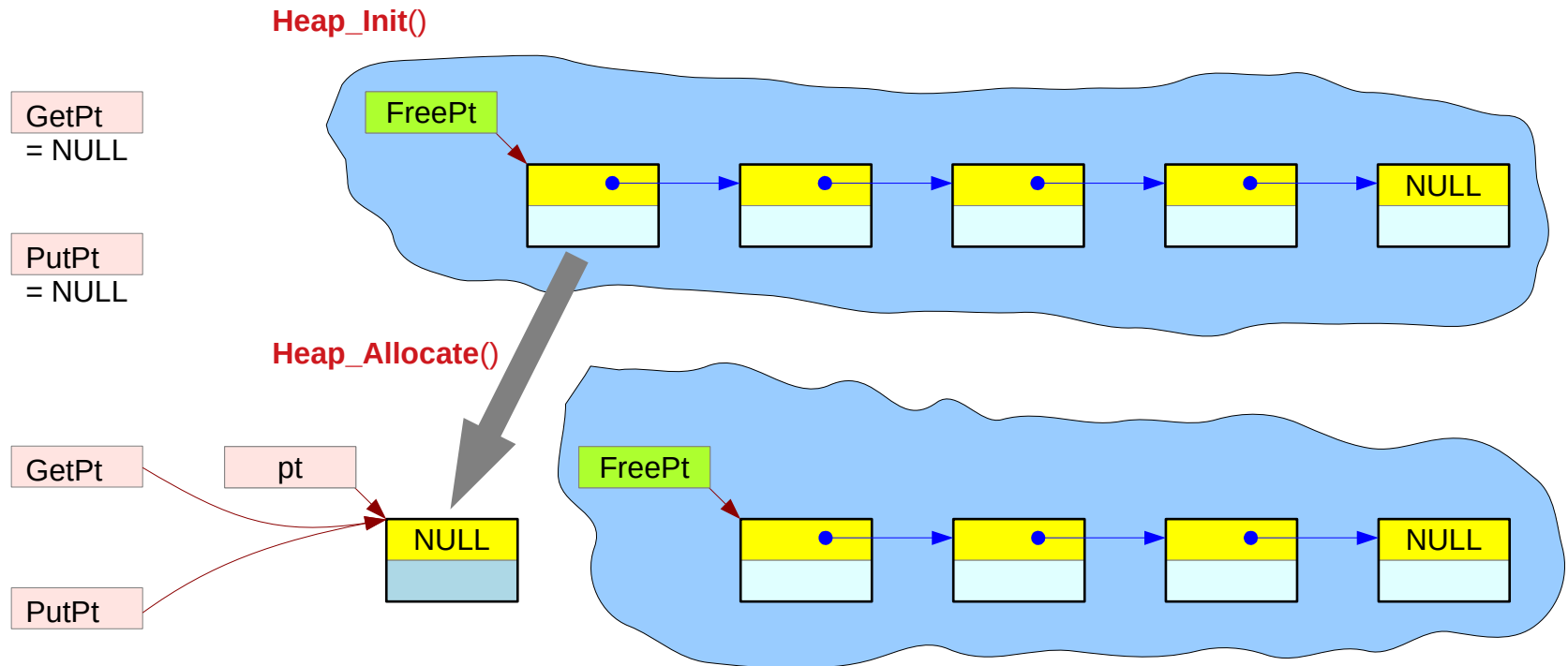
    pt = (nodeType*) Heap_Allocate();
    if (!pt) {
        return(0);         // full
    }

    pt->Data = theData;    // store
    pt->Next = NULL;

    if (PutPt) {
        PutPt->Next = pt;  // Link
    } else {
        GetPt = pt;       // first one
    }

    PutPt = pt;
    return(1);            // successful
}
```

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```

int Fifo_Put(int32_t theData) {
    NodeType *pt;
    pt = (nodeType*) Heap_Allocate();
    if (!pt) return(0);
    pt->Data = theData;
    pt->Next = NULL;
}

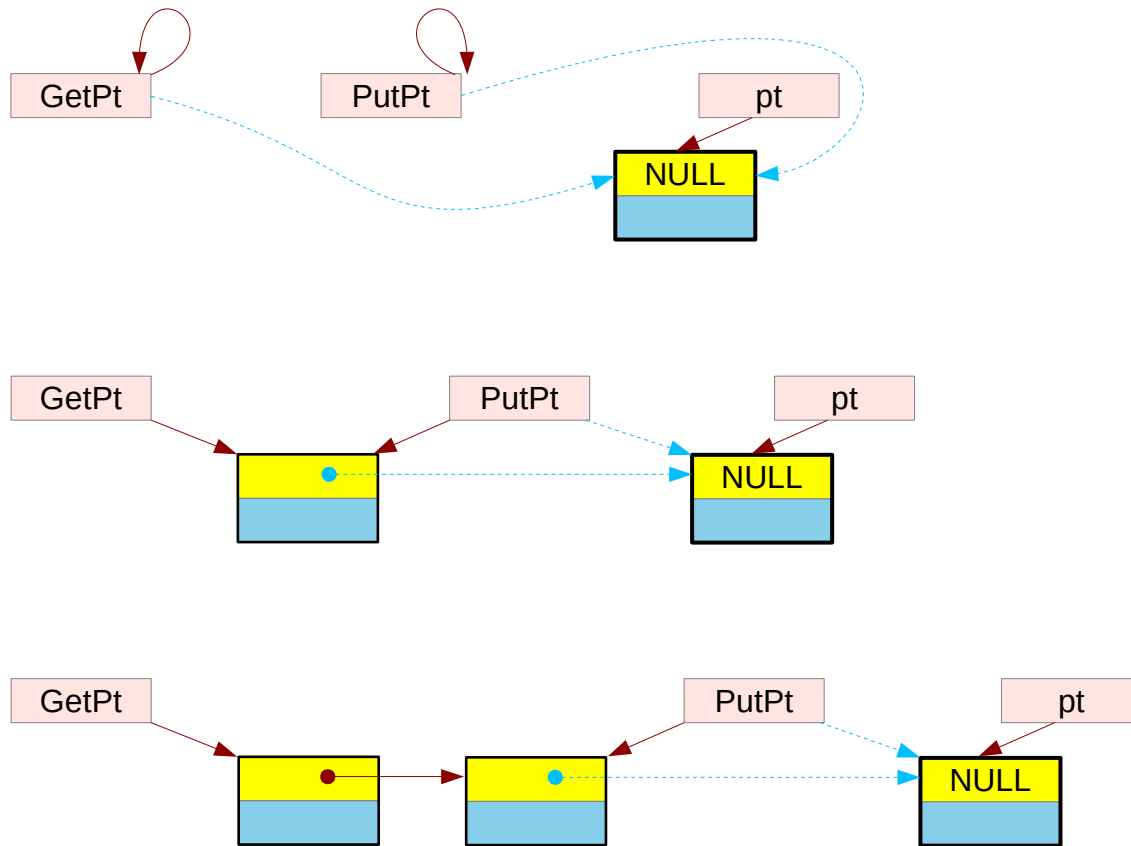
```

```

if (PutPt) PutPt->Next = pt;
else GetPt = pt;
PutPt = pt;
return(1);
}

```

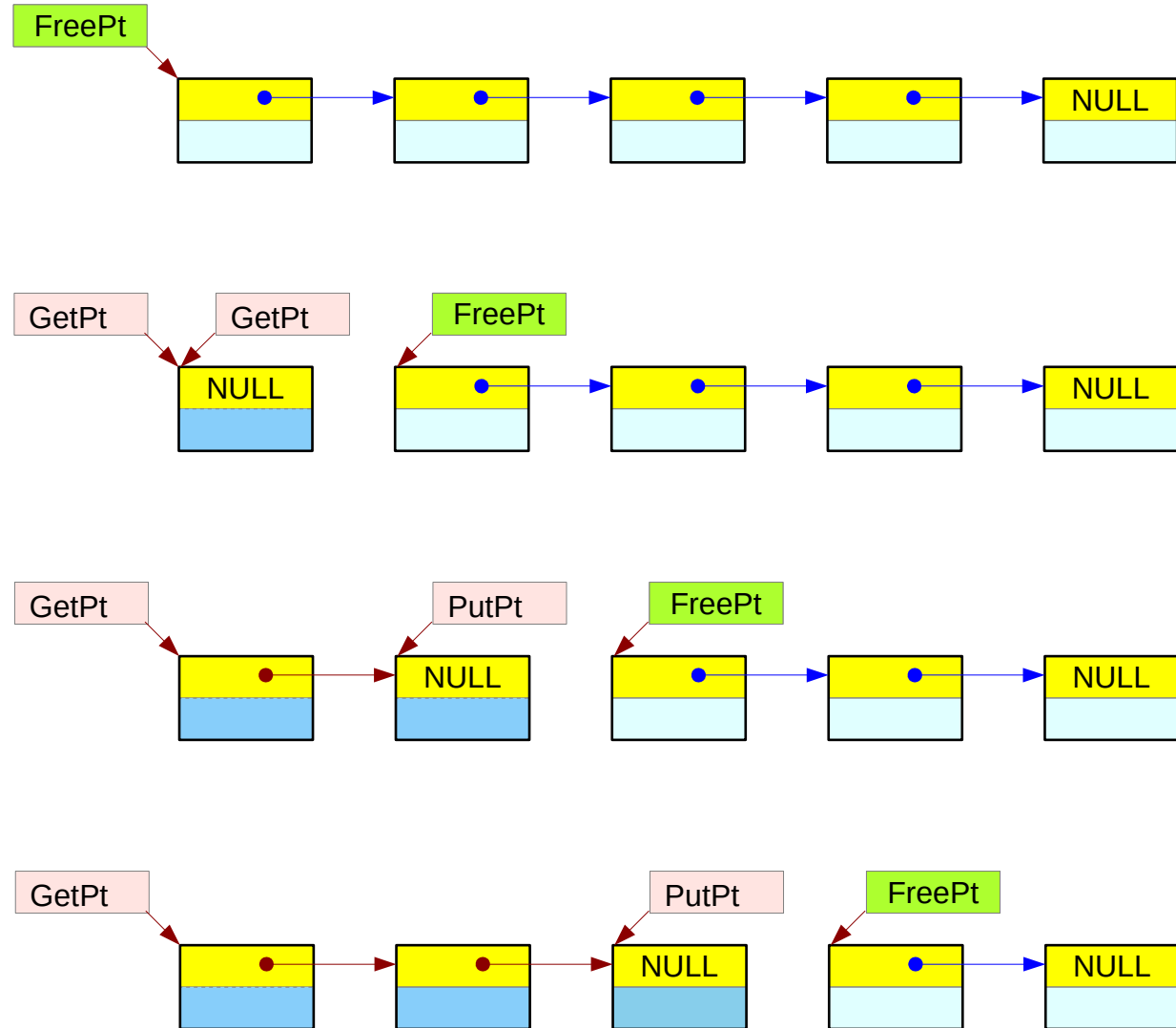
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```
int Fifo_Put(int32_t theData) {  
    NodeType *pt;  
    pt = (nodeType*) Heap_Allocate();  
    if (!pt) return(0);  
    pt->Data = theData;  
    pt->Next = NULL;  
    if (PutPt) PutPt->Next = pt;  
    else GetPt = pt;  
    PutPt = pt;  
    return(1);  
}
```

GetPt
= NULL

PutPt
= NULL



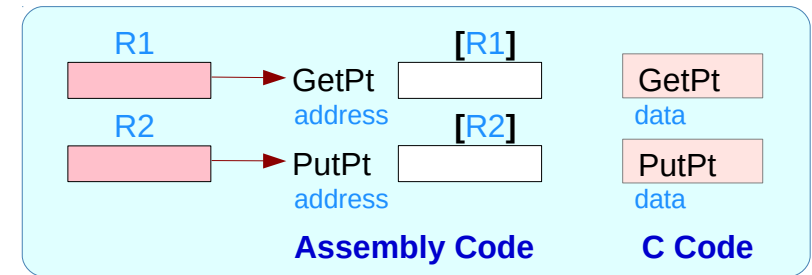
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Fifo_Put – overview

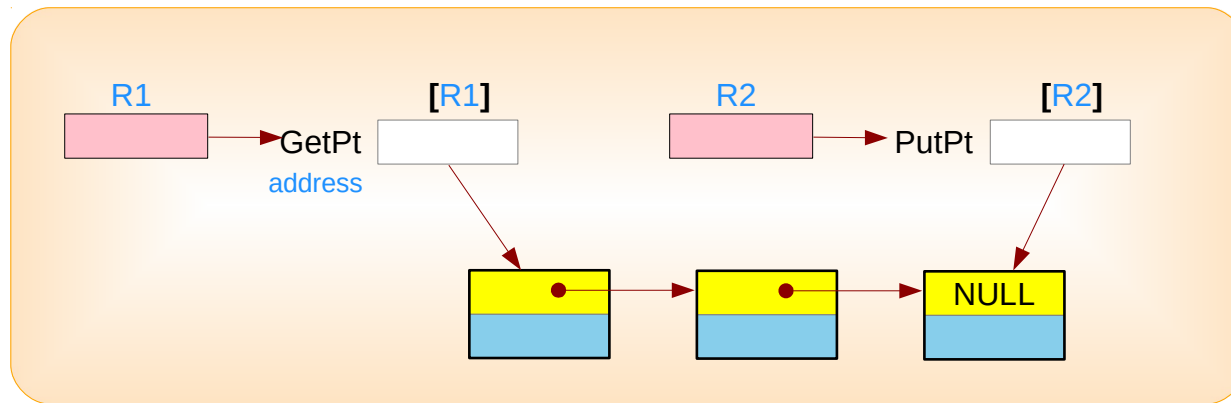
; Inputs: R0 value, data to put
; Outputs: R0=1 if successful
; R0=0 in unsuccessful

Fifo_Put

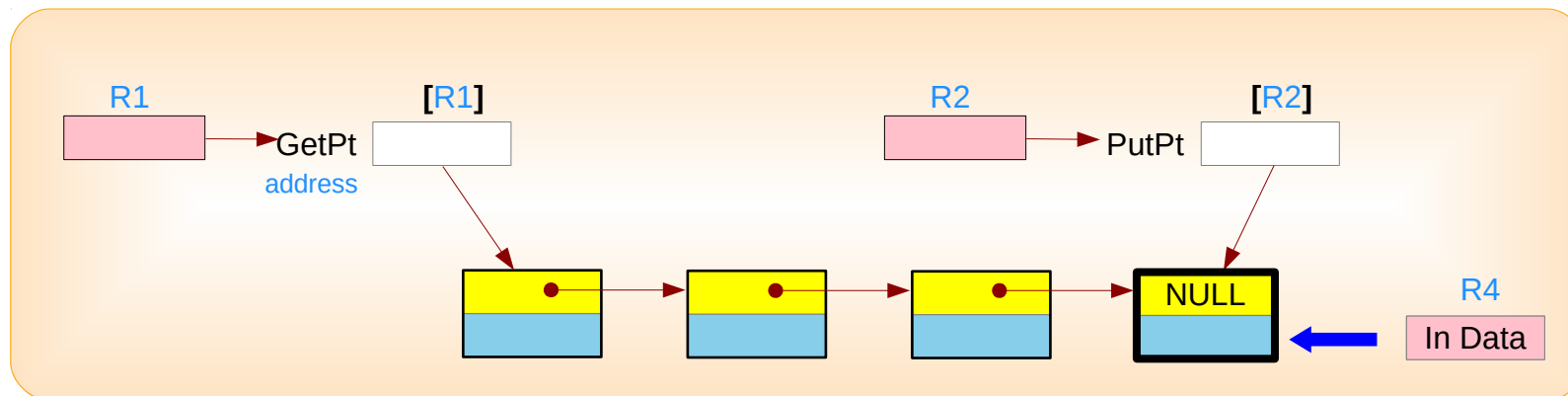
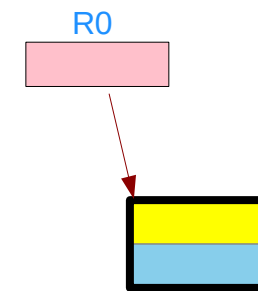
```
PUSH {R4, LR}
MOV R4, R0 ; copy the data to put into R4
BL Heap_Allocate ; returns the free node address in R0
CMP R0, #NULL ; R0 return value ; pt node address
BEQ Pful ; skip if full
STR R4, [R0, #Data] ; store 'data' ; R4 → pt's data
MOV R1, #NULL ; last node ; R1 ← #NULL
STR R1, [R0, #Next] ; store 'next' ; R1 → pt's next
LDR R2, =PutPt ; address PutPt ; R2 ← PutPt (address)
LDR R3, [R2] ; Put node address ; R3 ← [PutPt] (content)
CMP R3, #NULL ; previously empty? ; R3 == #NULL
BEQ PMT ; Put eMpTy routine – no link
STR R0, [R3, #Next] ; link previous ; R3 → [PutPt]'s next
B Pcon
PMT LDR R1, =GetPt ; address GetPt ; R1 ← GetPt (address)
STR R0, [R1] ; Get node address ; R0 → [GetPt] (content)
PCon STR R0, [R2] ; Points to newst ; R0 → [PutPt]
; Now one entry
MOV R0, #1 ; success
B Pdon
PFul MOV R0, #0 ; failure, full
PDon POP {R4, PC}
```



