Data Structures (8A)

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Please send corrections (or suggestions) to youngwlim@hotmail.com.

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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
```

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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
```

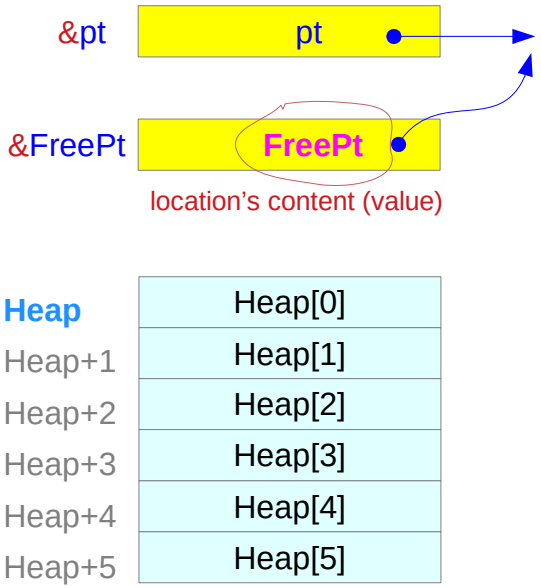
Pointer and array declarations – C and ARM assembly

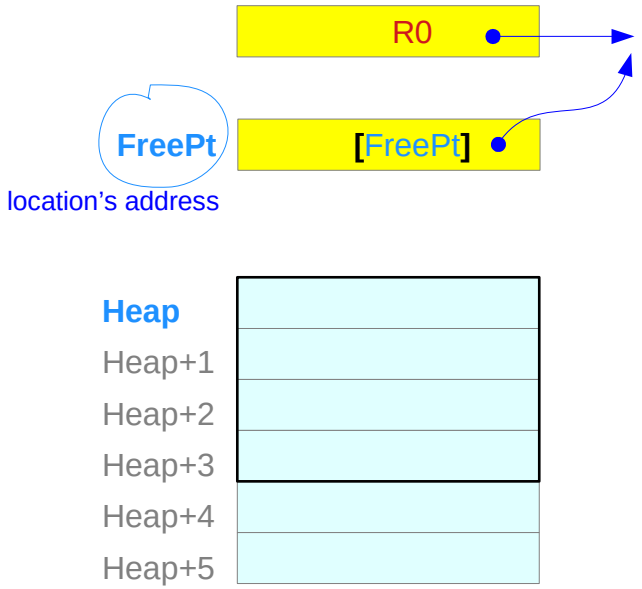
C code

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

ARM assembly code

```
FreePT   SPACE   4
Heap     SPACE   SIZE*NUM*4
```





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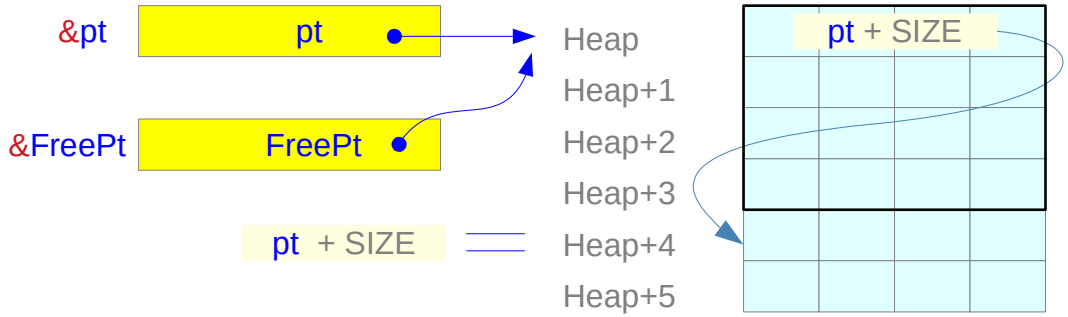
Heap_Init (1)

```
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;
```

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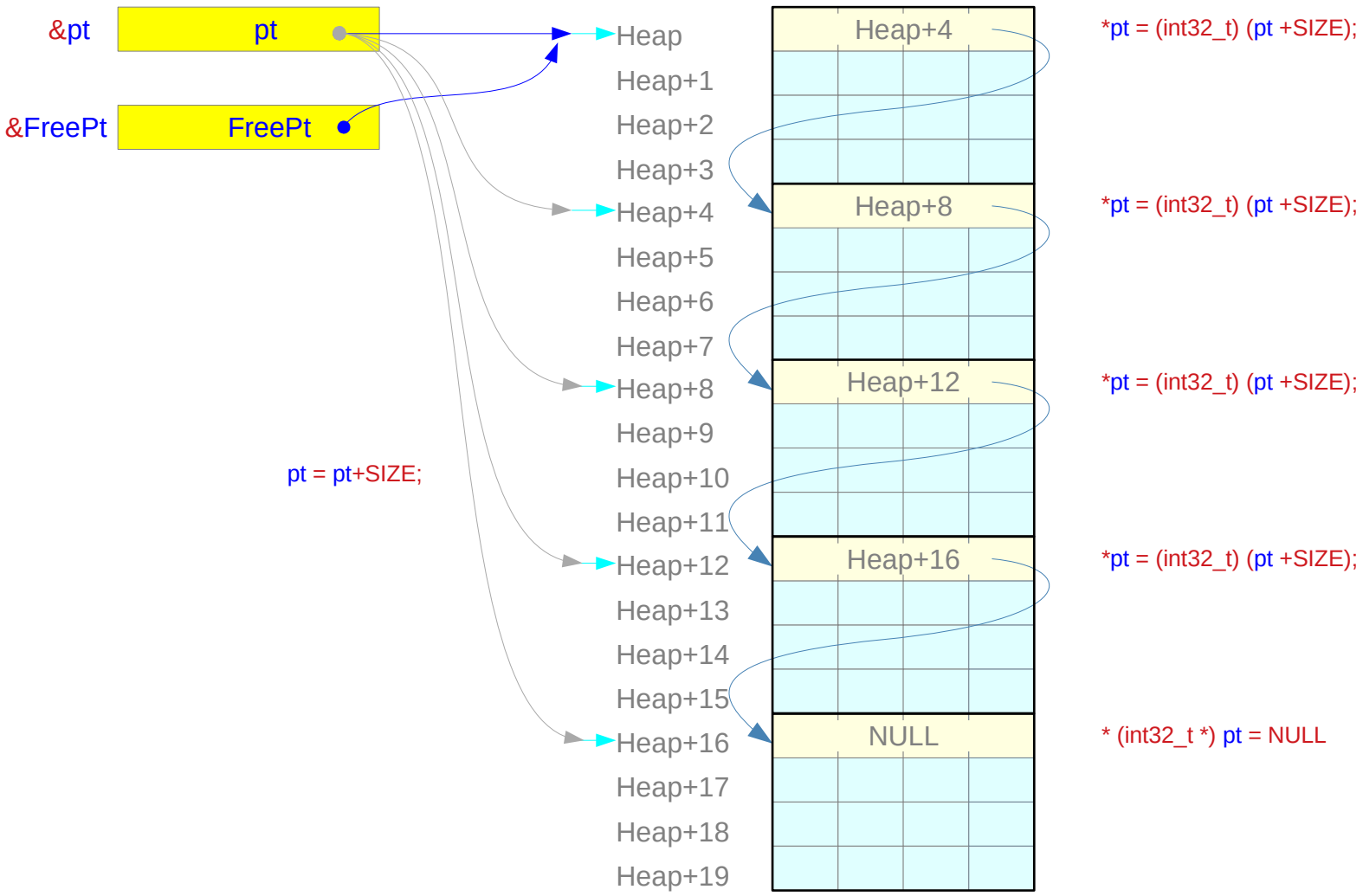
Heap_Init (2)