```
int Fifo_Put(int32_t theData) {
    NodeType *pt;
    pt = (NodeType*) Heap_Allocate();
    if (!pt) return(0);
    pt->Data = theData;
    pt->Next = NULL;
    if (PutPt) PutPt->Next = pt;
    else GetPt = pt;
    PutPt = pt;
    return(1);
}
```



returns a free node address



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Fifo_Put

PUSH {R4, LR}

MOV R4, R0

BL Heap_Allocate

CMP R0, #NULL

BEQ Pful

STR R4, [R0, #Data]

MOV R1, #NULL

STR R1, [R0, #Next]

LDR R2, =PutPt

LDR R3, [R2]

CMP R3, #NULL

BEQ PMT

STR R0, [R3, #Next]

B PCon

PMT LDR R1, =GetPt

STR R0, [R1]

PCon STR R0, [R2]

MOV R0, #1

B Pdon

PFul MOV R0, #0

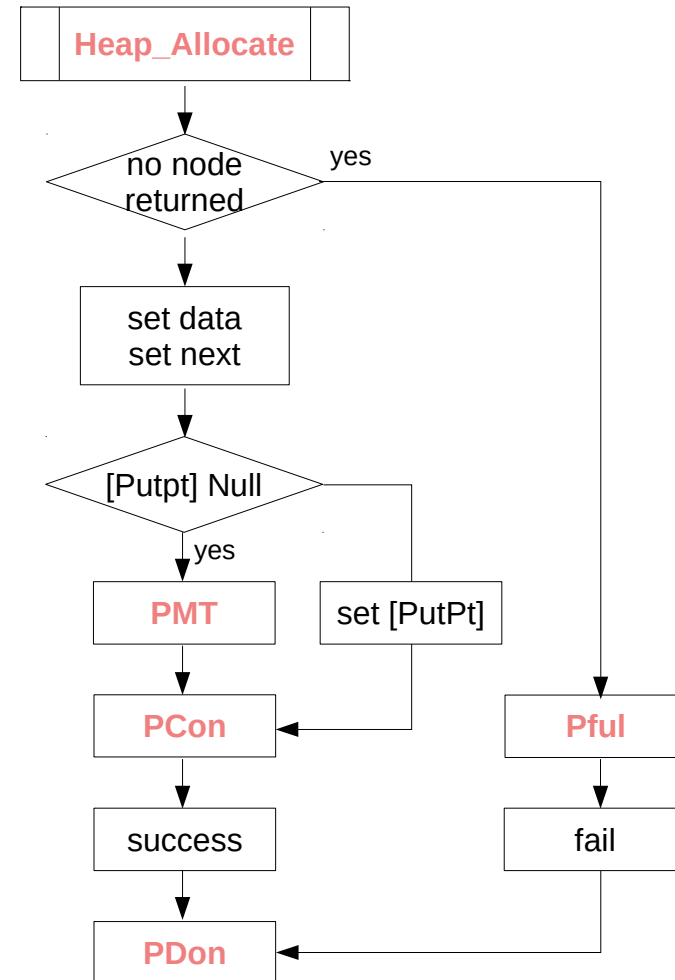
PDon POP {R4, PC}

Put_Full

Put_Empty

Put_Conclude

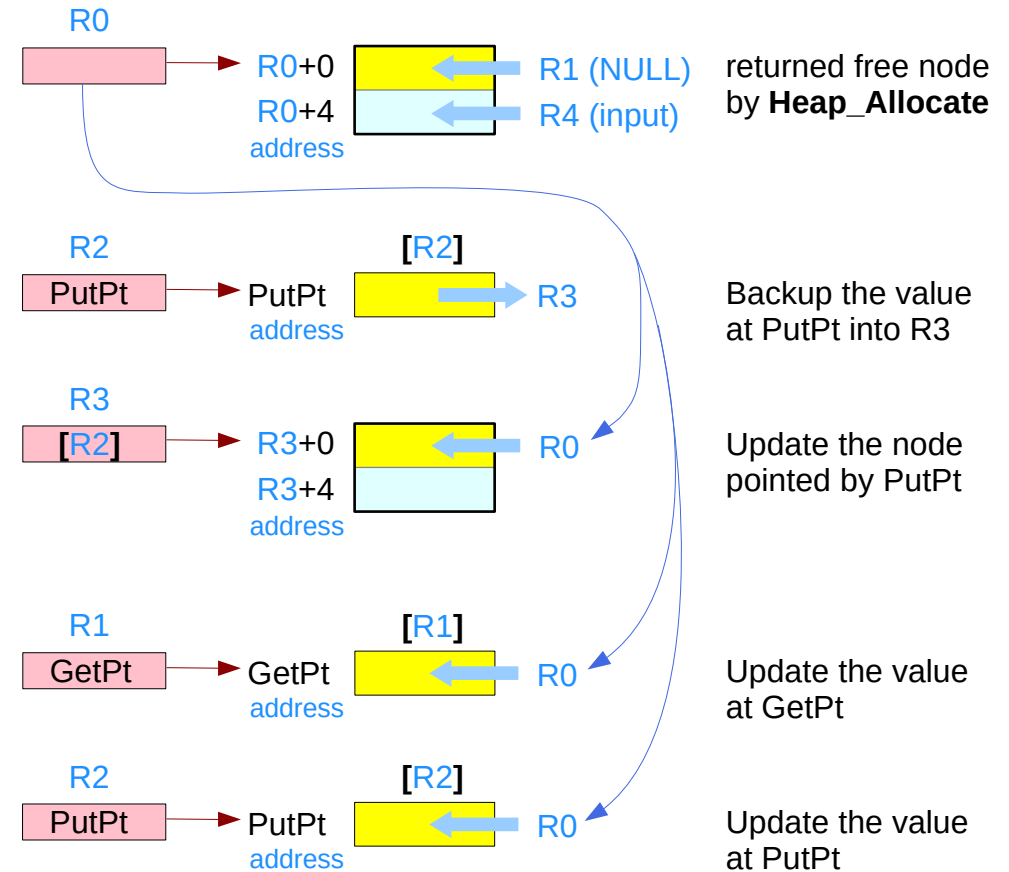
Put_Done



Fifo_Put

```

    PUSH {R4, LR}
    MOV R4, R0
BL   Heap_Allocate
    CMP R0, #NULL
    BEQ Pful
    STR R4, [R0, #Data]
    MOV R1, #NULL
    STR R1, [R0, #Next]
    LDR R2, =PutPt
    LDR R3, [R2]
    CMP R3, #NULL
    BEQ PMT
    STR R0, [R3, #Next]
    B Pcon
PMT  LDR R1, =GetPt
    STR R0, [R1]
PCon STR R0, [R2]
    MOV R0, #1
    B Pdon
PFull MOV R0, #0
PDon POP {R4, PC}
    
```



Fifo_Put

```
PUSH {R4, LR}
MOV R4, R0
```

BL Heap_Allocate

```
CMP R0, #NULL
BEQ Pful
```

```
STR R4, [R0, #Data]
```

```
MOV R1, #NULL
```

```
STR R1, [R0, #Next]
```

```
LDR R2, =PutPt
```

```
LDR R3, [R2]
```

```
CMP R3, #NULL
```

```
BEQ PMT
```

```
STR R0, [R3, #Next]
```

```
B Pcon
```

PMT LDR R1, =GetPt

```
STR R0, [R1]
```

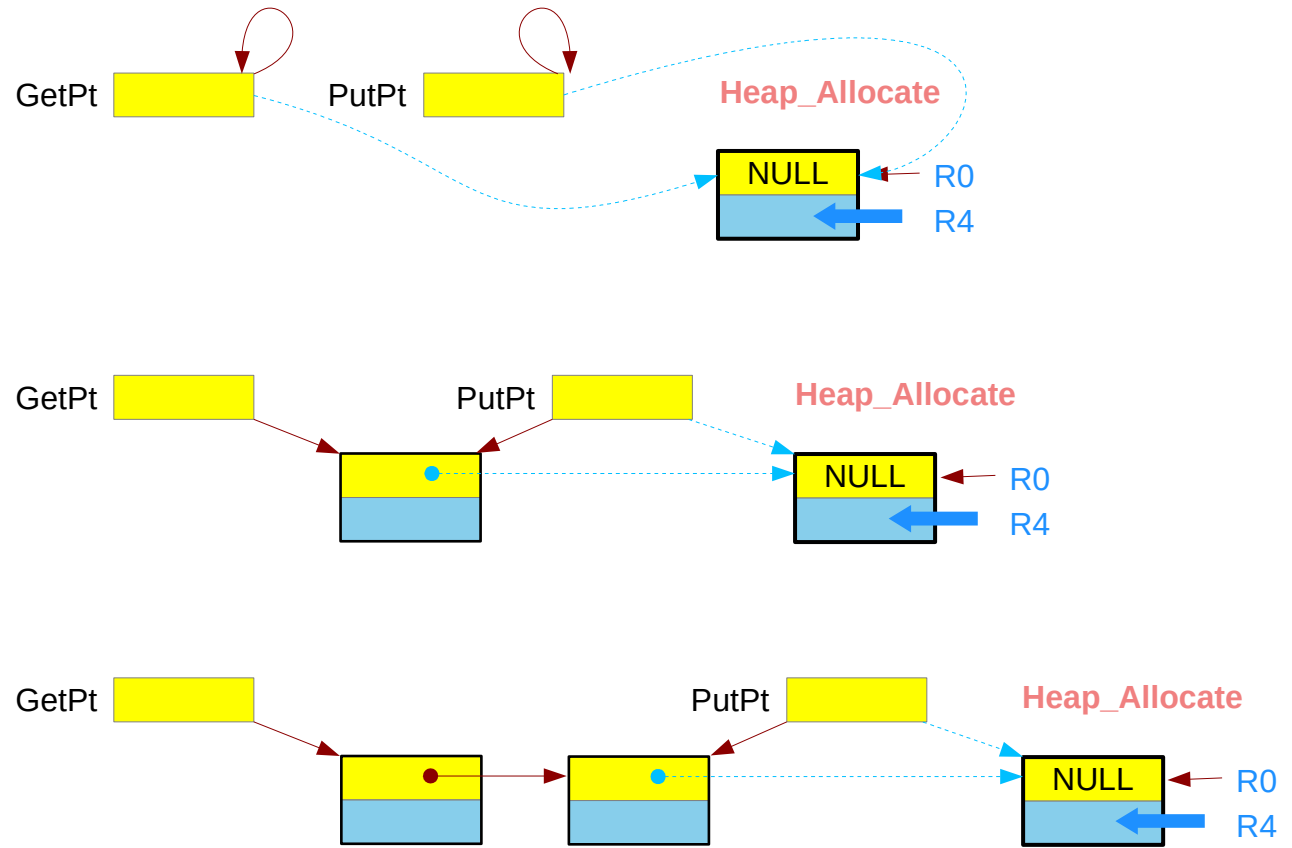
PCon STR R0, [R2]

```
MOV R0, #1
```

```
B Pdon
```

PFul MOV R0, #0

PDon POP {R4, PC}



```

; Inputs:    R0 value, data to put
; Outputs:   R0=1 if successful
;           R0=0 in unsuccessful
    
```

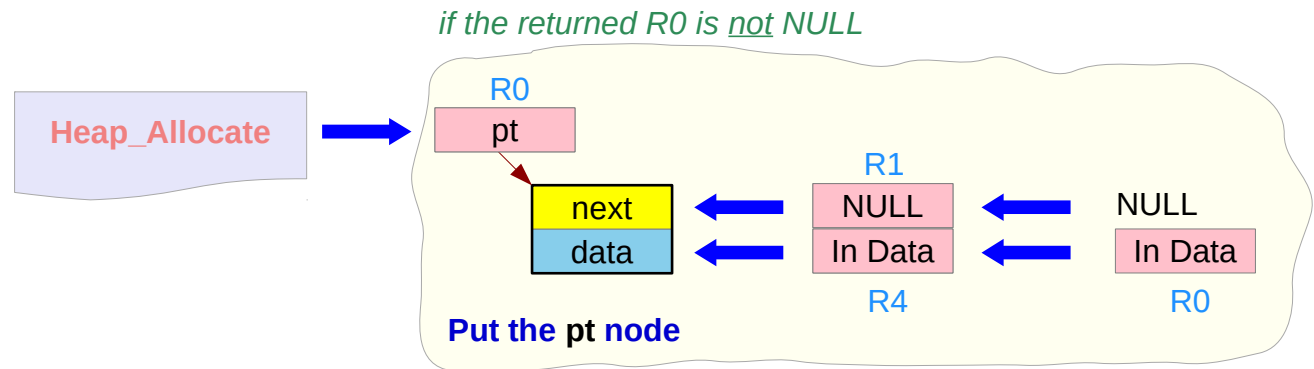
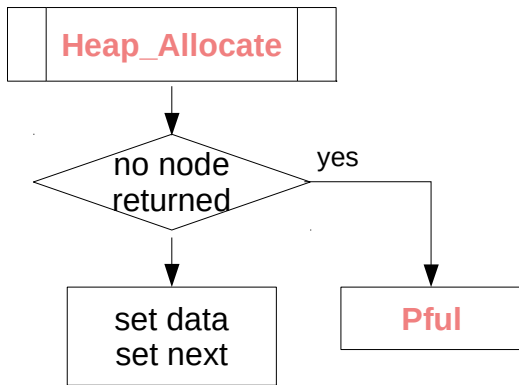
Fifo_Put

```

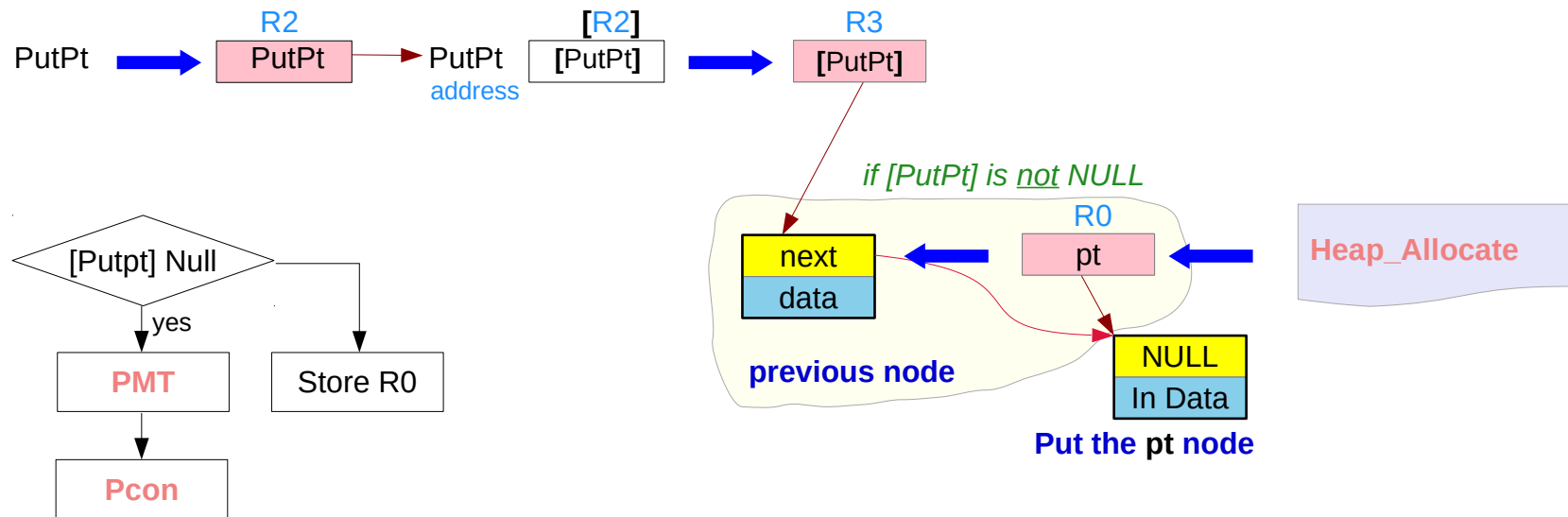
PUSH    {R4, LR}
MOV     R4, R0
BL      Heap_Allocate
CMP     R0, #NULL
BEQ     Pful
STR     R4, [R0, #Data]
MOV     R1, #NULL
STR     R1, [R0, #Next]
    
```

```

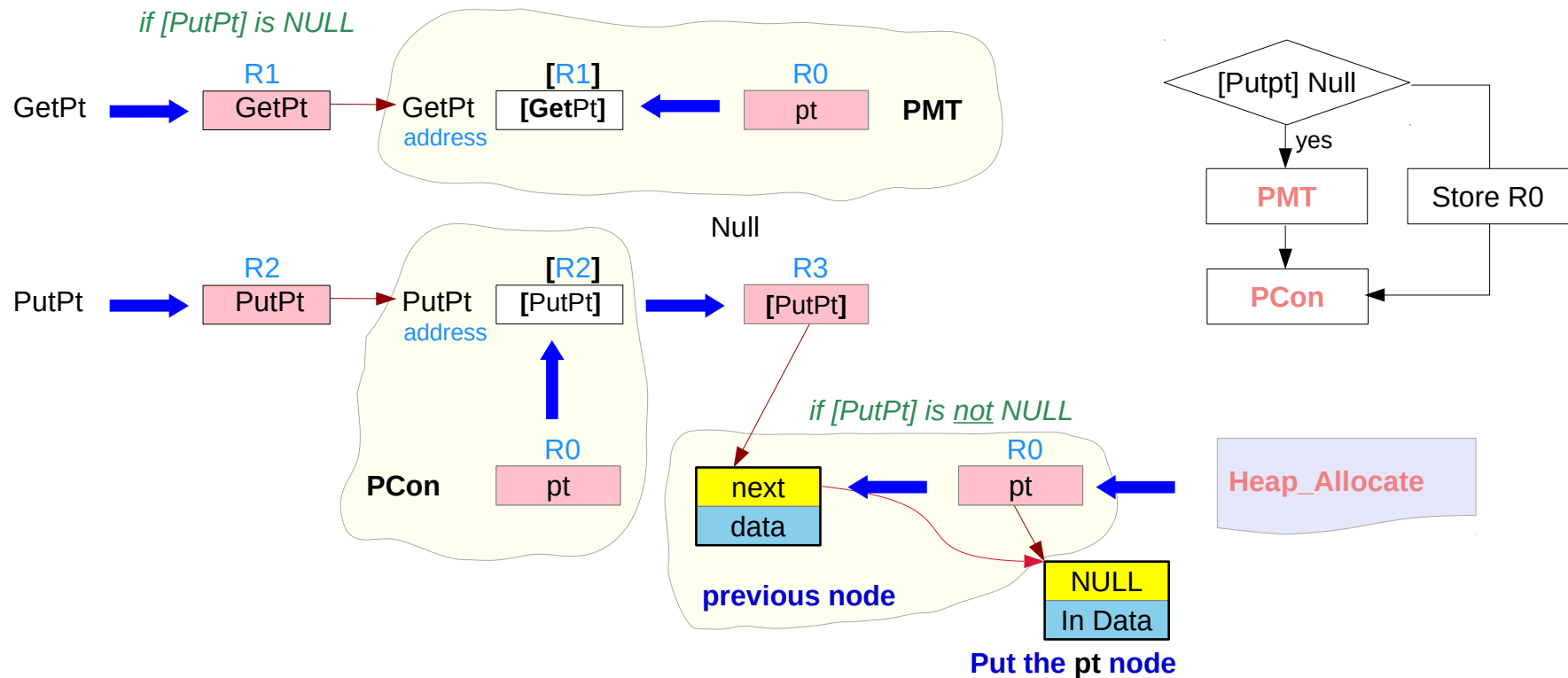
R0 In Data → R4 In Data
; copy the data to put into R4
; returns the free node address in R0
; R0 return value ; pt node address
; skip if full
; store 'data' ; R4 → pt's data
; last node ; R1 ← #NULL
; store 'next' ; R1 → pt's next
    