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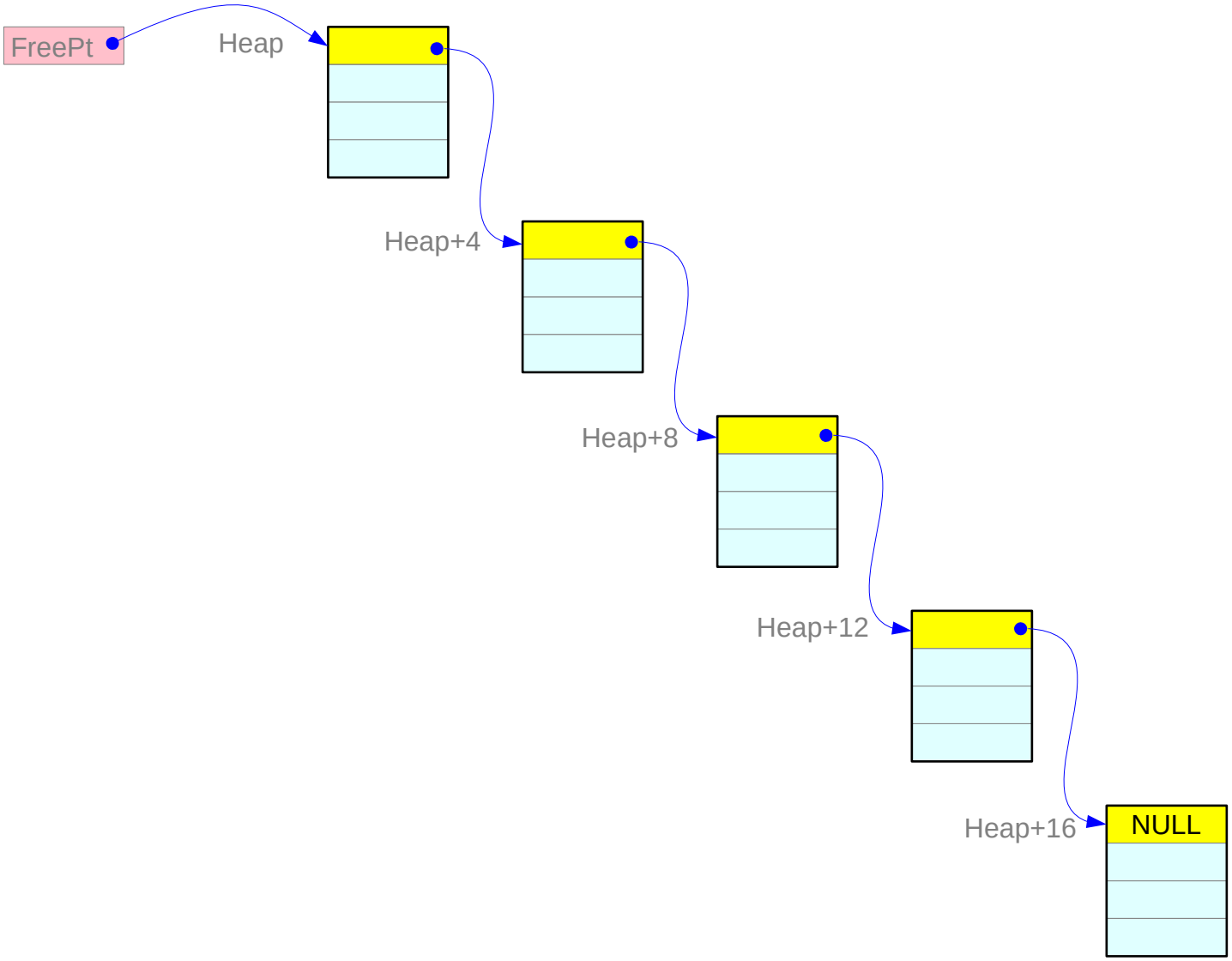
Heap_Init (3)



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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
```

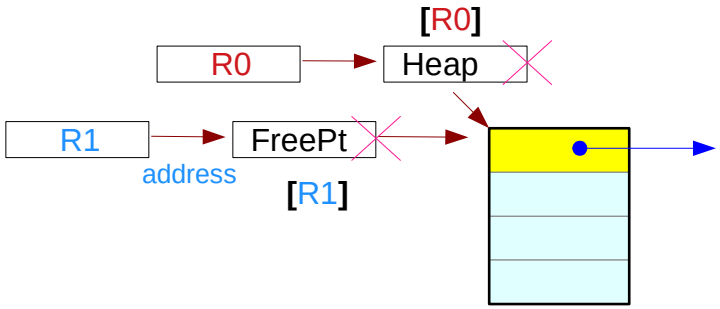
Heap_Init (2)

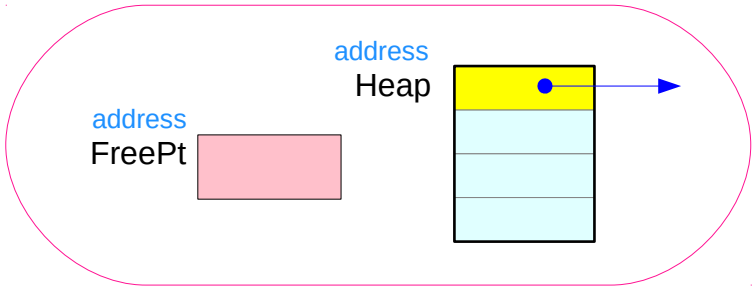
```
Heap_Init   LDR   R0, =Heap      ; pt              ; R0 ← Heap
            LDR   R1, =FreePt    ;                 ; R1 ← FreePt
            STR   R0, [R1]       ; *FreePT = Heap  ; [FreePt] ← Heap
```

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

~~[R0] ≡ Heap~~
~~[R1] ≡ FreePt~~

▼Heap, FreePt : all address labels of memory locations





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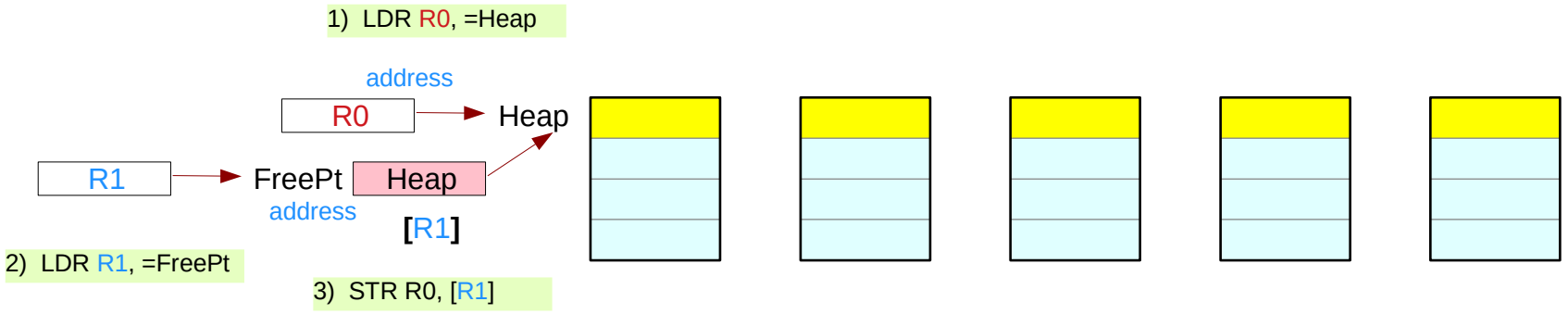
Heap_Init (3)

```
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
```

address
R0 ≡ Heap
R1 ≡ FreePt
address



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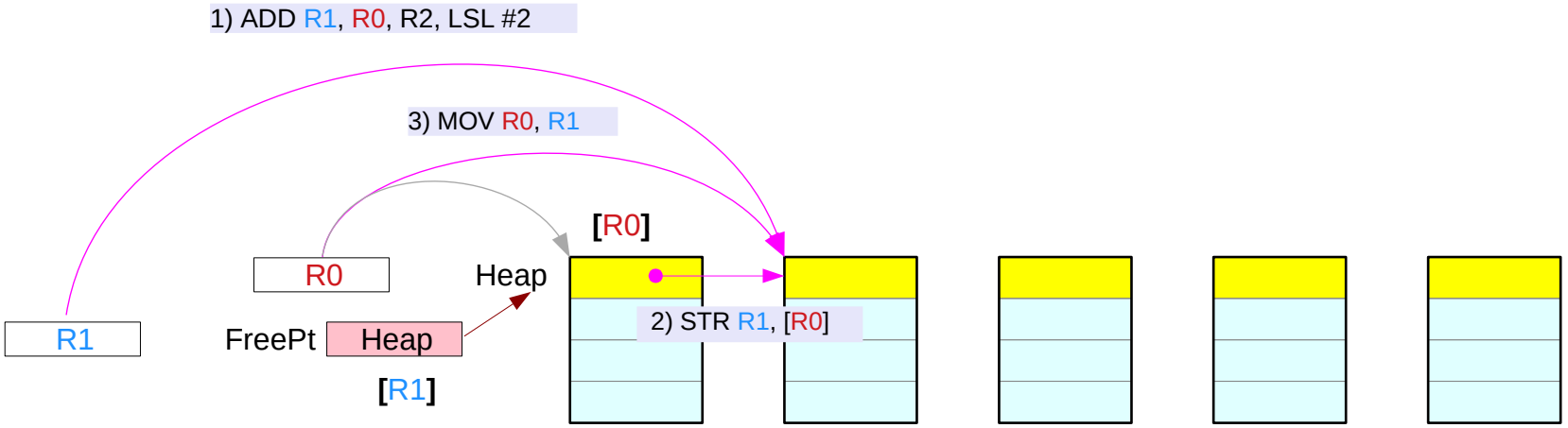
Heap_Init (4)

```
                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 ← R0 + R2*4
```

R0 ~ pt



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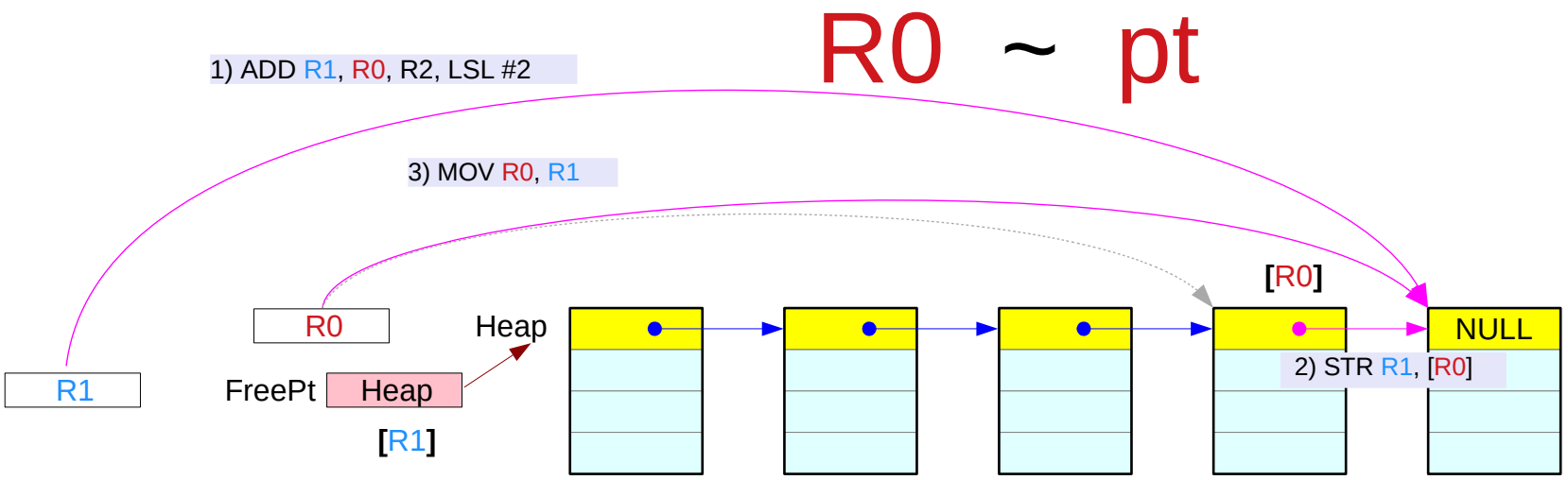
Heap_Init (5)

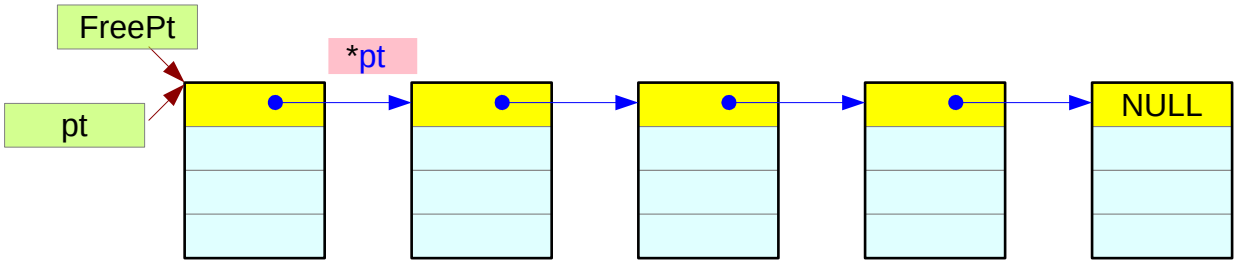
```
imLoop      ADD     R1, R0, R2, LSL #2      ;  pt + SIZE          ; R1 ← R0 + R2*4
            STR     R1, [R0]                ; *pt = pt + SIZE     ; [R0] ← R0 + R2*4
            MOV     R0, R1                  ;  pt = pt + SIZE     ; R0 ← R0 + R2*4
            SUBS    R3, R3, #1               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

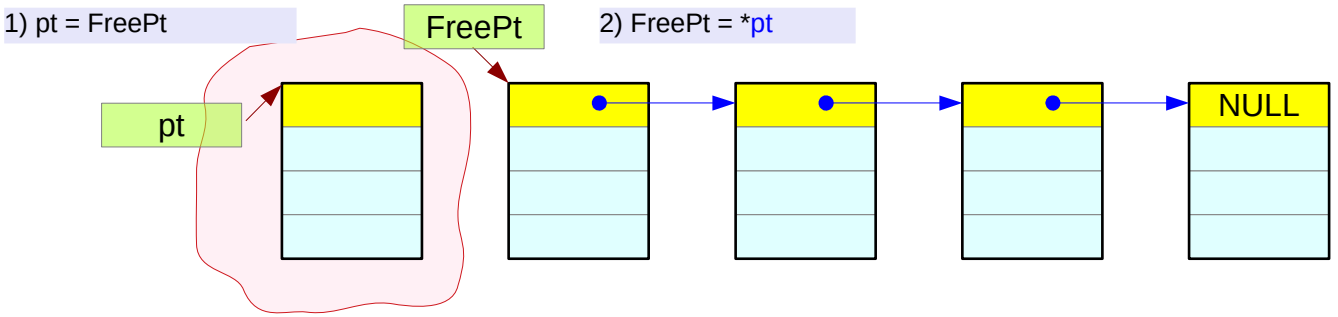


Heap_Allocate

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

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






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

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

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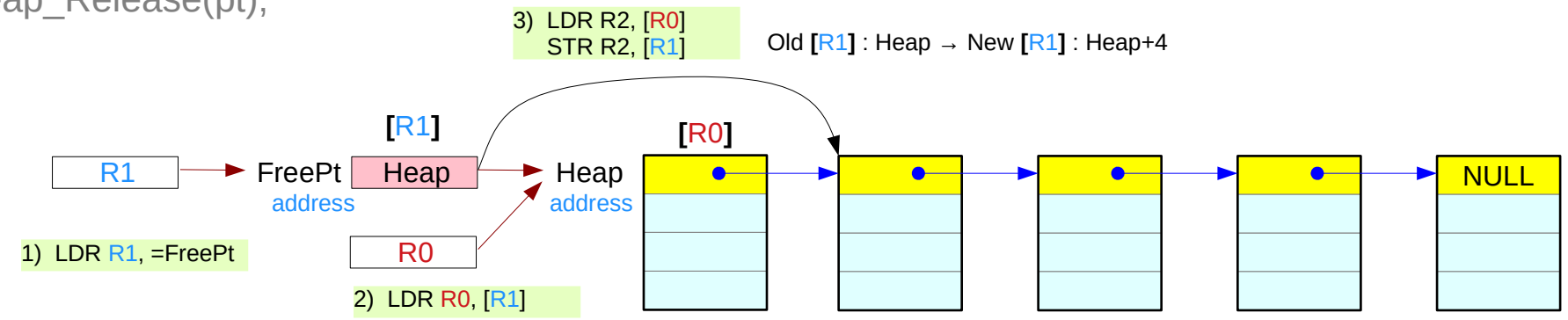
Heap_Allocate

```
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
```