```



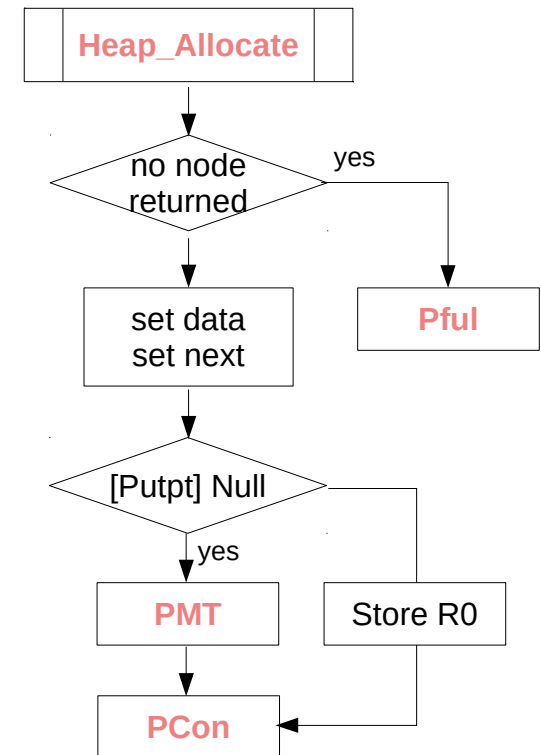
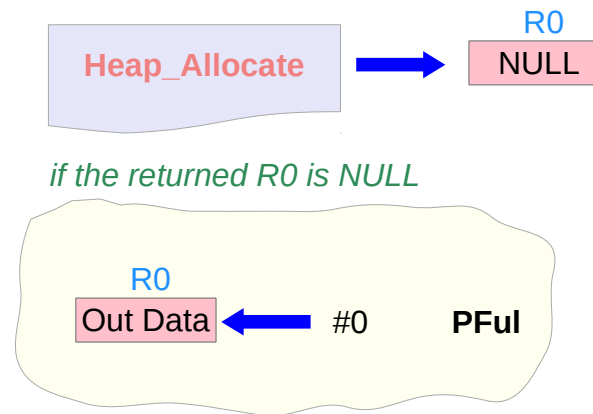
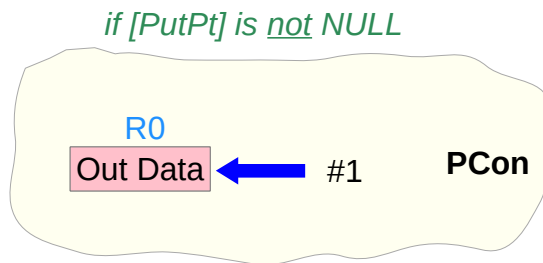
LDR	R2, =PutPt	; address PutPt	; R2 ← PutPt (address)
LDR	R3, [R2]	; Put node address	; R3 ← [PutPt] (content)
CMP	R3, #NULL	; previously empty?	; R3 == #NULL
BEQ	PMT	; Put eMpTy routine – no link	
STR	R0, [R3, #Next]	; link previous	; R3 → [PutPt]'s next
B	Pcon		



PMT	LDR R1, =GetPt	; address GetPt	; R1 ← GetPt (address)
	STR R0, [R1]	; Get node address	; R0 → [GetPt] (content)
PCon	STR R0, [R2]	; Points to newst	; R0 → [PutPt]
		; Now one entry	



	MOV	R0, #1	; success
	B	Pdon	
PFul	MOV	R0, #0	; failure, full
PDon	POP	{R4, PC}	



```
Int Fifo_Get(int32_t *datap) {
    NodeType *pt;

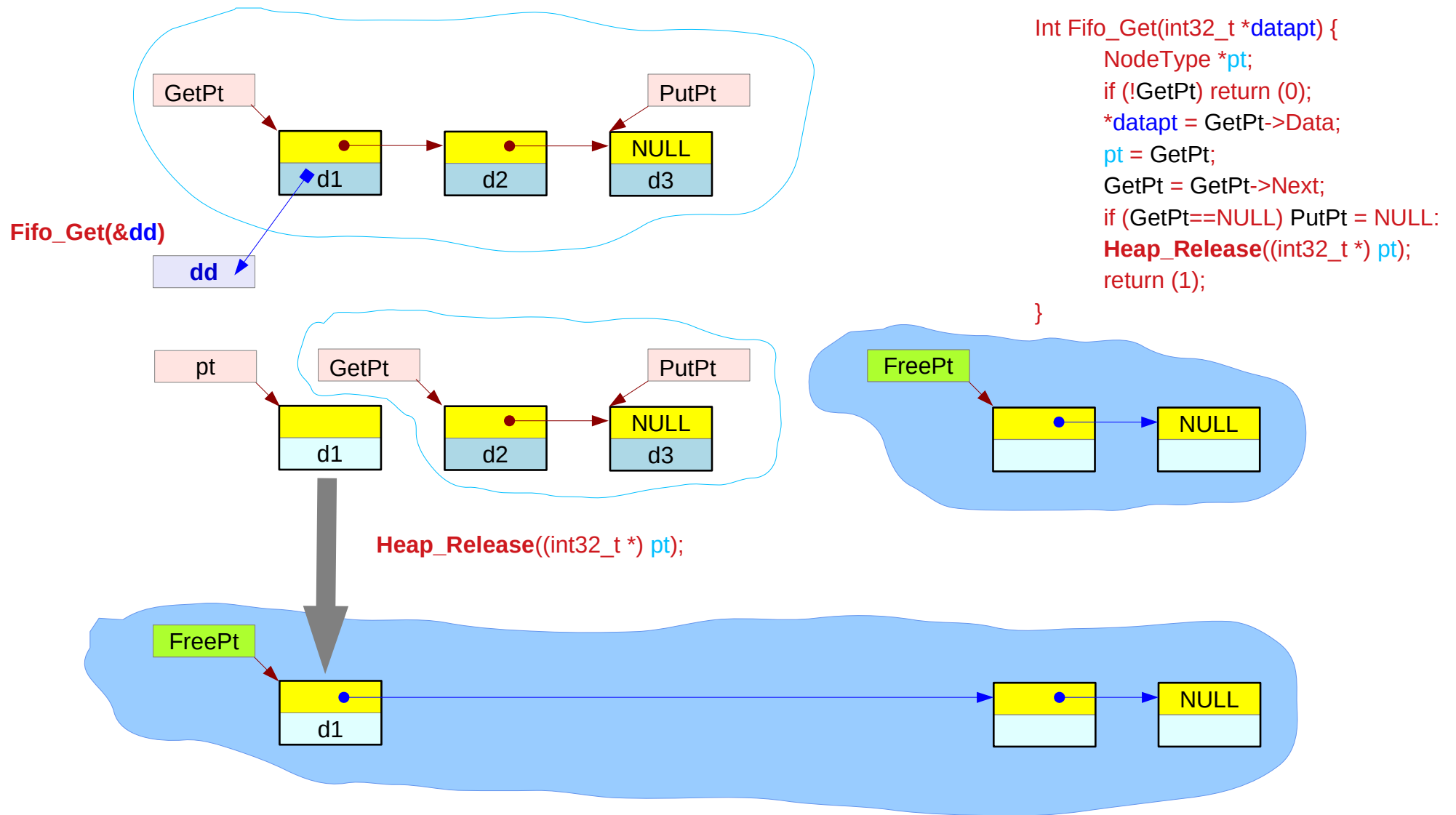
    if (!GetPt) {
        return (0);           // empty
    }

    *datap = GetPt->Data;
    pt = GetPt;
    GetPt = GetPt->Next;

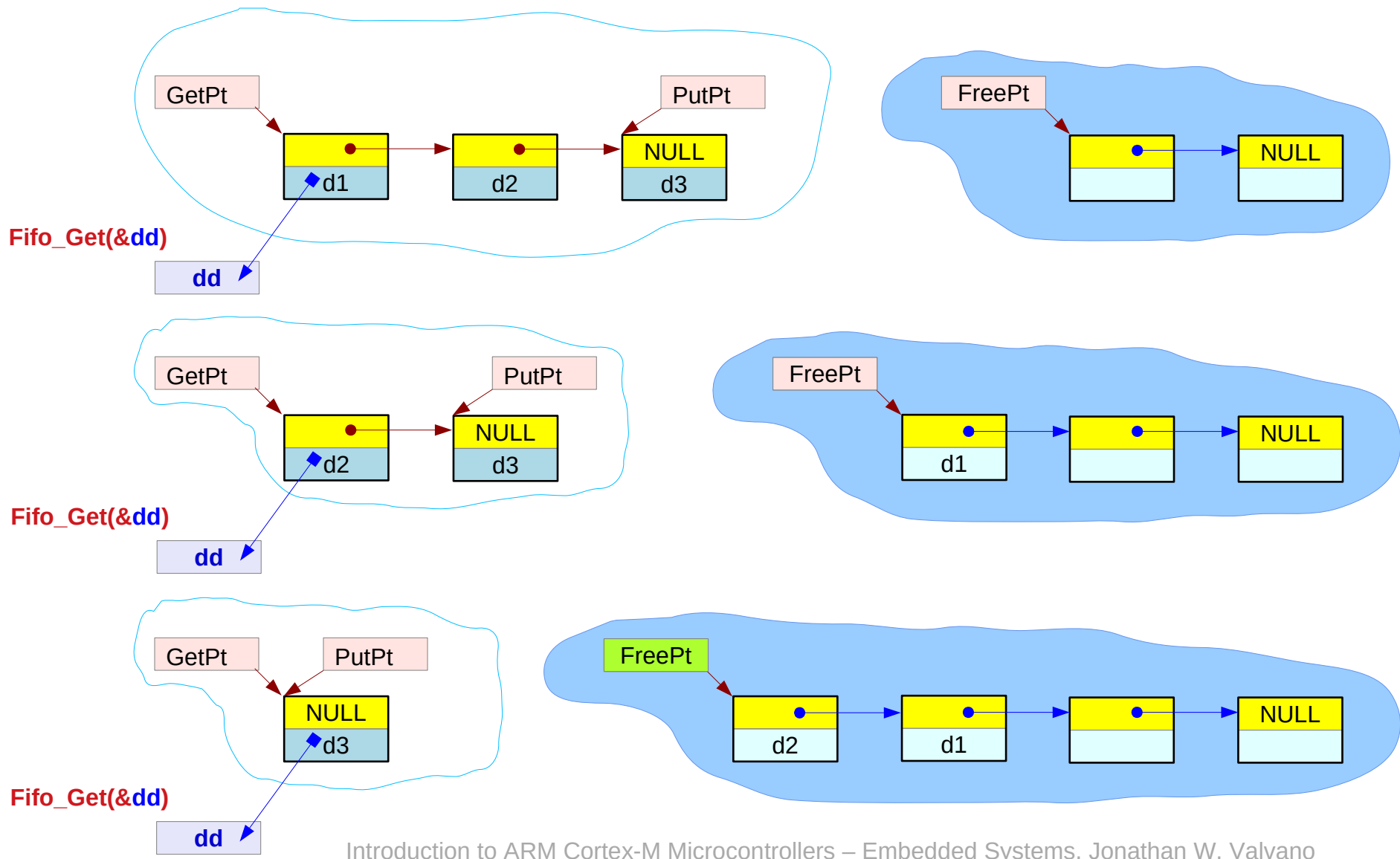
    if (GetPt==NULL) {       // one entry
        PutPt = NULL;
    }

    Heap_Release((int32_t *) pt);

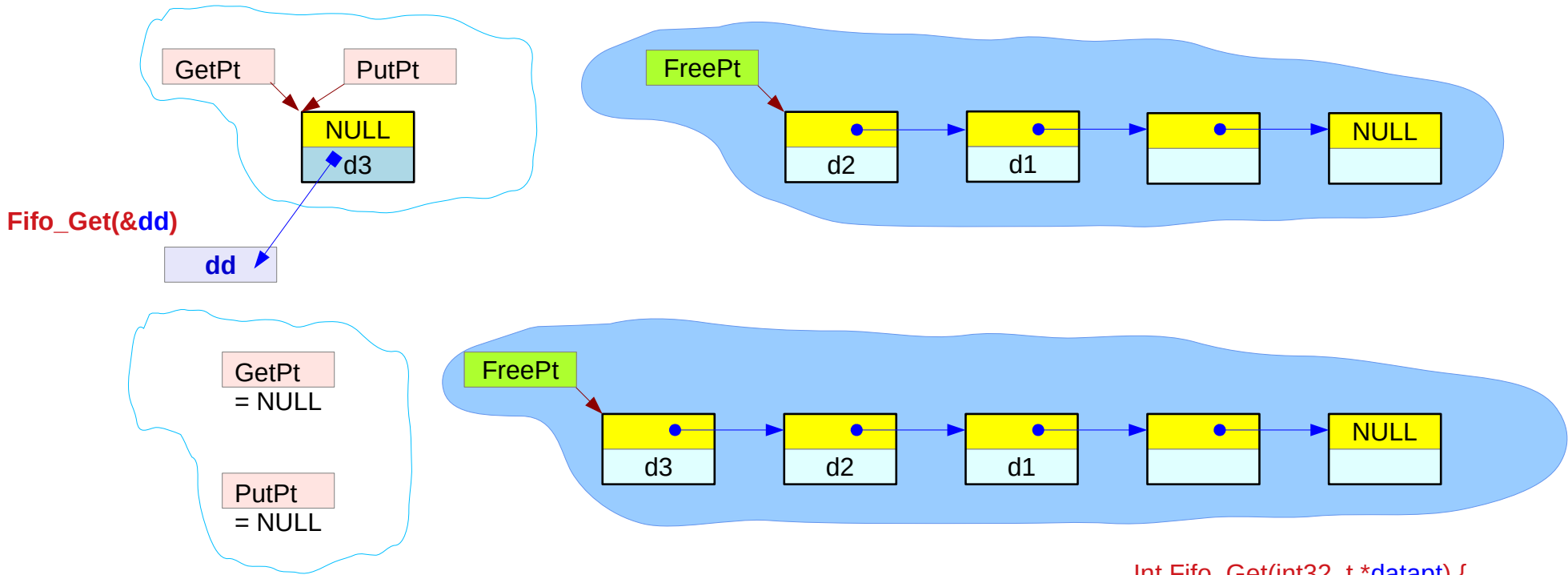
    return (1);             // success
}
```



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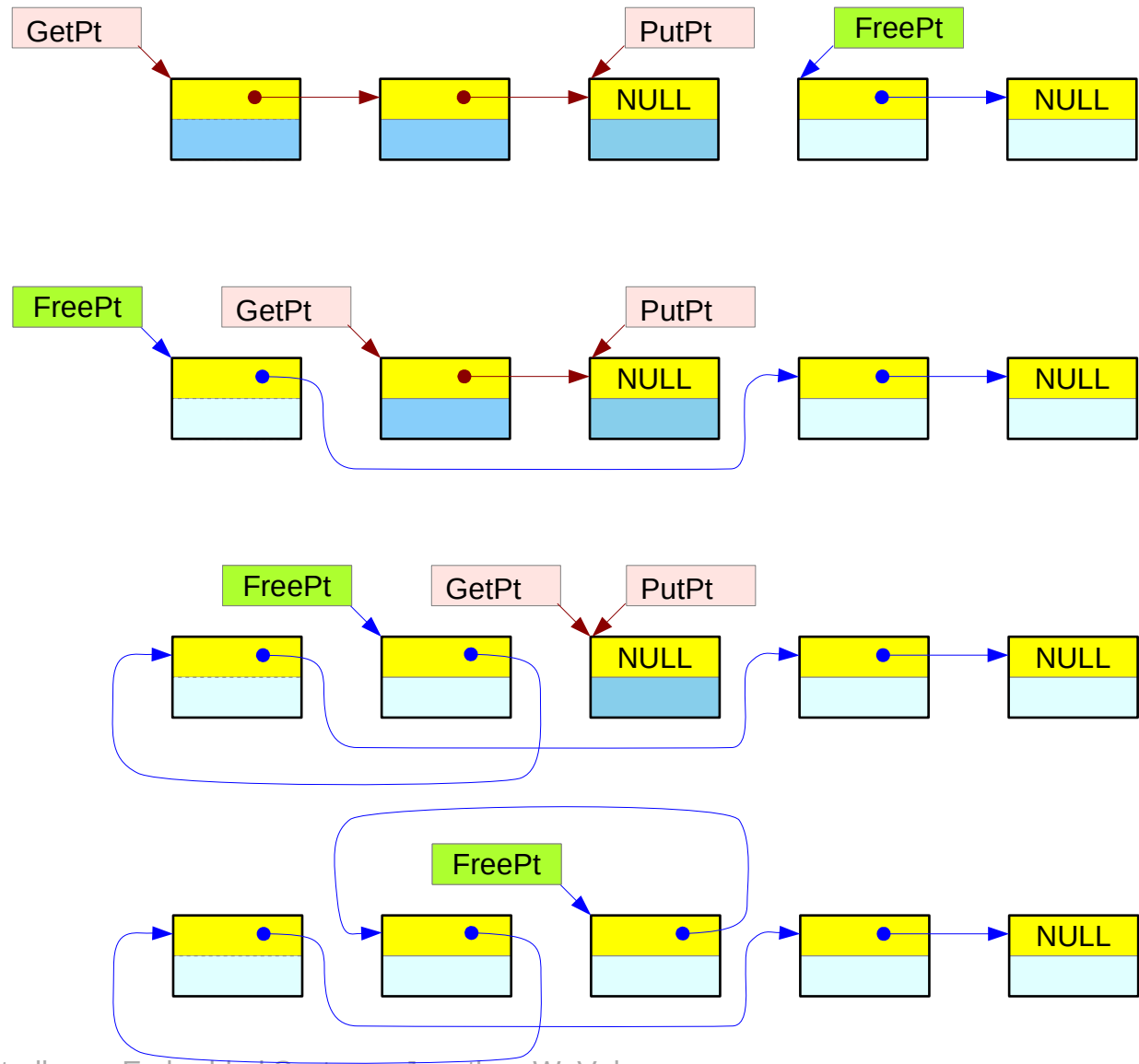


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```

Int Fifo_Get(int32_t *datap) {
    NodeType *pt;
    if (!GetPt) return (0);
    *datap = GetPt->Data;
    pt = GetPt;
    GetPt = GetPt->Next;
    if (GetPt==NULL) PutPt = NULL;
    Heap_Release((int32_t *) pt);
    return (1);
}
    
```



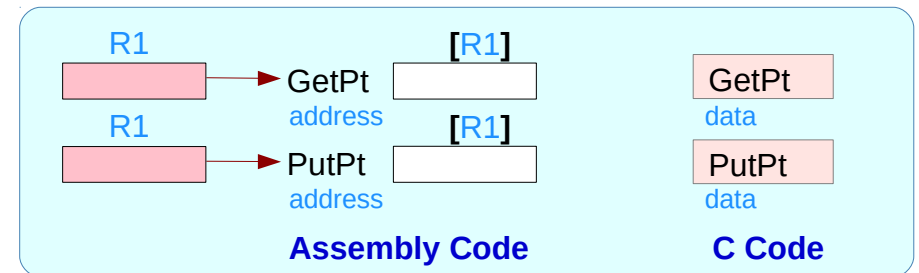
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; Inputs: R0 points to an empty place
 ; Outputs: data removed to place
 R0=0 if successful
 R0=1 if empty

Fifo_Get

```

PUSH {R4, LR}
LDR R1, =GetPt      ; address GetPt      ; R1 ← GetPt (address)
LDR R2, [R1]        ; Get node address ; R2 ← [GetPt] (content)
CMP R2, #NULL
BEQ GMT             ; empty if NULL
LDR R3, [R2, #Data] ; read 'data'      ; R3 ← pt's data
STR R3, [R0]        ; store 'data'     ; int Fifo_Get(int32_t *datap)
LDR R3, [R2, #Next] ; read 'next'     ; R3 ← pt's next
STR R3, [R1]        ; store 'next'     ; R3 → [GetPt]
CMP R3, #NULL      ; the last node   ; pt node
BNE GCon           ; if not empty     ; pt's next <> NULL
LDR R1, =PutPt     ; address PutPt   ; R1 ← PutPt (address)
STR R3, [R1]       ; Put node address ; NULL → [PutPt] (content)
MOV R0, R2         ; old data       ; R0 ← [GetPt] ; input arg
BL Heap_Release
MOV R0, #1         ; success
B GDon
GMT               ; failure, empty
GDon             POP {R4, PC}
    
```

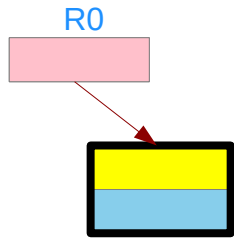
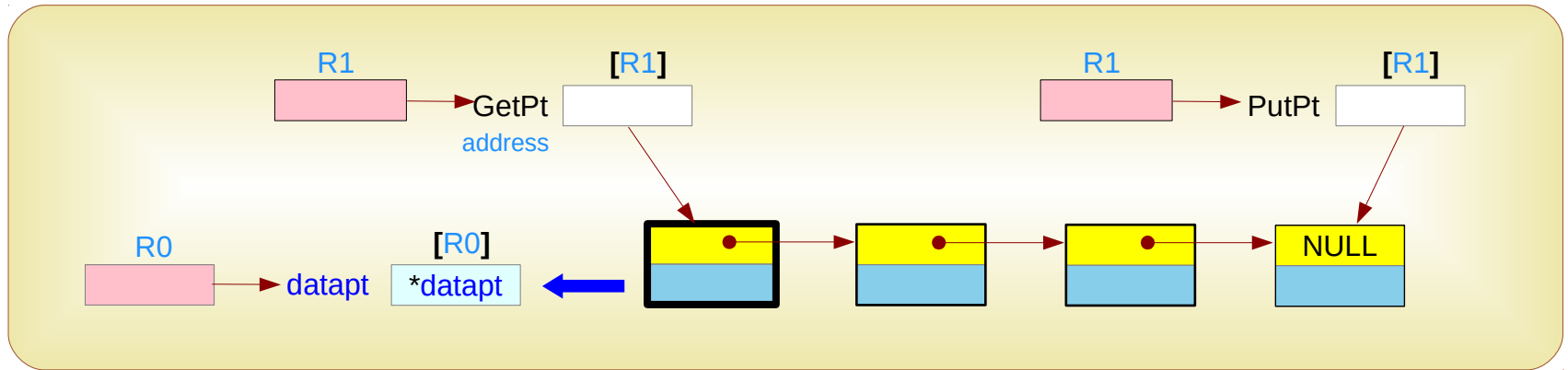


```

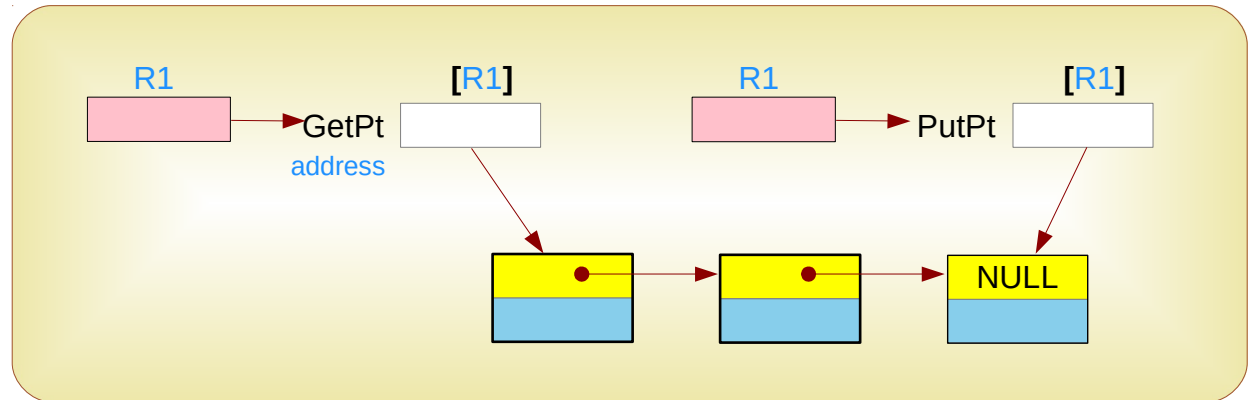
int Fifo_Get(int32_t *datap) {
    NodeType *pt;

    if (!GetPt) return (0);
    *datap = GetPt->Data;
    pt = GetPt;
    GetPt = GetPt->Next;
    if (GetPt==NULL) PutPt = NULL;
    Heap_Release((int32_t *) pt);
    return (1);
}
    
```

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argument : a release node address



Fifo_Get

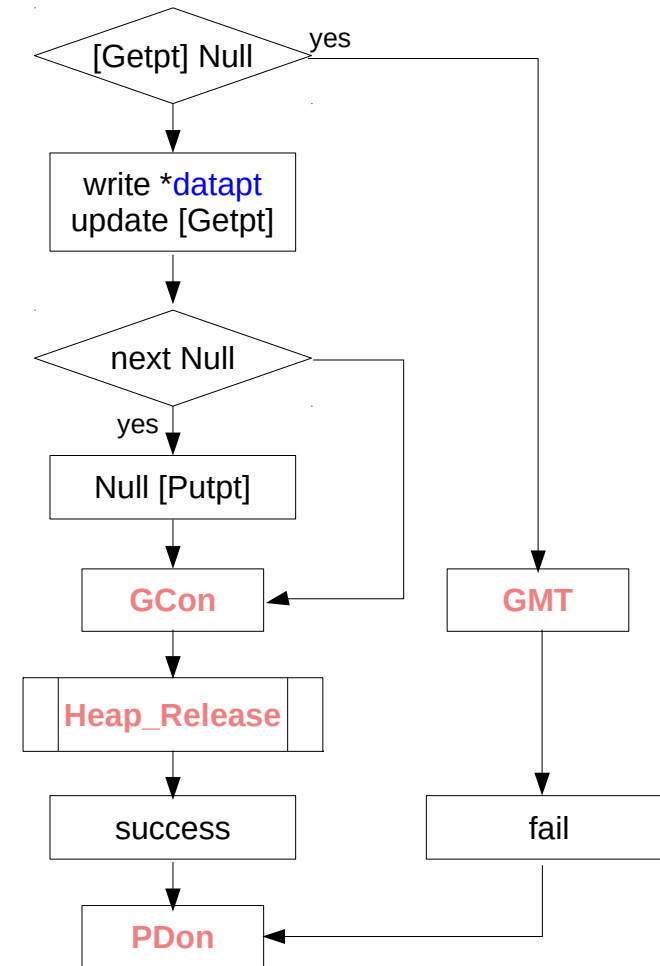
```

PUSH {R4, LR}
LDR R1, =GetPt
LDR R2, [R1]
CMP R2, #NULL
◇ BEQ GMT
LDR R3, [R2, #Data]
STR R3, [R0]
LDR R3, [R2, #Next]
STR R3, [R1]
CMP R3, #NULL
◇ BNE GCon
LDR R1, =PutPt
STR R3, [R1]
Gcon MOV R0, R2
◇ BL Heap_Release
MOV R0, #1
◇ B GDon
GMT MOV R0, #0
GDon POP {R4, PC}
    
```

Get_Empty

Get_Conclude

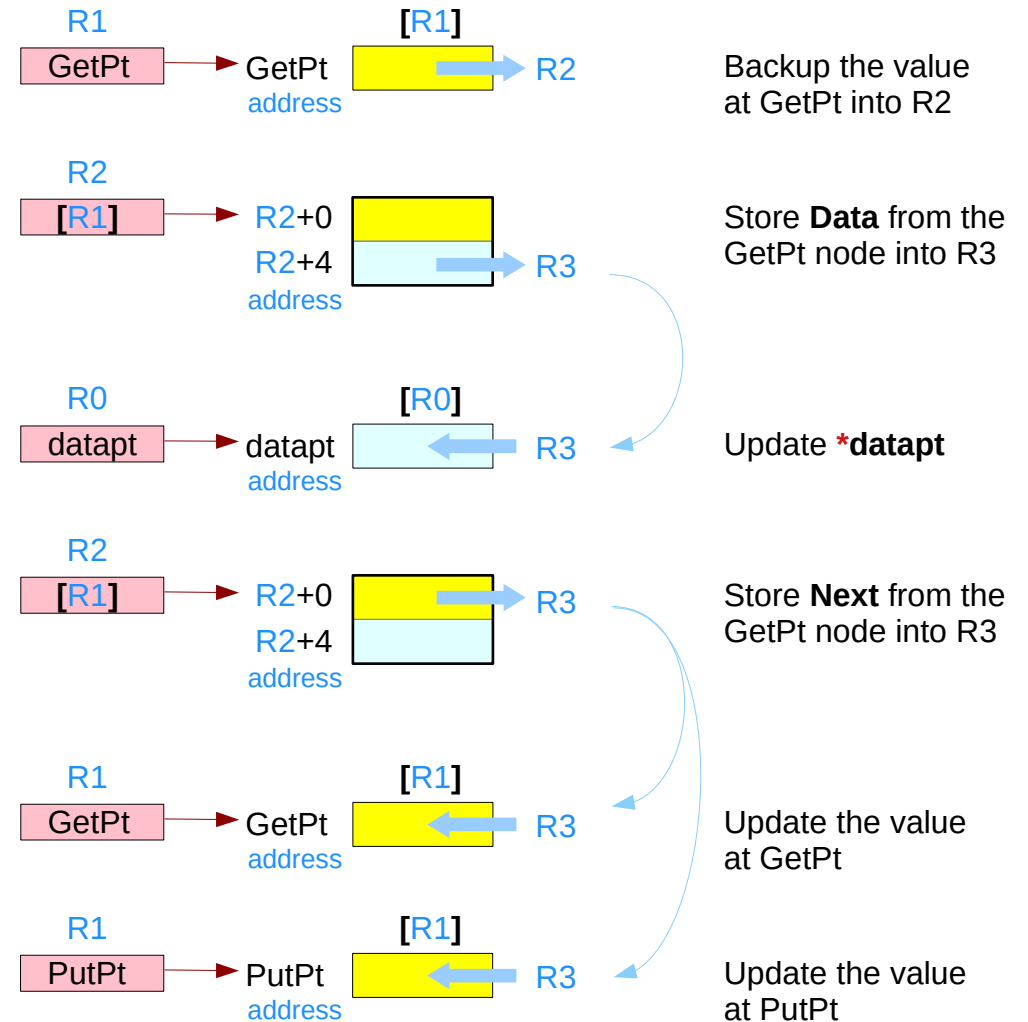
Get_Done



Fifo_Get

```

PUSH {R4, LR}
LDR R1, =GetPt
LDR R2, [R1]
CMP R2, #NULL
BEQ GMT
LDR R3, [R2, #Data]
STR R3, [R0]
LDR R3, [R2, #Next]
STR R3, [R1]
CMP R3, #NULL
BNE GCon
LDR R1, =PutPt
STR R3, [R1]
Gcon MOV R0, R2
BL Heap_Release
MOV R0, #1
B GDon
GMT MOV R0, #0
GDon POP {R4, PC}
    
```



Fifo_Get

```
PUSH {R4, LR}
```

```
LDR R1, =GetPt
```

```
LDR R2, [R1]
```

```
CMP R2, #NULL
```

```
BEQ GMT
```

```
LDR R3, [R2, #Data]
```

```
STR R3, [R0]
```

```
LDR R3, [R2, #Next]
```

```
STR R3, [R1]
```

```
CMP R3, #NULL
```

```
BNE GCon
```

```
LDR R1, =PutPt
```

```
STR R3, [R1]
```

```
GCon MOV R0, R2
```

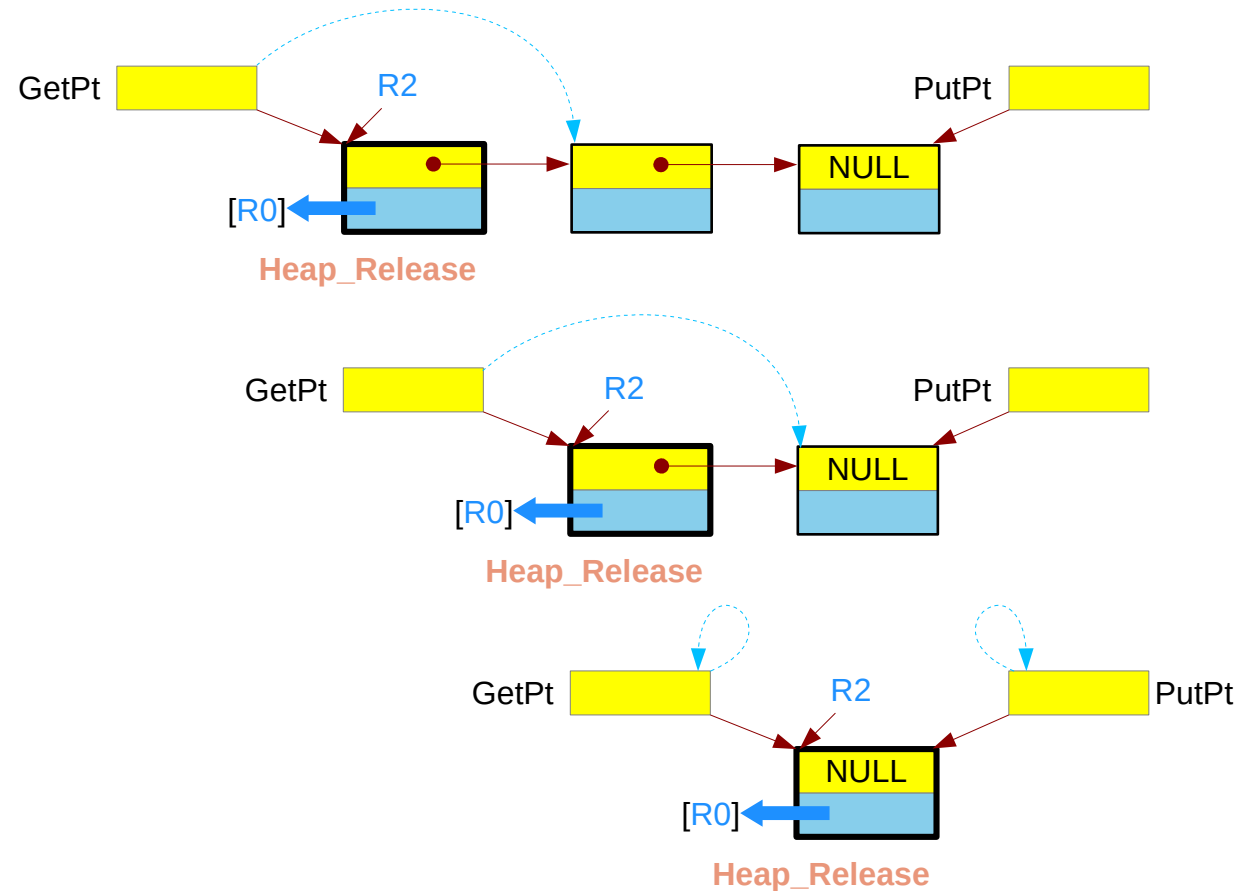
```
BL Heap_Release
```

```
MOV R0, #1
```