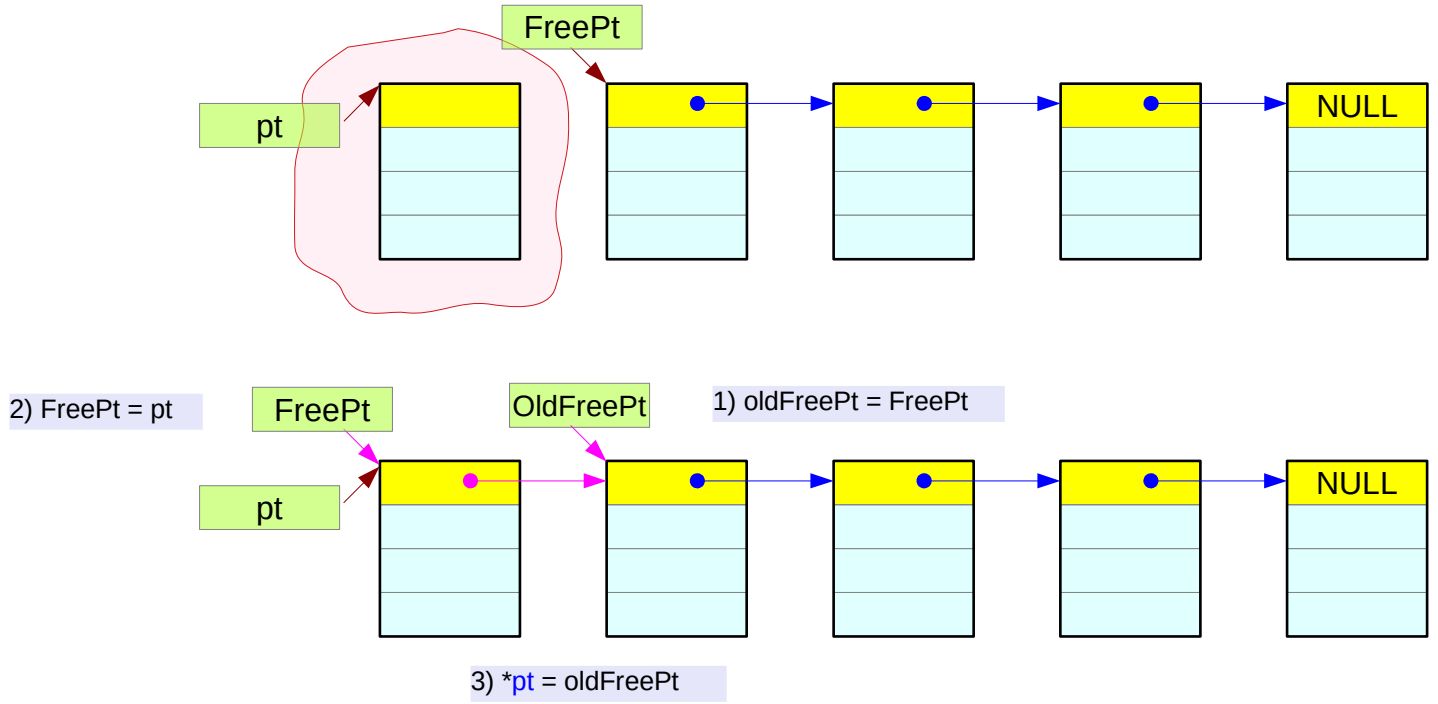
```
pt = Heap_Allocate();
Heap_Release(pt);
```



Heap_Release

```
int32_t *Heap_Release(int32_t *pt) {
        int32_t *   oldFreePt;

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



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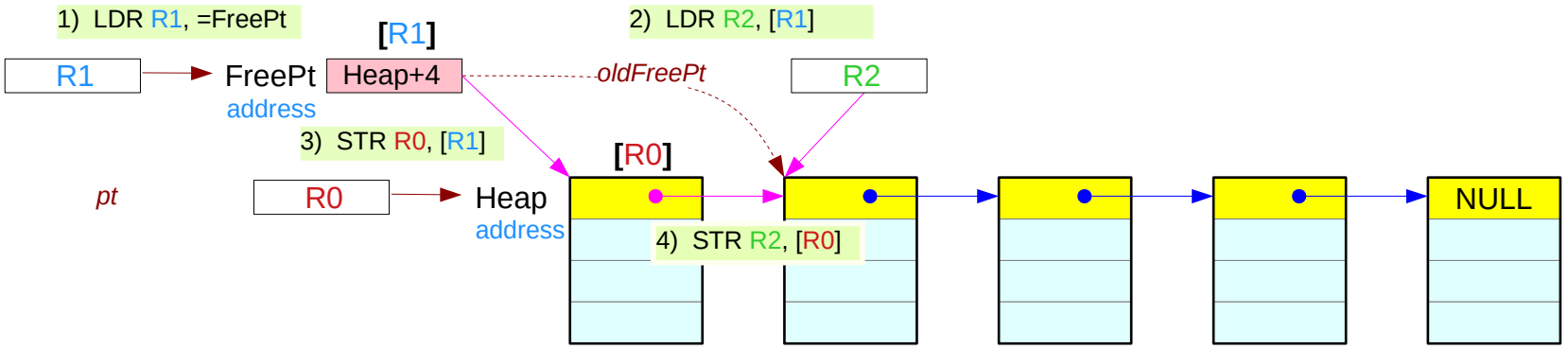
Heap_Release

```
Heap_Release:                          ; R0 : block being released pt
        LDR     R1, =FreePt
        LDR     R2, [R1]               ; R2 : oldFreePt
        STR     R0, [R1]               ; FreePt = pt
        STR     R2, [R0]               ; *pt=oldFreePt
        BX      LR
```



Fifo

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

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

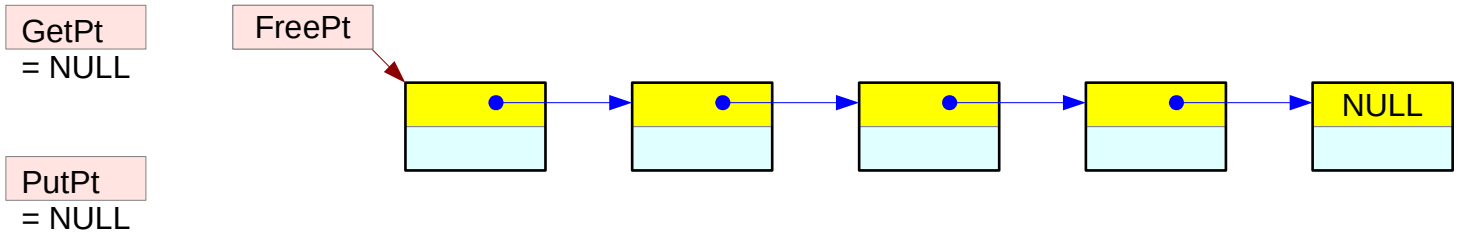
```
; put in RAM
NEXT    EQU     0     ; next
Data    EQU     4     ; 32-bit data for node

GetPt   SPACE   4     ; pointer to oldest node
PutPt   SPACE   4     ; pointer to newest node
```

Fifo_Init

C code

```
void Fifo_Init(void) {
      GetPt = NULL;                  // Empty when null
      PutPt = NULL;
      Heap_Init();
}
```



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
```

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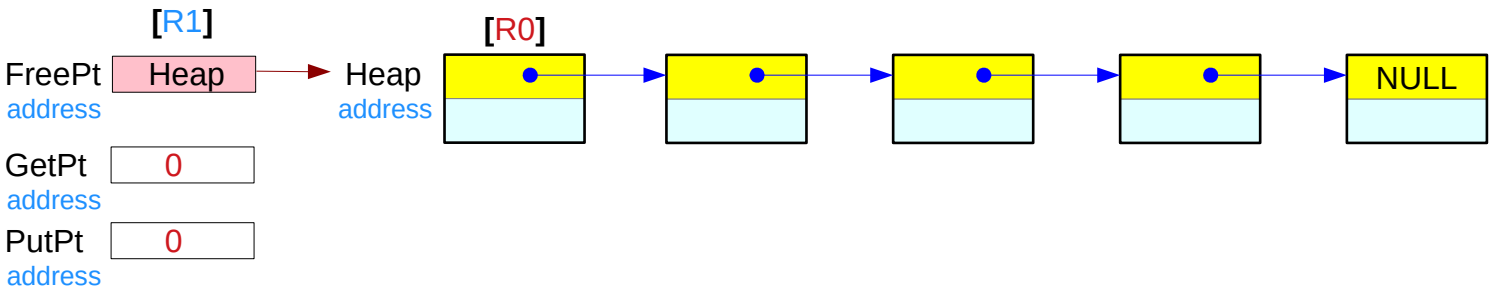
Fifo_Init

```
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



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Fifo_Put

C code