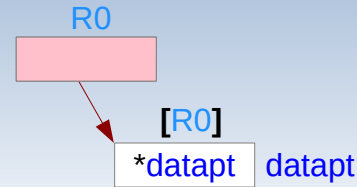
```
B GDon
```

```
GMT MOV R0, #0
```

```
GDon POP {R4, PC}
```



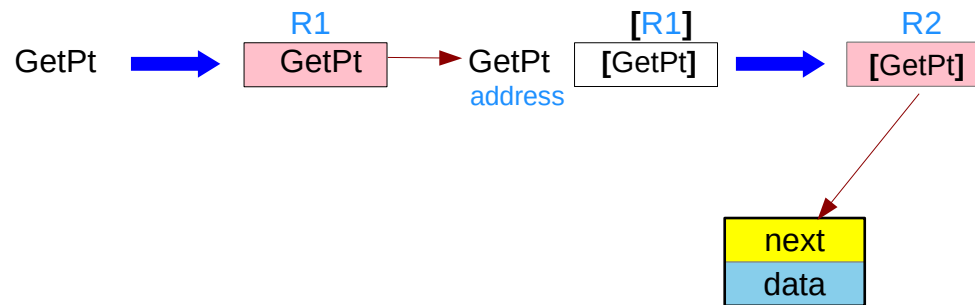
; Inputs: R0 points to an empty place
 ; Outputs: data removed to place
 R0=0 if successful
 R0=1 if empty



Fifo_Get

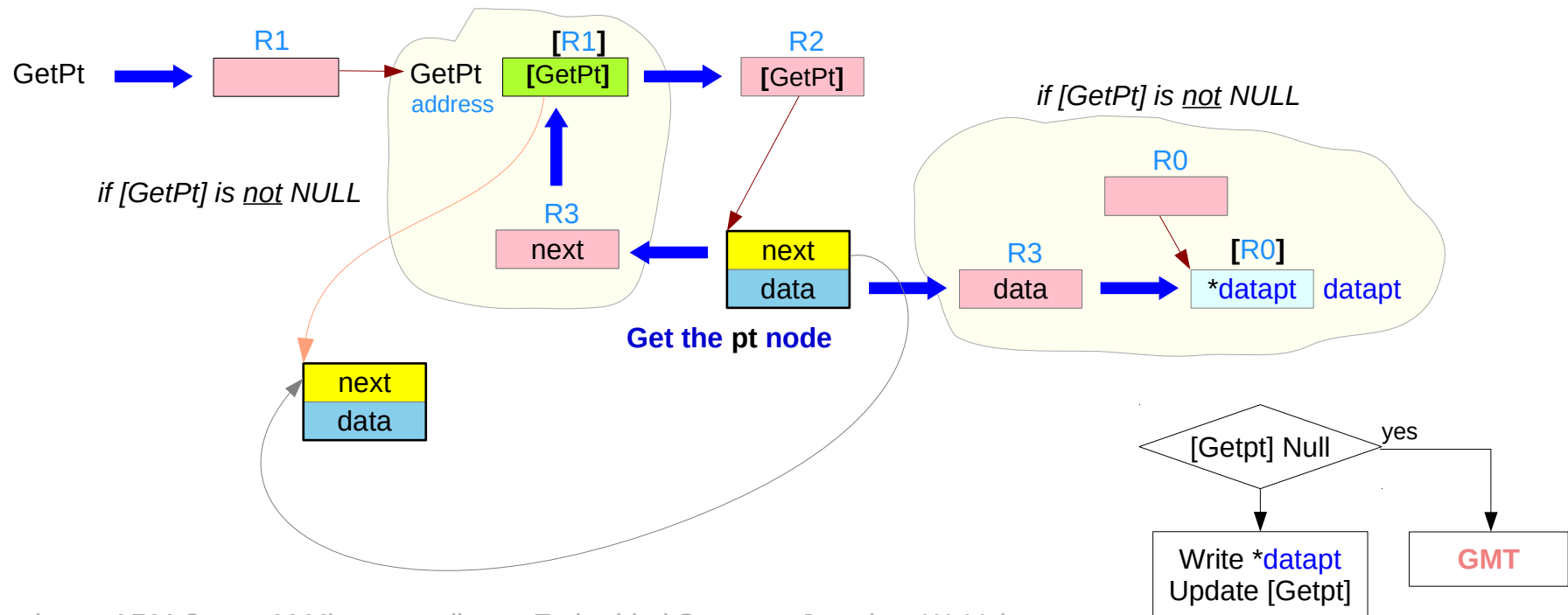
```

PUSH    {R4, LR}
LDR     R1, =GetPt    ; address GetPt    ; R1 ← GetPt (address)
LDR     R2, [R1]      ; Get node address ; R2 ← [GetPt] (content)
    
```



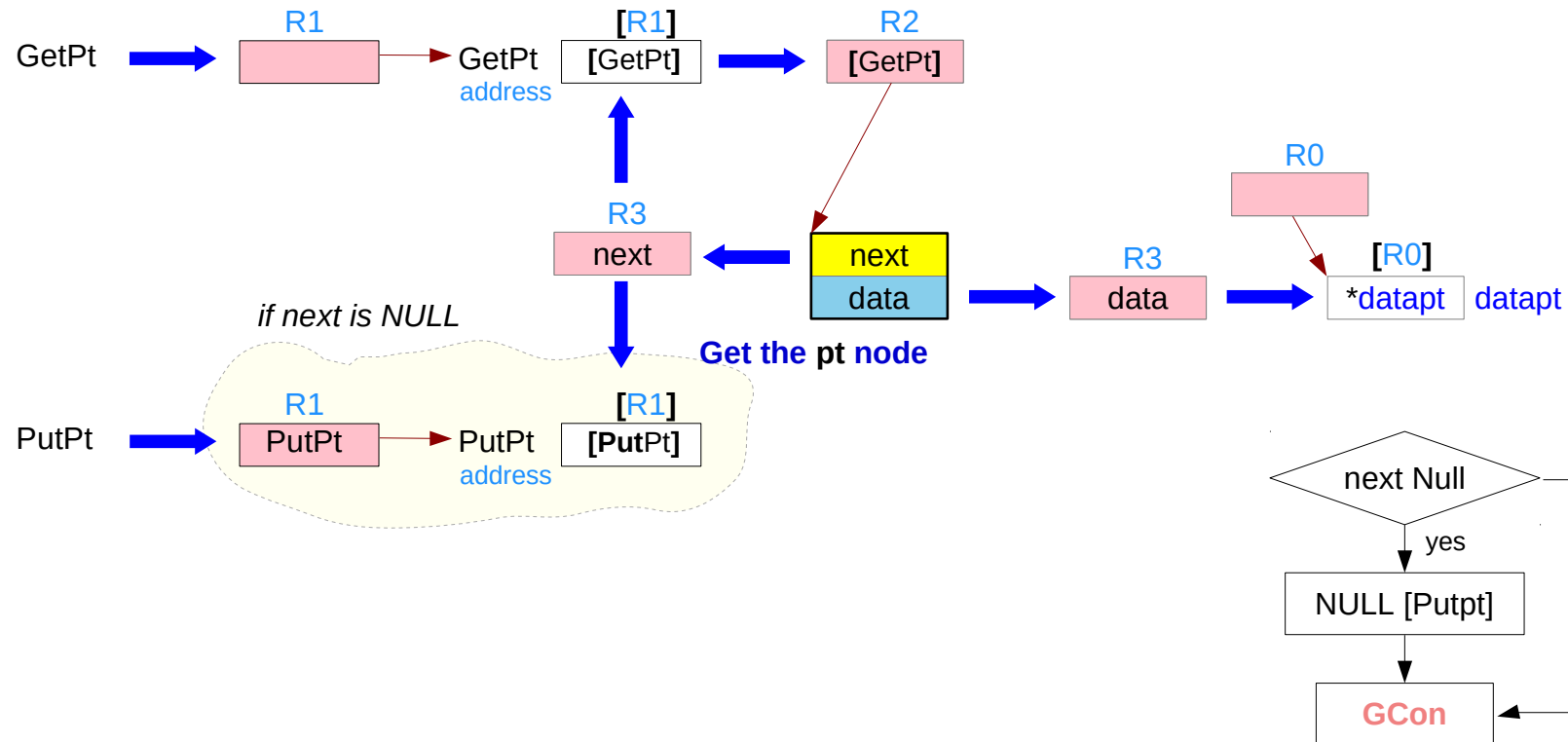
Get the pt node

CMP	R2, #NULL		
BEQ	GMT		; empty if NULL
LDR	R3, [R2, #Data]		; read 'data' ; R3 ← pt's data
STR	R3, [R0]		; store 'data' ; int Fifo_Get(int32_t *datapt)
LDR	R3, [R2, #Next]		; read 'next' ; R3 ← pt's next
STR	R3, [R1]		; store 'next' ; R3 → [GetPt]



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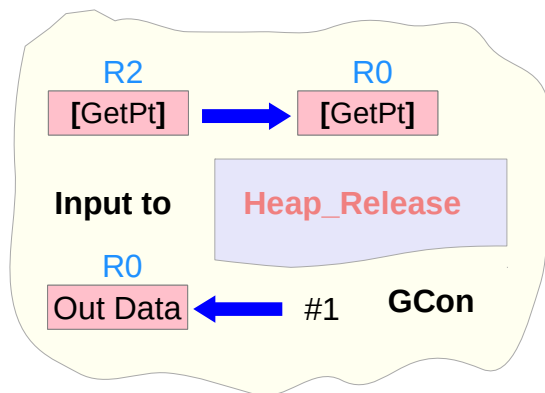
CMP	R3, #NULL	; the last node	; pt node
BNE	GCon	; if not empty	; pt's next <> NULL
LDR	R1, =PutPt	; address PutPt	; R1 ← PutPt (address)
STR	R3, [R1]	; Put node address	; NULL → [PutPt] (content)



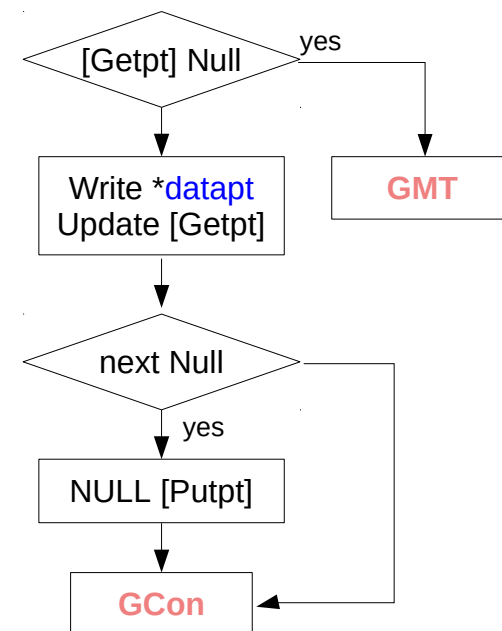
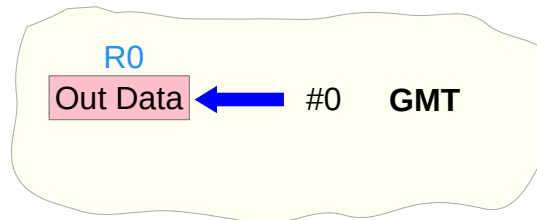
GCon	MOV R0, R2 ; old data ; R0 ← [GetPt] ; input arg
	BL Heap_Release
	MOV R0, #1 ; success
	B GDon
GMT	MOV R0, #0 ; failure, empty
GDon	POP {R4, PC}



if [GetPt] is not NULL



if [GetPt] is NULL



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Matrix read

```
uint8_t  M[2][3];      // byte matrix with 2 rows and 3 columns

// Base + n*i + j

// Read an 8-bit value from (i, j)
// row or column major by compiler
// Input:  i is the row index
           j is the column index
// Output: retrieved value
// Assume: (0 <= i <= 1) and
//          (0 <= j <= 2)

uint8_t Matrix_read(uint8_t base[], uint8_t i, uint8_t j) {
    return base[i][j];
}
```

Accessing and storing matrices

Store in <u>row</u> major order	Store in <u>column</u> major order
<p>byte matrix uint8_t M[2][3]; Base + (3*i + j)</p>	<p>byte matrix uint8_t M[2][3]; Base + (2*j + i)</p>
<p>halfword matrix uint16_t M[2][3]; Base + 2*(3*i + j)</p>	<p>halfword matrix uint16_t M[2][3]; Base + 2*(2*j + i)</p>
<p>word matrix uint32_t M[2][3]; Base + 4*(3*i + j)</p>	<p>word matrix uint32_t M[2][3]; Base + 4*(2*j + i)</p>

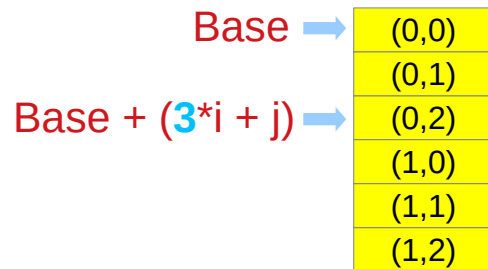
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Matrix M[m][n] in row major order

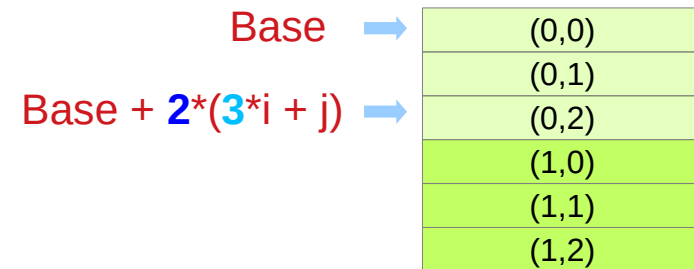
(0,0)	(0,1)	(0,2)
(1,0)	(1,1)	(1,2)

(0,0)	(0,1)	(0,2)
(1,0)	(1,1)	(1,2)

byte matrix `uint8_t M[2][3];`

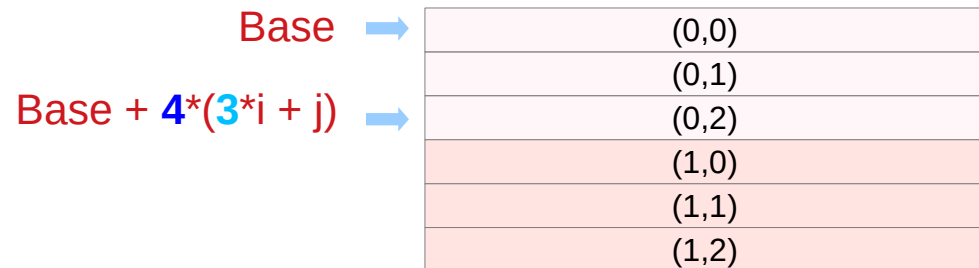


halfword matrix `uint16_t M[2][3];`



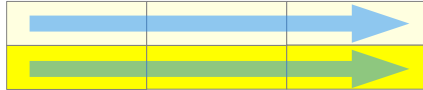
(0,0)	(0,1)	(0,2)
(1,0)	(1,1)	(1,2)

word matrix `uint32_t M[2][3];`



row major order vs column major order

(0,0)	(0,1)	(0,2)
(1,0)	(1,1)	(1,2)

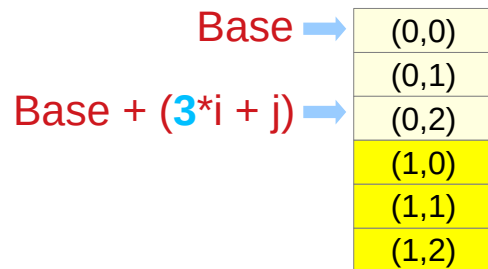


(0,0)	(0,1)	(0,2)
(1,0)	(1,1)	(1,2)



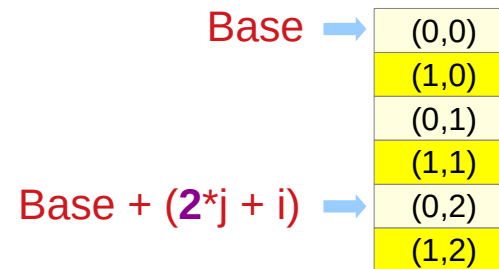
```
uint8_t M[2][3];
```

byte matrix – row major order



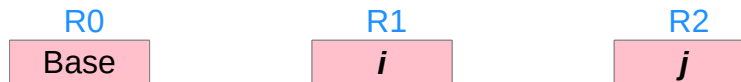
```
uint8_t M[2][3];
```

byte matrix – column major order



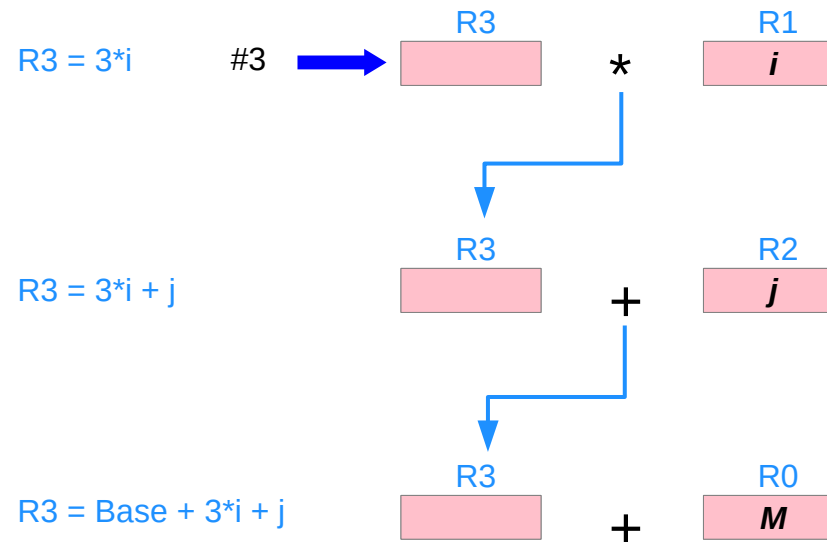
Matrix

```
; Read an 8-bit value from (i, j)                ;; Base + n*i + j
; Input:  Base    (R0)    pointer to matrix      ;; R0 + n*R1 + R2
;         i       (R1)    is the row index
;         j       (R2)    is the column index
; Assume: (0 <= R1 <= 1)
;         (0 <= R2 <= 2)
Matrix_read
    MOV     R3, #3                ; R3 = 3 columns M[2][3]
    MUL     R3, R3, R1           ; R3 = 3*i
    ADD     R3, R3, R2           ; R3 = 3*i + j
    ADD     R3, R3, R0           ; R3 = Base + 3*i + j
    LDRB   R0, [R3]             ; R0 = M[i, j]
    BX     LR                    ; return
```



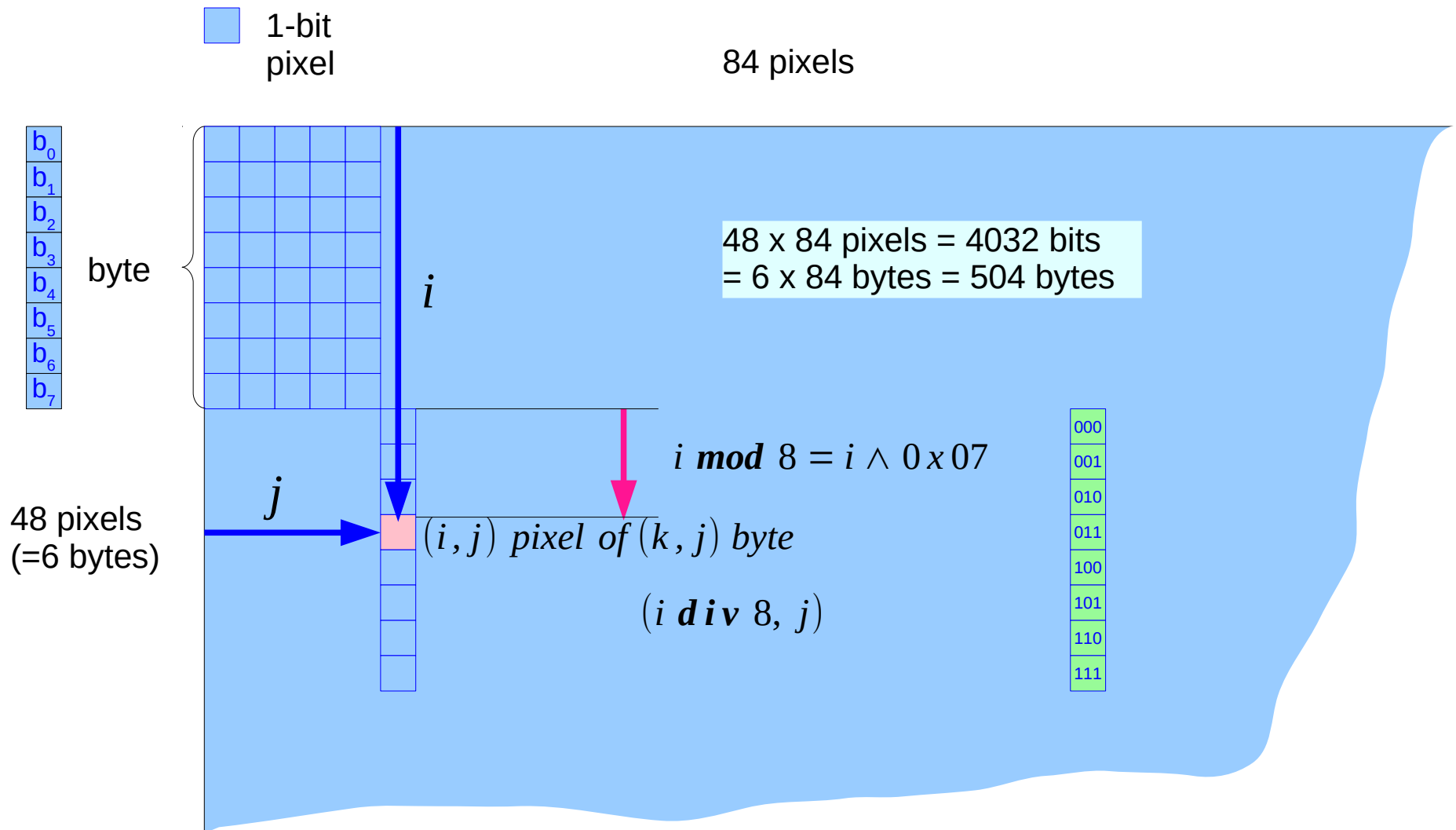
Matrix

```
Matrix_read
MOV R3, #3          ; R3 = 3 columns M[2][3]
MUL R3, R3, R1      ; R3 = 3*i
ADD R3, R3, R2      ; R3 = 3*i + j
ADD R3, R3, R0      ; R3 = Base + 3*i + j
LDRB R0, [R3]       ; R0 = M[i, j]
BX LR               ; return
```



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48 x 84 B/W Image



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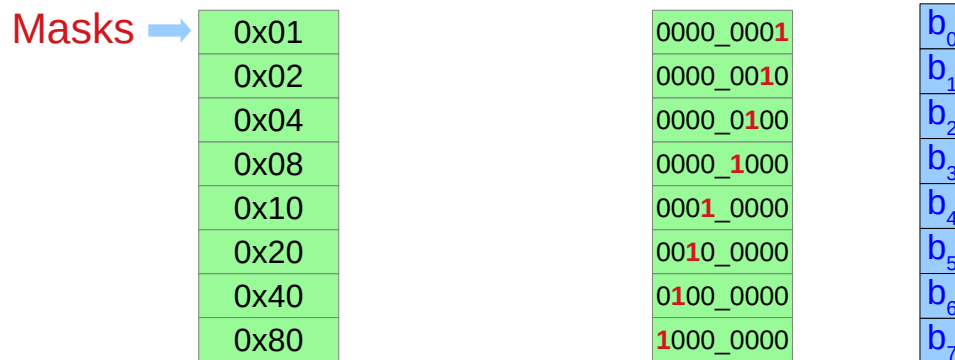
Matrix

```
uint8_t Screen[504]           // stores the next image to be printed on the screen

Screen + 84*(i>>3)           // Screen + 84*(i div 8)
Screen + 84*(i>>3) + j;      // Screen + 84*(i div 8) + j

k = i & 0x07;                 // i mod 8

Masks FCB  0x01, 0x02, 0x04, 0x08, 0x10, 0x20, 0x40, 0x80
```



FCB Directive

fcf Form Constant Byte

```
(<label>) fcb <expr>(,<expr>,....,<expr>) (<comment>)  
(<label>) dc.b <expr>(,<expr>,....,<expr>) (<comment>)  
(<label>) db <expr>(,<expr>,....,<expr>) (<comment>)  
(<label>) .byte <expr>(,<expr>,....,<expr>) (<comment>)
```

The FCB directive may have one or more operands separated by commas. The value of each operand is truncated to eight bits, and is stored in a single byte of the object program. Multiple operands are stored in successive bytes. The operand may be a numeric constant, a character constant, a symbol, or an expression. If multiple operands are present, one or more of them can be null (two adjacent commas), in which case a single byte of zero will be assigned for that operand. An error will occur if the upper eight bits of the evaluated operands' values are not all ones or all zeros.

A string can be included, which is stored as a sequence of ASCII characters. The delimiters supported by TExaS are " ' and \. The string is not terminated, so the programmer must explicitly terminate it. For example:

```
str1 fcb "Hello World",0
```

<http://users.ece.utexas.edu/~valvano/assmbly/syntax.htm#fcb>

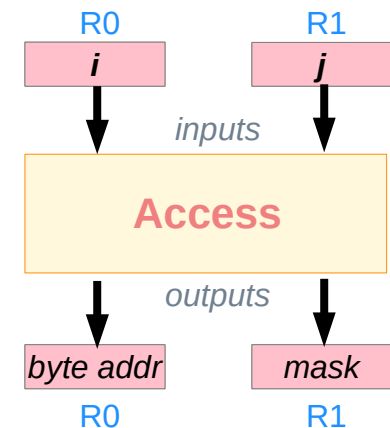
Matrix

; Input : R0 the row index i (0 to 47 in this case), Y-coordinate
; R1 the column index j (0 to 83 in this case), X-coordinate
; Output: **R0** points to the byte of interest
R1 the Mask to access that 1-bit pixel

Access

; Access the Image pixel at (i, j)

LDR	R3, =Masks	; R3 = Masks (pointer)
AND	R2, R0, #0x07	; R2 = $k = i \& 0x07$
LDRB	R4, [R3, R2]	; R2 = Mask[k]
LDR	R3, =Screen	; R3 = Screen (pointer)
LSR	R0, R0, #3	; R0 = $R0 \gg 3$ ($i \text{ div } 8$)
MOV	R2, #84	
MUL	R2, R0, R2	; R2 = $84 * (i \gg 3)$
ADD	R0, R2, R3	; R0 = Screen + $84 * (i \gg 3)$ (pointer)
ADD	R0, R0, R1	; R0 = Screen + $84 * (i \gg 3) + j$ (pointer)
MOV	R1, R4	; R1 is Masks[i mod 8]
BX	LR	

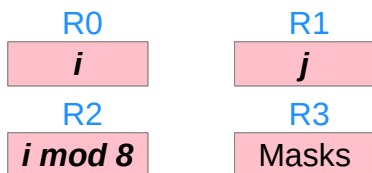


Matrix

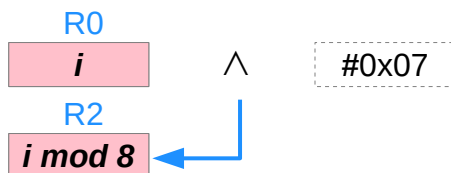
Access

```

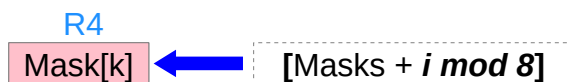
LDR R3, =Masks
AND R2, R0, #0x07
LDRB R4, [R3, R2]
LDR R3, =Screen
LSR R0, R0, #3
MOV R2, #84
MUL R2, R0, R2
ADD R0, R2, R3
ADD R0, R0, R1
MOV R1, R4
BX LR
    
```



```
AND R2, R0, #0x07
```



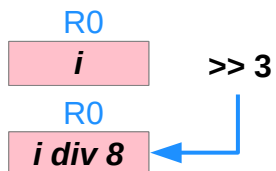
```
LDRB R4, [R3, R2]
```



```
LDR R3, =Screen
```



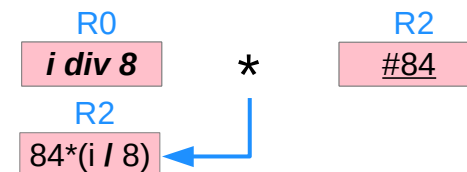
```
LSR R0, R0, #3
```



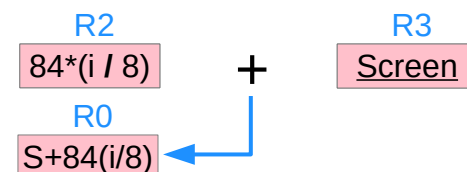
```
MOV R2, #84
```



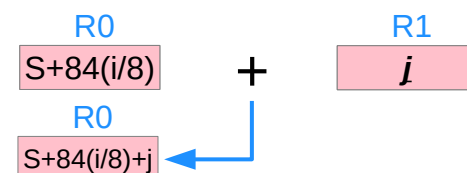
```
MUL R2, R0, R2
```



```
ADD R0, R2, R3
```

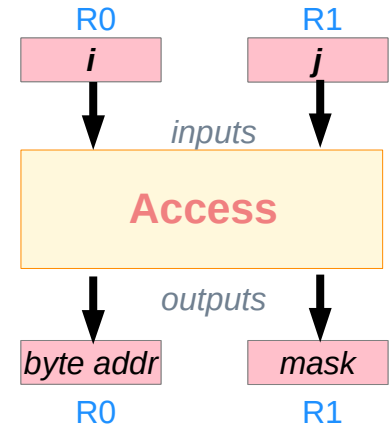


```
ADD R0, R0, R1
```



Clear a pixel

; Clear the Image pixel at (i, j) , turning it dark
 ; Input: R0 the row index i (0 to 47 in this case) Y-coordinate
 R1 the column index j (0 to 83 in this case) X-coordinate
 ; Output: none modifies R0, R1, R2, R3



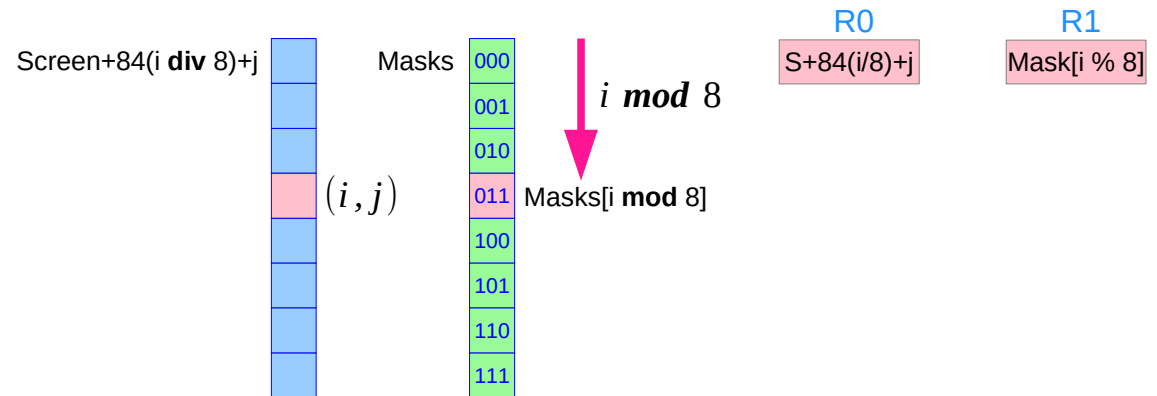
ClrPxl

```

PUSH   {LR}
BL     Access
LDRB   R3, [R0]
BIC    R3, R3, R1
STRB   R3, [R0]
POP    {PC}
  
```

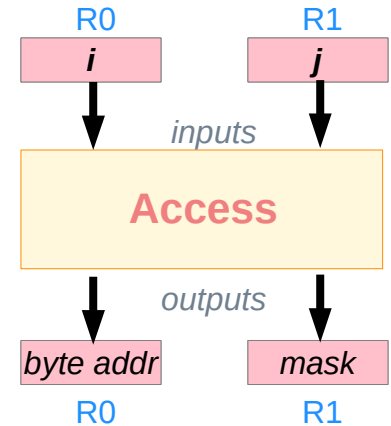
```

; get pointer to pixel to change
; R3 = [R0] = read 8 pixels
; R3 = R3 & ~R1   clear proper pixel
; [R0] = R3 = write 8 pixels
  
```



Set a pixel

; Set the Image pixel at (I, j) to the given value
 ; Input: R0 the row index I (0 to 47 in this case) Y-coordinate
 R1 the column index j (0 to 83 in this case) X-coordinate
 ; Output: none modifies R0, R1, R2, R3



SetPxl

PUSH	{LR}	
BL	Access	; get pointer to pixel to change
LDRB	R3, [R0]	; R3 = [R0] = read 8 pixels
ORR	R3, R3, R1	; R3 = R3 R1 set proper pixel
STRB	R3, [R0]	; [R0] = R3 = write 8 pixels
POP	{PC}	