```
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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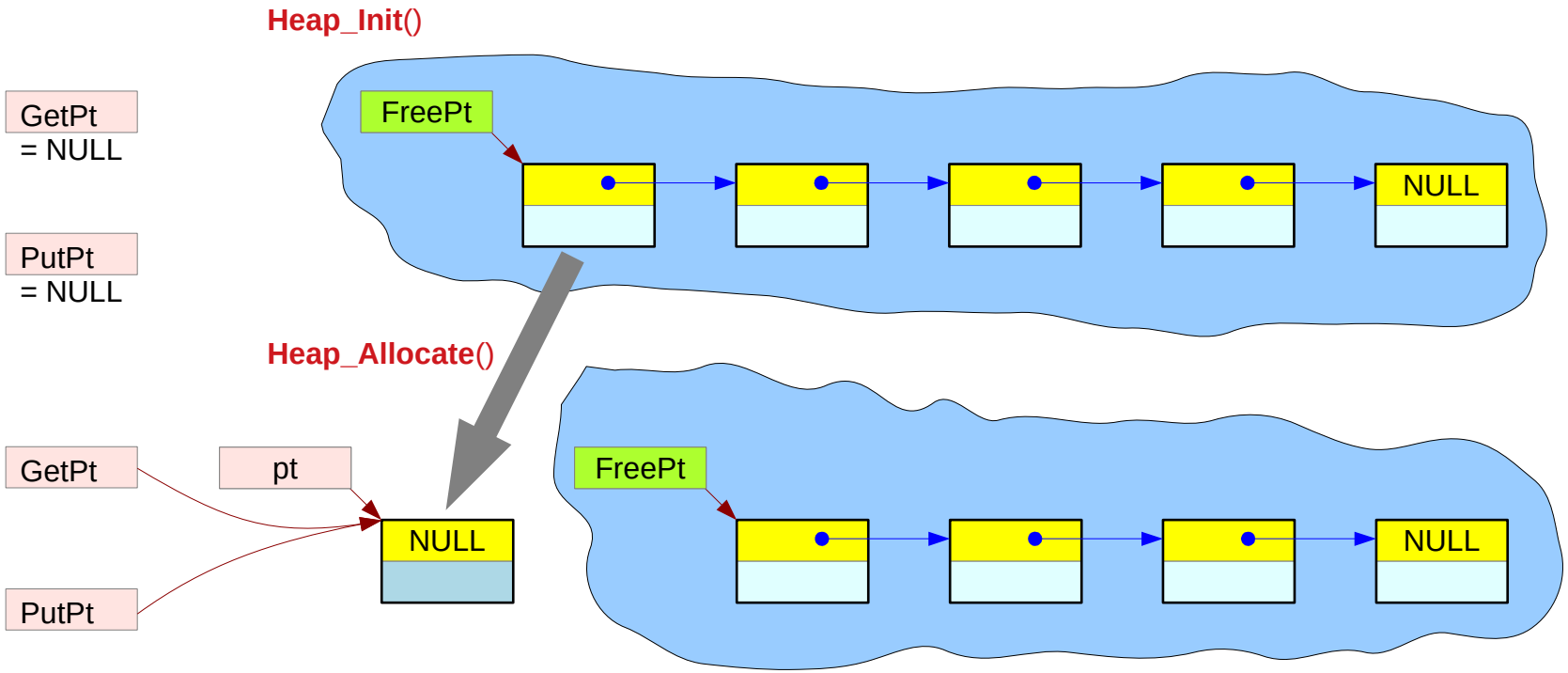
Fifo_Put – first put

C code




```
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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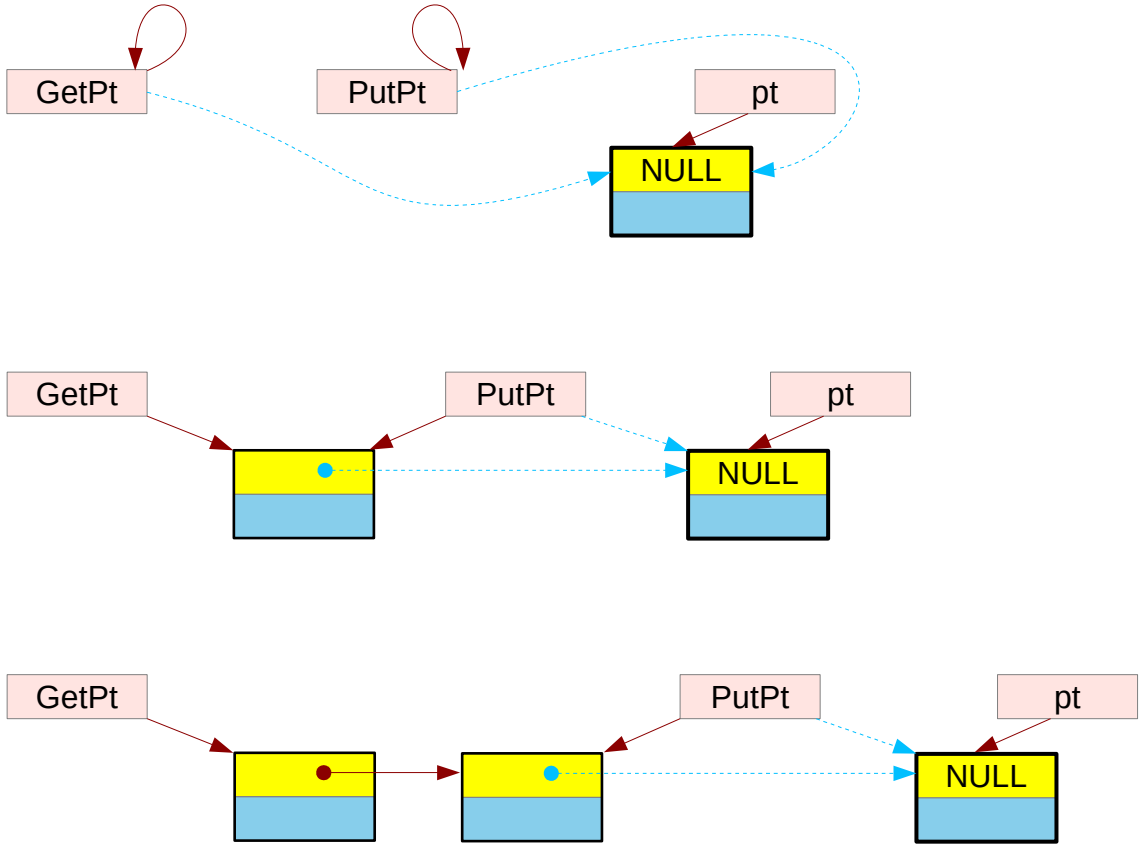
Fifo_Put – subsequent puts

C code




```
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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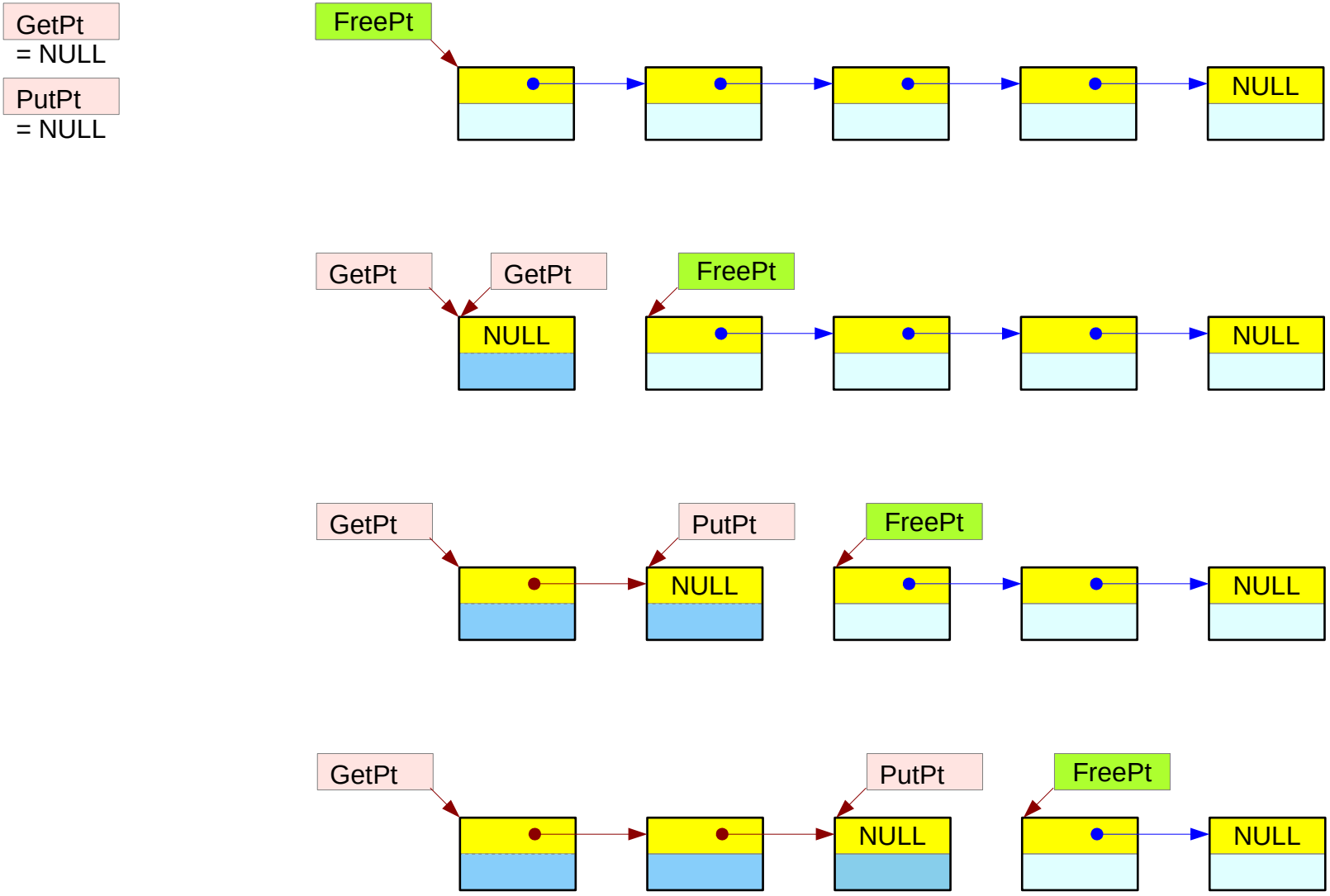
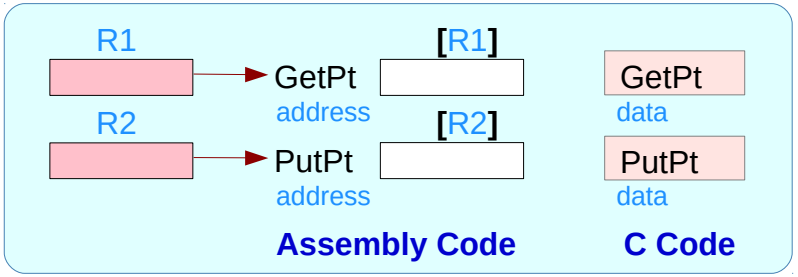

GetPt
= NULL
PutPt
= NULL
FreePt
NULL
GetPt
GetPt
FreePt
NULL
NULL
GetPt
PutPt
FreePt
NULL
NULL
GetPt
PutPt
FreePt
NULL
NULL

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);
}
```

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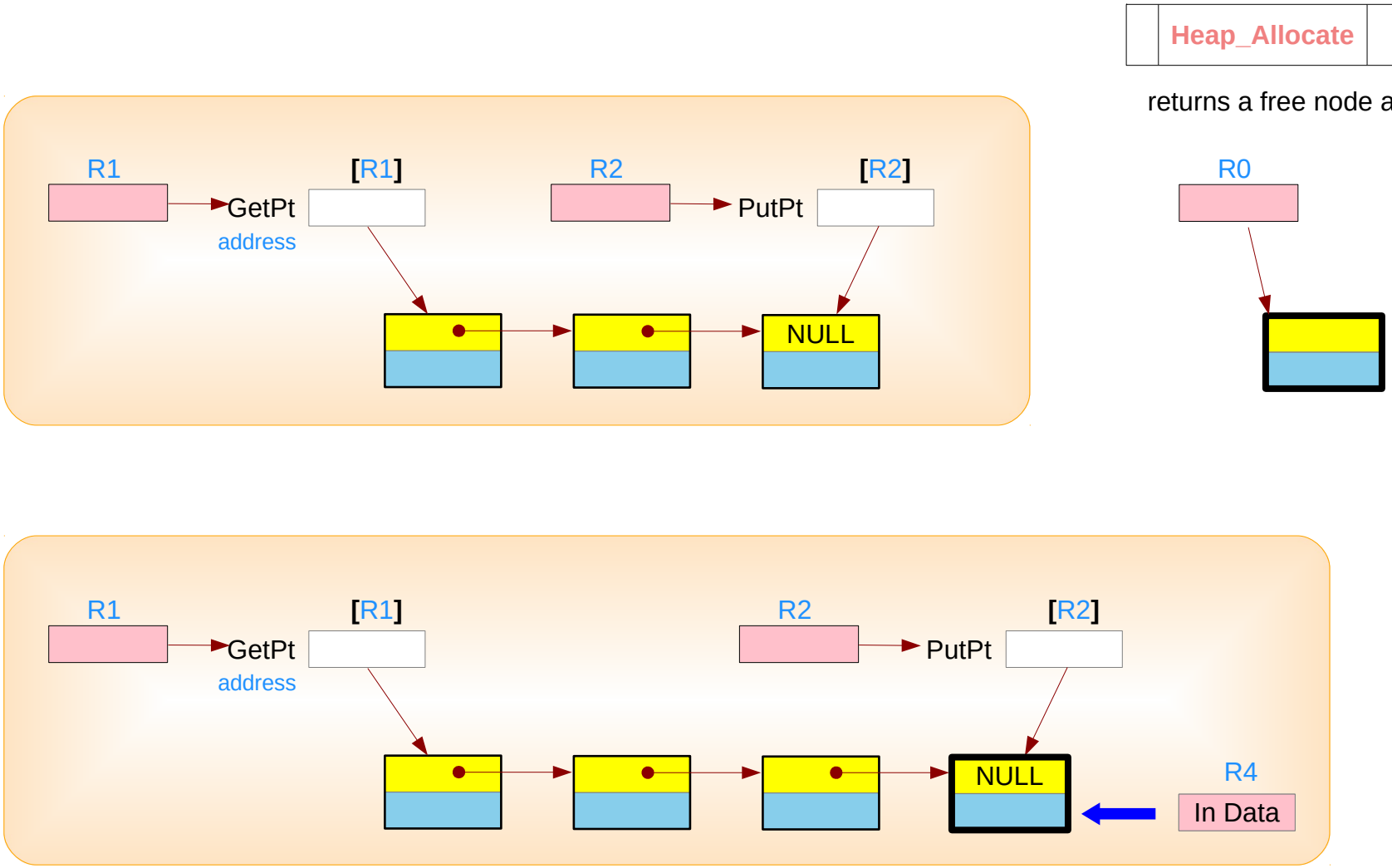
Fifo_Put – put operation



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Fifo_Put – flow chart view

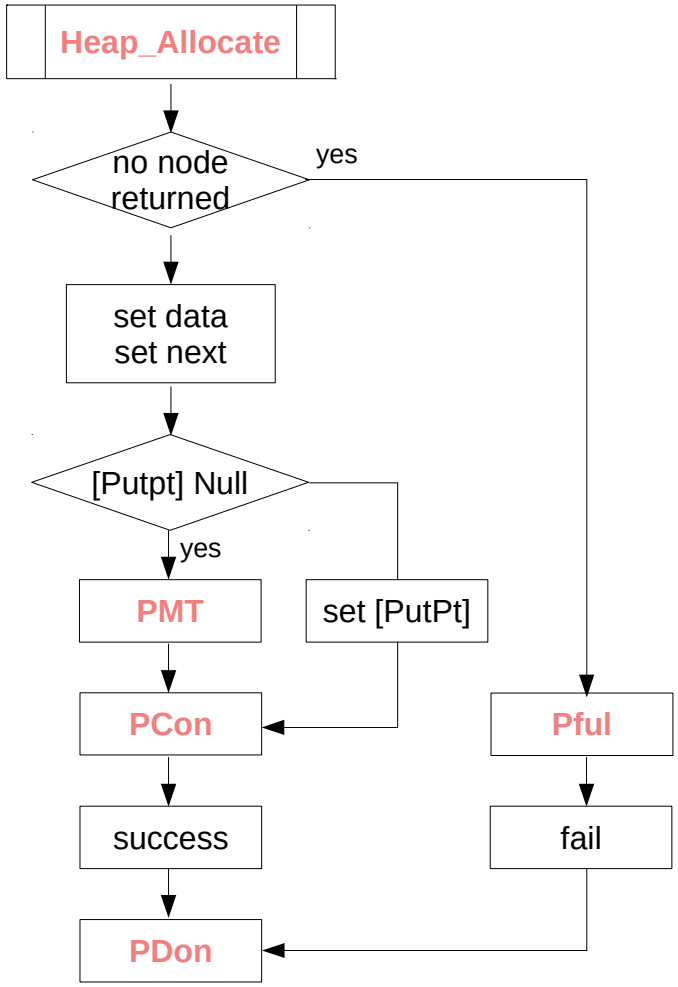
```
Fifo_Put
        PUSH {R4, LR}
        MOV  R4, R0
BL      Heap_Allocate
        CMP  R0, #NULL
        BEQ  Pful
        STR  R4, [R0, #Data]
        MOV  R1, #NULL
        STR  R1, [R0, #Next]
        LDR  R2, =PutPt
        LDR  R3, [R2]
        CMP  R3, #NULL
        BEQ  PMT
        STR  R0, [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