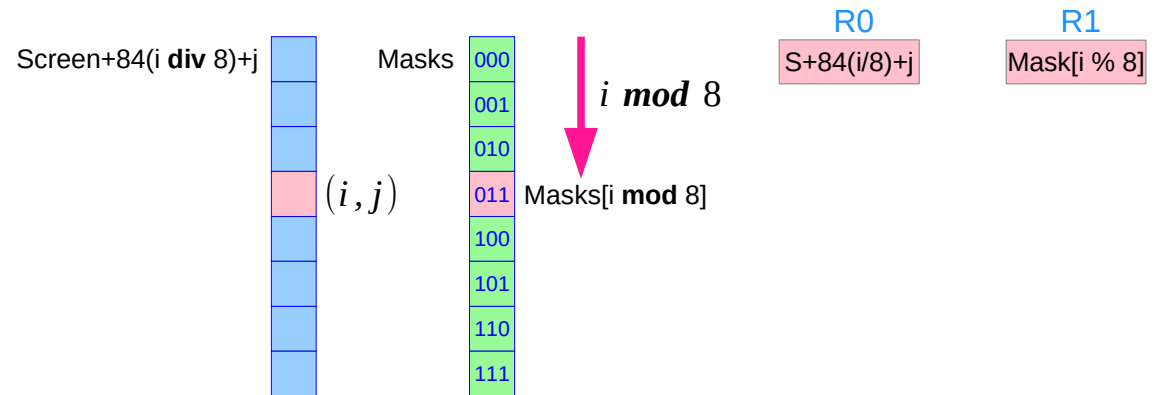


Table for a sine wave

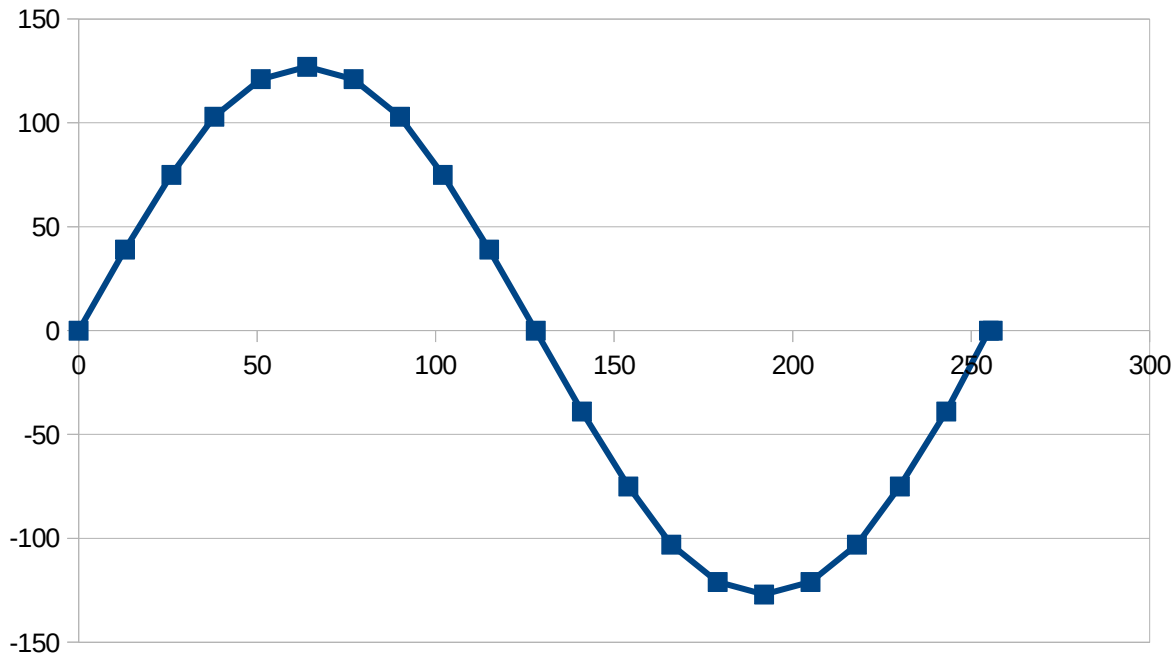
```
const int32_t lxTabl[22] = {  
    0,13,26,38,51,64,77,90,102,  
    115,128,141,154,166,179,192,205,  
    218,230,243,255, 256};
```

```
const int32_t lyTabl[22] = {  
    0,39,75,103,121,127,121,103,  
    75,39,0,-39,-75,-103,-121,-127,  
    -121,-103,-75,-39,0,0};
```

lxTabl	DCD	0,13,26,38,51,64,77,90,102
	DCD	115,128,141,154,166,179,192,205
	DCD	218,230,243,255, 256

lyTabl	DCD	0,39,75,103,121,127,121,103
	DCD	75,39,0,-39,-75,-103,-121,-127
	DCD	-121,-103,-75,-39,0,0

X and Y tables



```
const int32_t lxTabl[22] = {  
    0,13,26,38,51,64,77,90,102,  
    115,128,141,154,166,179,192,205,  
    218,230,243,255, 256};
```

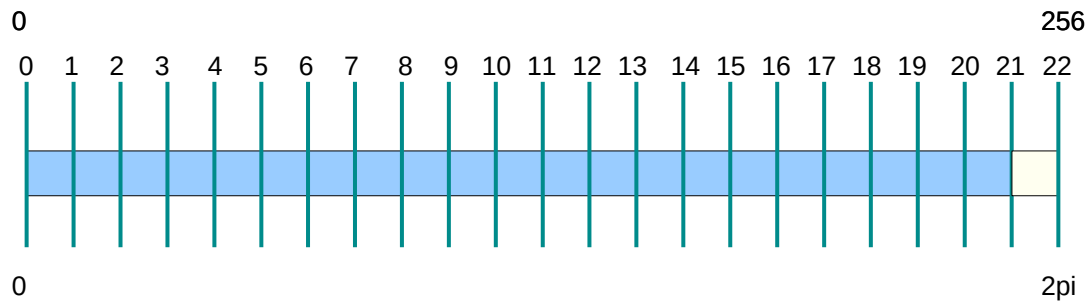
```
const int32_t lyTabl[22] = {  
    0,39,75,103,121,127,121,103,  
    75,39,0,-39,-75,-103,-121,-127,  
    -121,-103,-75,-39,0,0};
```

	lxTabl	lyTabl
1	0	0
2	13	39
3	26	75
4	38	103
5	51	121
6	64	127
7	77	121
8	90	103
9	102	75
10	115	39
11	128	0
12	141	-39
13	154	-75
14	166	-103
15	179	-121
16	192	-127
17	205	-121
18	218	-103
19	230	-75
20	243	-39
21	255	0
22	256	0

Introduction to ARM Cortex-M Microcontrollers – Embedded Systems, Jonathan W. Valvano

Quantized X – method 1

$$QX = \text{round}(256 * i / 22)$$
$$X = 2 * \text{PI} / 256 * QX$$



```
const int32_t lxTabl[22] = {  
    0,13,26,38,51,64,77,90,102,  
    115,128,141,154,166,179,192,205,  
    218,230,243,255, 256};
```

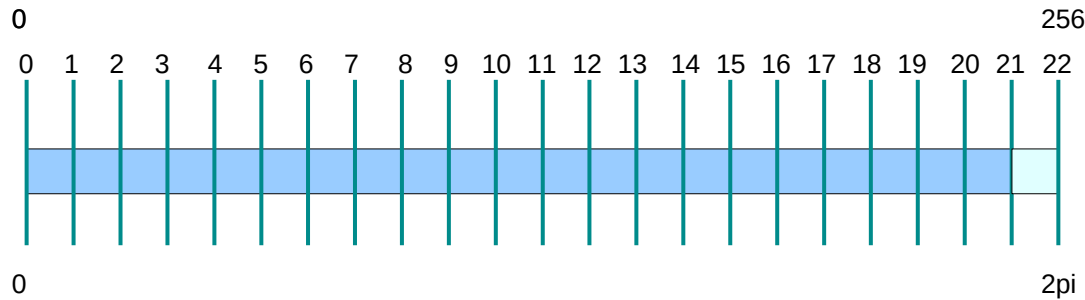
```
const int32_t lyTabl[22] = {  
    0,39,75,103,121,127,121,103,  
    75,39,0,-39,-75,-103,-121,-127,  
    -121,-103,-75,-39,0,0};
```

	lxTabl	lyTabl	QX	X	sin(X)
1	0	0	0	0.000	0.000
2	13	39	12	0.295	0.290
3	26	75	23	0.565	0.535
4	38	103	35	0.859	0.757
5	51	121	47	1.154	0.914
6	64	127	58	1.424	0.989
7	77	121	70	1.718	0.989
8	90	103	81	1.988	0.914
9	102	75	93	2.283	0.757
10	115	39	105	2.577	0.535
11	128	0	116	2.847	0.290
12	141	-39	128	3.142	0.000
13	154	-75	140	3.436	-0.290
14	166	-103	151	3.706	-0.535
15	179	-121	163	4.001	-0.757
16	192	-127	175	4.295	-0.914
17	205	-121	186	4.565	-0.989
18	218	-103	198	4.860	-0.989
19	230	-75	209	5.130	-0.914
20	243	-39	221	5.424	-0.757
21	255	0	233	5.719	-0.535
22	256	0	244	5.989	-0.290

Quantized X – method 2

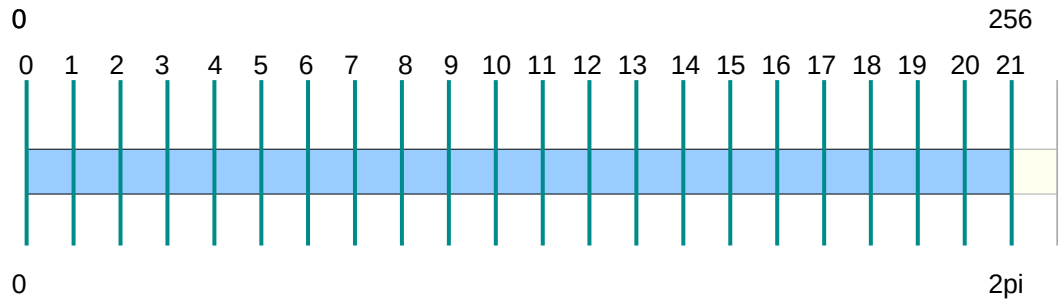
$$QX_ = \text{round}(256 * i / 22)$$

$$X_ = 2 * \text{PI} / 256 * QX_$$



$$QX = \text{round}(256 * i / 21)$$

$$X = 2 * \text{PI} / 256 * QX$$



	lxTabl	lyTabl	QX_	X_	SIN(X_)
1	0	0	0	0.000	0.000
2	13	39	12	0.295	0.290
3	26	75	24	0.589	0.556
4	38	103	37	0.908	0.788
5	51	121	49	1.203	0.933
6	64	127	61	1.497	0.997
7	77	121	73	1.792	0.976
8	90	103	85	2.086	0.870
9	102	75	98	2.405	0.672
10	115	39	110	2.700	0.428
11	128	0	122	2.994	0.147
12	141	-39	134	3.289	-0.147
13	154	-75	146	3.583	-0.428
14	166	-103	158	3.878	-0.672
15	179	-121	171	4.197	-0.870
16	192	-127	183	4.491	-0.976
17	205	-121	195	4.786	-0.997
18	218	-103	207	5.081	-0.933
19	230	-75	219	5.375	-0.788
20	243	-39	232	5.694	-0.556
21	255	0	244	5.989	-0.290
22	256	0	256	6.283	0.000

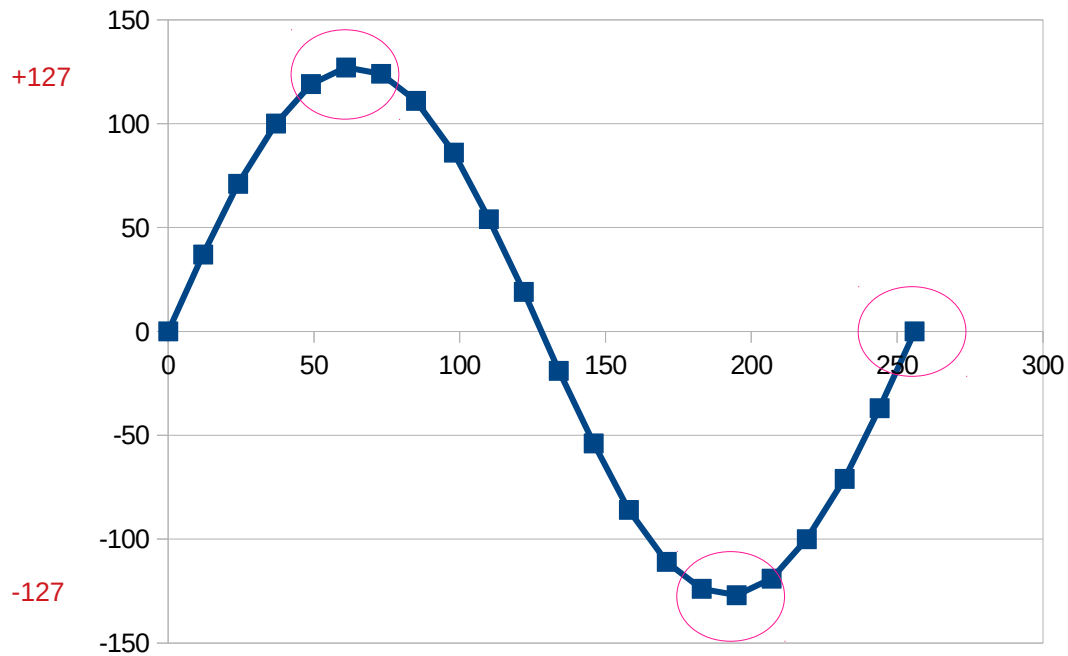
Plot of (QX, QY)

$QX = \text{round}(256 * i / 22)$

$X = 2 * \text{PI} / 256 * QX$

$Y = \sin(X)$

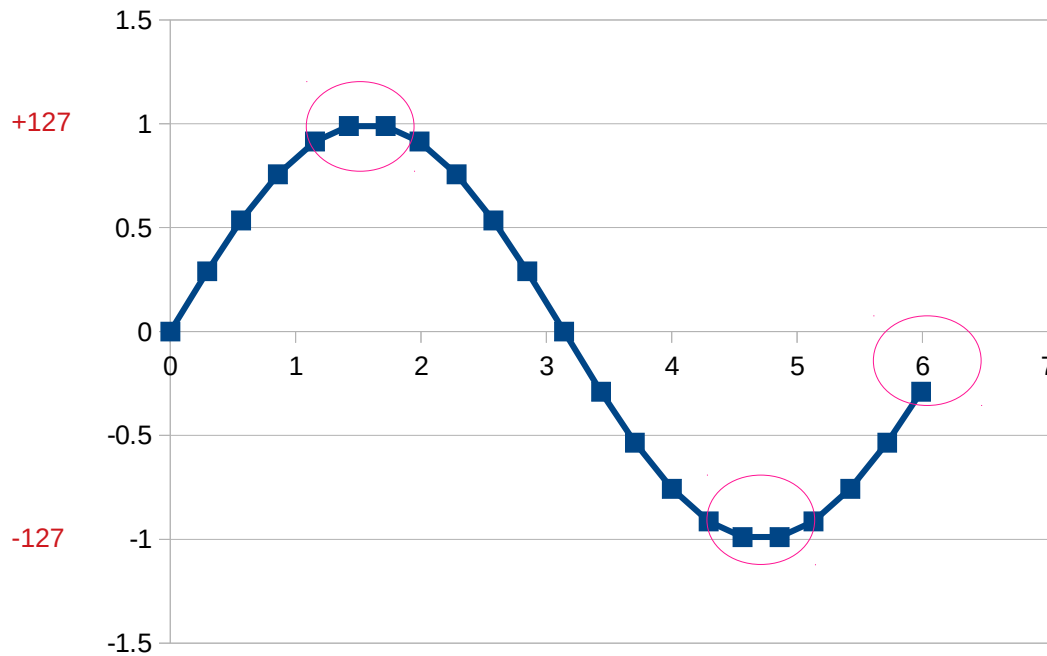
$QY = \text{round}(127 * Y / \text{max}(Y))$



	QX	X	SIN(X)	QY
1	0	0.000	0.000	0
2	12	0.295	0.290	37
3	24	0.589	0.556	71
4	37	0.908	0.788	100
5	49	1.203	0.933	119
6	61	1.497	0.997	127
7	73	1.792	0.976	124
8	85	2.086	0.870	111
9	98	2.405	0.672	86
10	110	2.700	0.428	54
11	122	2.994	0.147	19
12	134	3.289	-0.147	-19
13	146	3.583	-0.428	-54
14	158	3.878	-0.672	-86
15	171	4.197	-0.870	-111
16	183	4.491	-0.976	-124
17	195	4.786	-0.997	-127
18	207	5.081	-0.933	-119
19	219	5.375	-0.788	-100
20	232	5.694	-0.556	-71
21	244	5.989	-0.290	-37
22	256	6.283	0.000	0

Plot of (QX_, QY_)

```
QX_ = round(256 * i / 22)
X_ = 2*PI/256 * QX_
Y_ = sin(X_)
QY_ = round(127*Y_)
```



	QX_	X_	Y_=sin(X_)	QY_
1	0	0	0	0
2	12	0.295	0.29	37
3	23	0.565	0.535	68
4	35	0.859	0.757	96
5	47	1.154	0.914	116
6	58	1.424	0.989	126
7	70	1.718	0.989	126
8	81	1.988	0.914	116
9	93	2.283	0.757	96
10	105	2.577	0.535	68
11	116	2.847	0.29	37
12	128	3.142	0	0
13	140	3.436	-0.29	-37
14	151	3.706	-0.535	-68
15	163	4.001	-0.757	-96
16	175	4.295	-0.914	-116
17	186	4.565	-0.989	-126
18	198	4.86	-0.989	-126
19	209	5.13	-0.914	-116
20	221	5.424	-0.757	-96
21	233	5.719	-0.535	-68
22	244	5.989	-0.29	-37