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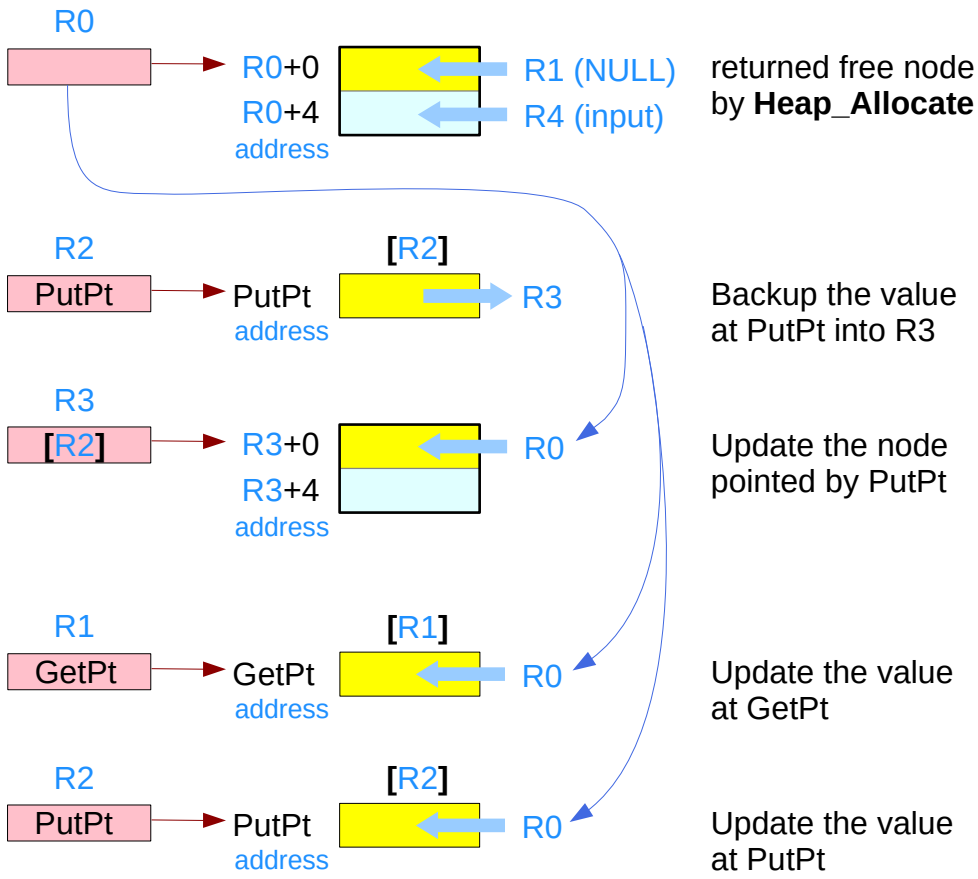
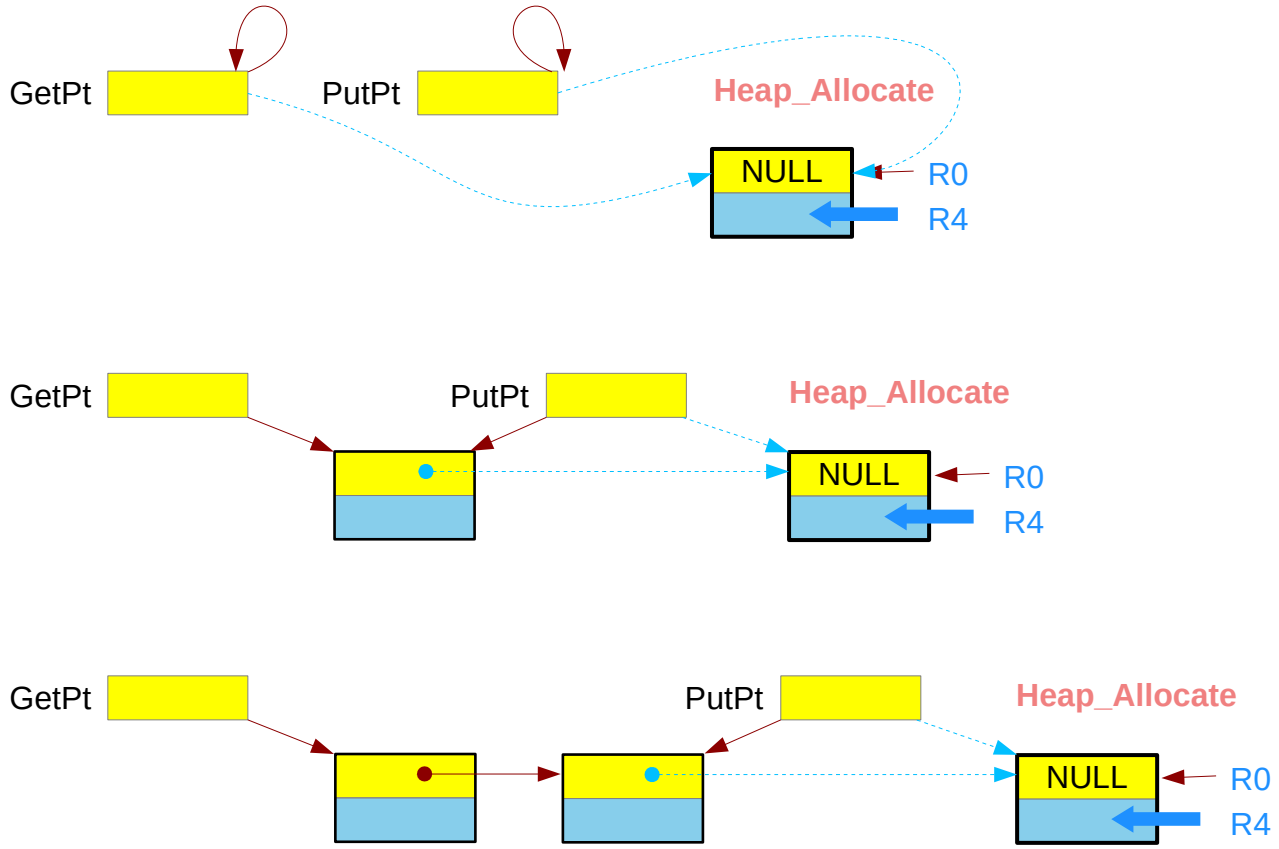
Fifo_Put – load and store view

```
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}
```



Fifo_Put – example cases

```
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}
```