Table

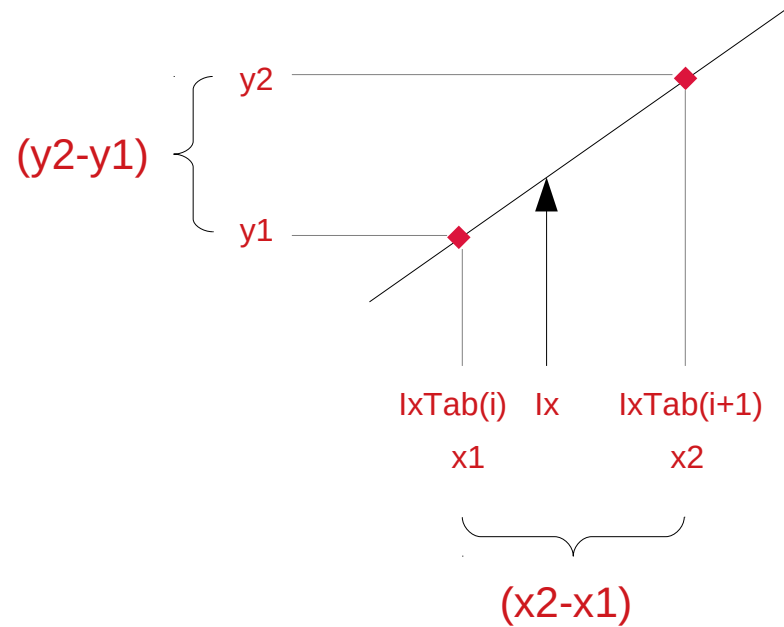
```
// lx is 0 to 255 (pi/128)
// ly is -127 to +127 (1/256)

int32_t Sin(int32_t lx) {
    int32_t x1, x2, y1, y2;
    int i=0;

    while (lx >= lxTab(i+1)) {
        i++;
    }

    // lx < lxTab(i+1)
    x1 = lxTab[i];
    x2 = lxTab[i+1];
    y1 = lyTab[i];
    y2 = lyTab[i+1];

    return ((y2-y1)*(lx-x1))/(x2-x1) + y1;
}
```



$$y = m(x - x_1) + y_1$$
$$= \frac{(y_2 - y_1)}{(x_2 - x_1)}(x - x_1) + y_1$$

Sine Table

; Input : R0 is 0 to 255, lx
; Output: R0 is -127 to +127, ly

```
Sin      PUSH {R4-R6, LR}
        LDR  R1, =lxTab      ; find x1 <= lx < x2
        LDR  R2, =lyTab
Lookx1   LDR  R6, [R1, #4]    ; R6 = x2
        CMP  R0, R6         ; check lx < x2
        BLO  Found         ; R1 >= x1
        ADD  R1, #4         ; R1 = R1 + 4
        ADD  R2, #4         ; R2 = R2 + 4
        B    Lookx1

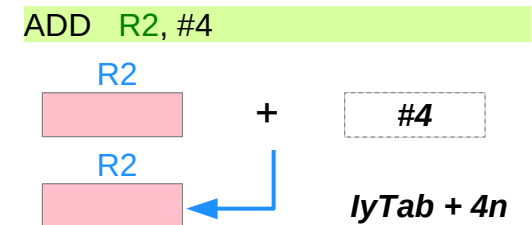
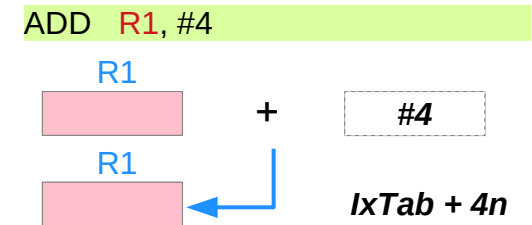
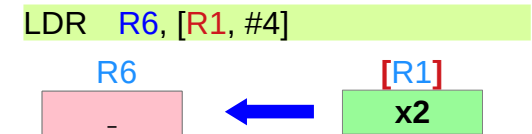
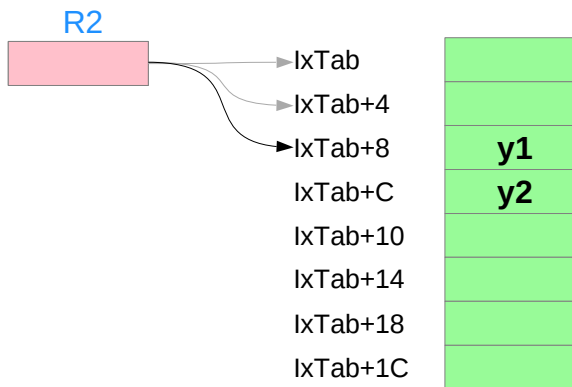
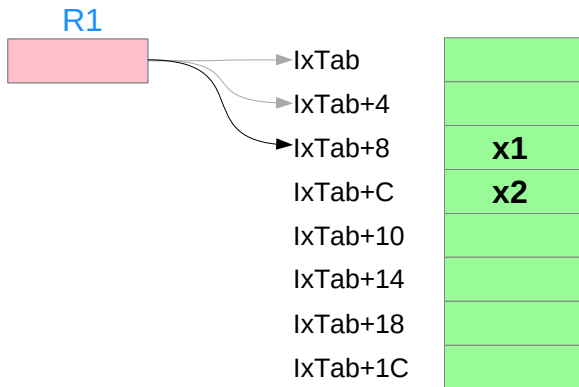
Found    LDR  R4, [R1]      ; R4 = x1
        SUB  R4, R0, R4     ; R4 = lx - x1
        LDR  R5, [R2, #4]  ; R5 = y2
        LDR  R2, [R2]      ; R2 = y1
        SUB  R5, R2        ; R5 = y2 - y1
        LDR  R1, [R1]      ; R1 = x1
        SUB  R6, R1        ; R6 = x2 - x1
        MUL  R0, R4, R5     ; R0 = (y2 - y1) * (lx - x1)
        SDIV R0, R0, R6    ; R0 = (y2 - y1) * (lx - x1) / (x2 - x1)
        ADD  R0, R2        ; R0 = (y2 - y1) * (lx - x1) / (x2 - x1) + ly
        POP  {R0-R6, PC}
```

Sin

```

; Input : R0 is 0 to 255, lx      ; lxtab[0] <= lx < lxtab[21]
Sin  PUSH{R4-R6, LR}
     LDR  R1, =lxtab             ; find x1 <= lx < x2
     LDR  R2, =lytab
Lookx1
     LDR  R6, [R1, #4]          ; x2
     CMP  R0, R6                ; check lx < x2
     BLO  Found                 ; R1 >= x1
     ADD  R1, #4                 ; R1 ← R1 + 4
     ADD  R2, #4                 ; R2 ← R2 + 4
     B    Lookx1

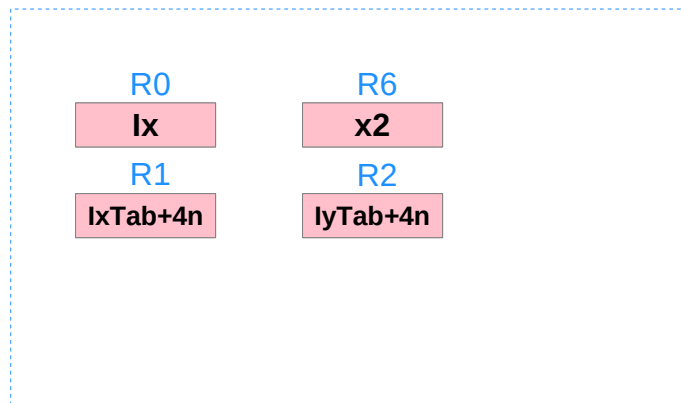
```



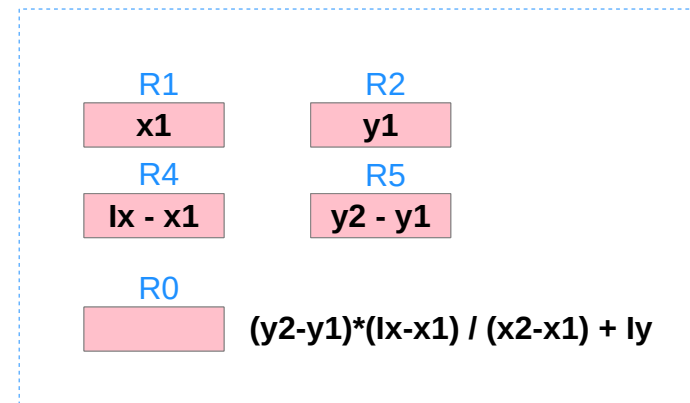
Input & output registers of Found

```
; Output: R0 is -127 to +127, ly
Found    LDR  R4, [R1]           ; R4 = x1
        SUB  R4, R0, R4         ; R4 = lx - x1
        LDR  R5, [R2, #4]      ; R5 = y2
        LDR  R2, [R2]          ; R2 = y1
        SUB  R5, R2             ; R5 = y2 - y1
        LDR  R1, [R1]          ; R1 = x1
        SUB  R6, R1            ; R6 = x2 - x1
        MUL  R0, R4, R5        ; R0 = (y2 - y1) * (lx - x1)
        SDIV R0, R0, R6        ; R0 = (y2 - y1) * (lx - x1) / (x2 - x1)
        ADD  R0, R2           ; R0 = (y2 - y1) * (lx - x1) / (x2 - x1) + ly
        POP  {R0-R6, PC}
```

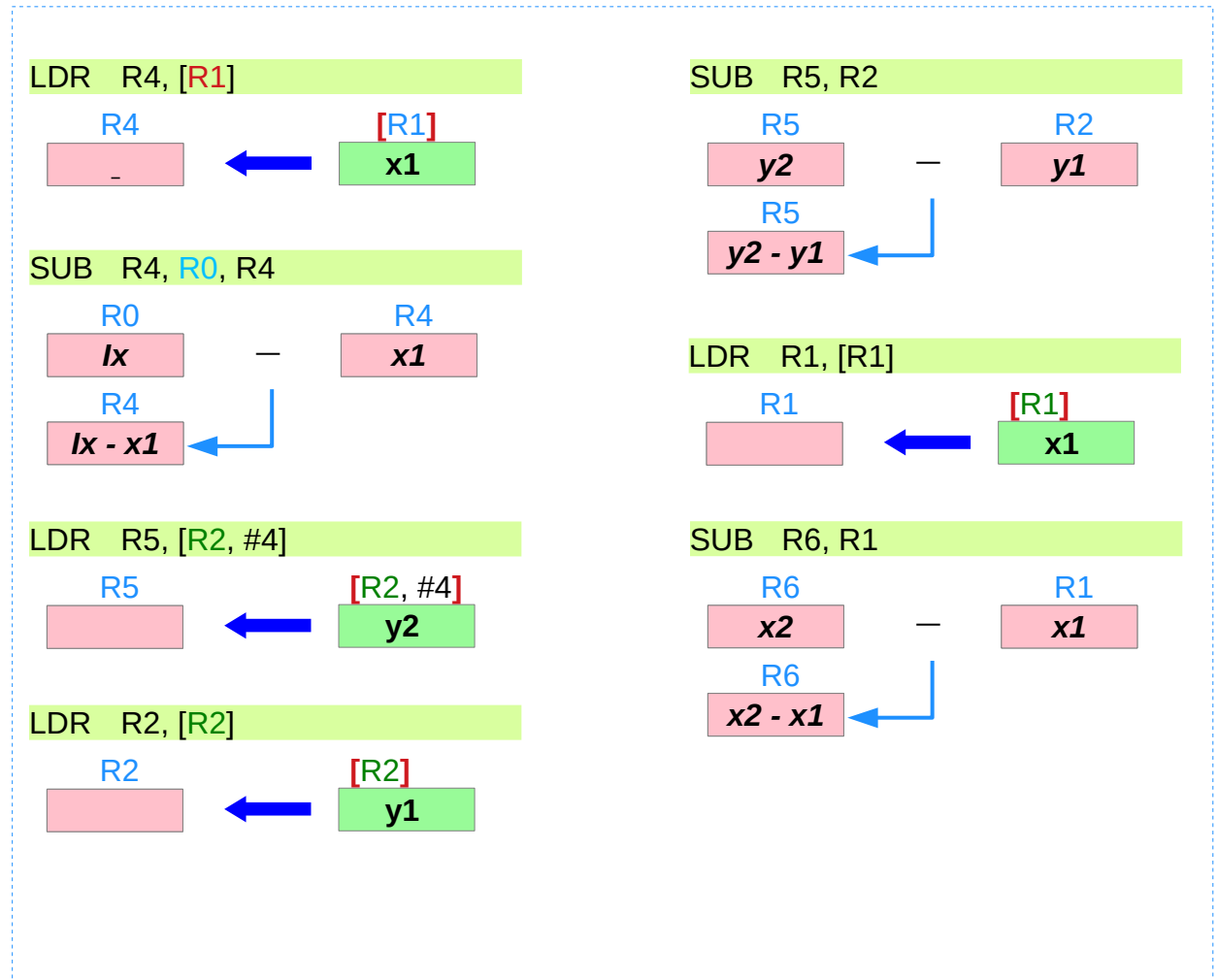
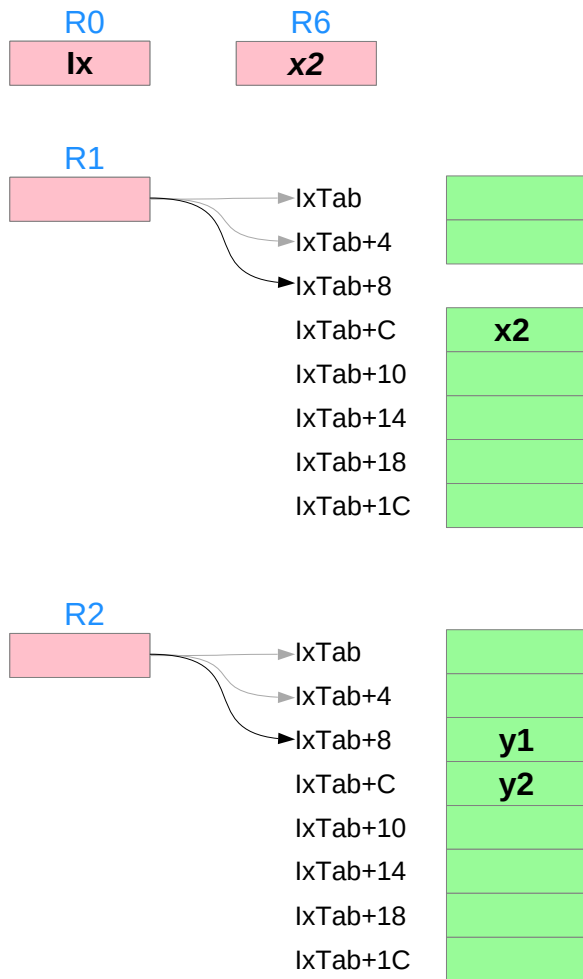
Input registers of Found



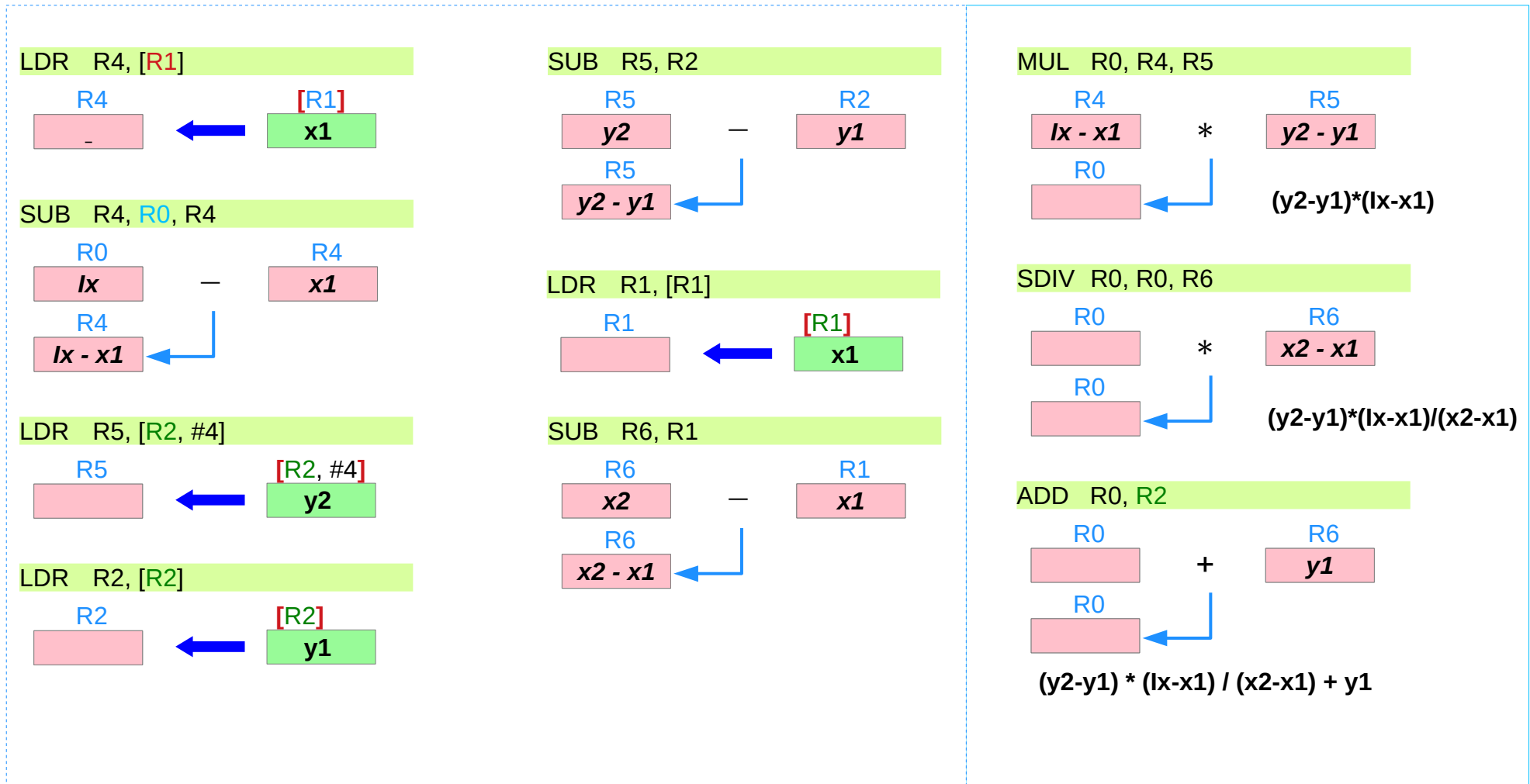
Output registers of Found



Steps of Found (1)



Steps of Found (2)



SDIV, UDIV

SDIV performs a signed integer division of the value in **Rn** by the value in **Rm**.

UDIV performs an unsigned integer division of the value in **Rn** by the value in **Rm**.

For both instructions, if the value in **Rn** is not divisible by the value in **Rm**, the result is rounded towards zero.

Restrictions : Do not use **SP** and do not use **PC**.

Condition flags : These instructions do not change the flags.

Examples

SDIV R0, R2, R4 ; Signed divide, $R0 = R2/R4$

UDIV R8, R8, R1 ; Unsigned divide, $R8 = R8/R1$.

<https://developer.arm.com/documentation/dui0552/a/the-cortex-m3-instruction-set/multiply-and-divide-instructions/sdiv-and-udiv>

Pointer access to an array

References

- [1] <ftp://ftp.geoinfo.tuwien.ac.at/navratil/HaskellTutorial.pdf>
- [2] <https://www.umiacs.umd.edu/~hal/docs/daume02yaht.pdf>