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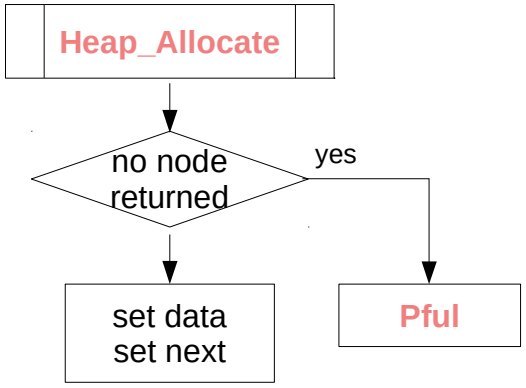
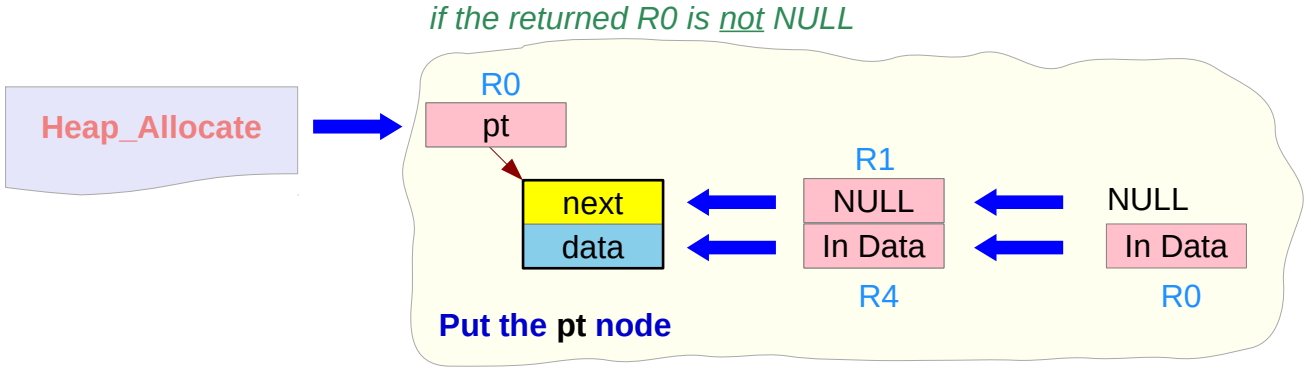
Fifo_Put – detailed view (1)

```
; 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
```





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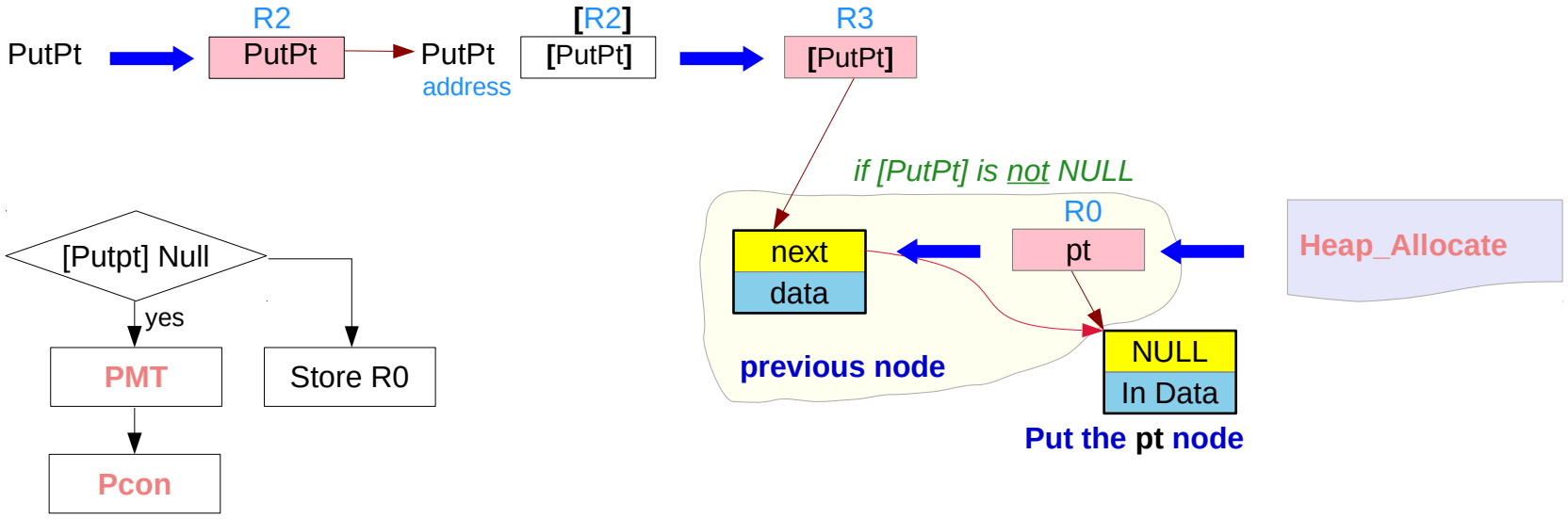
R4 : In Data

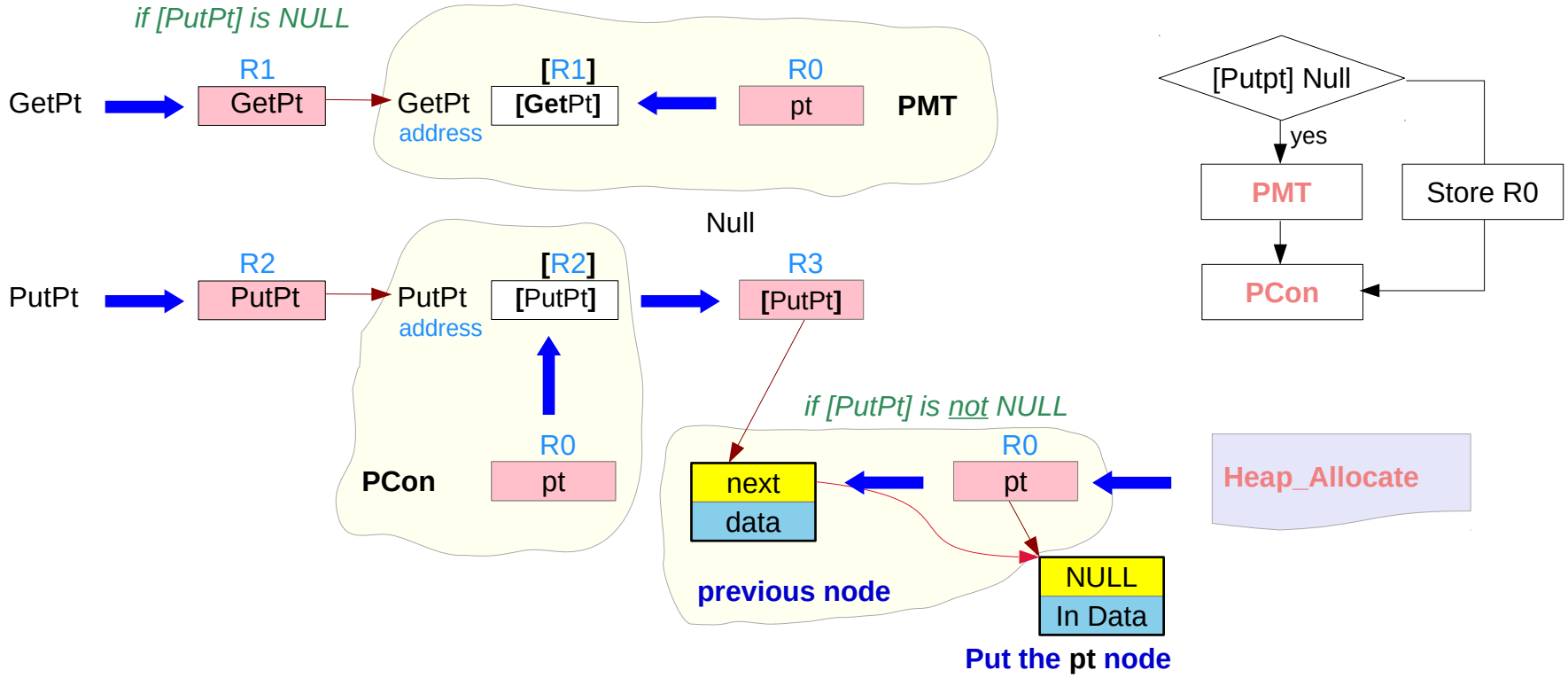
Fifo_Put – detailed view (2)

```
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
```



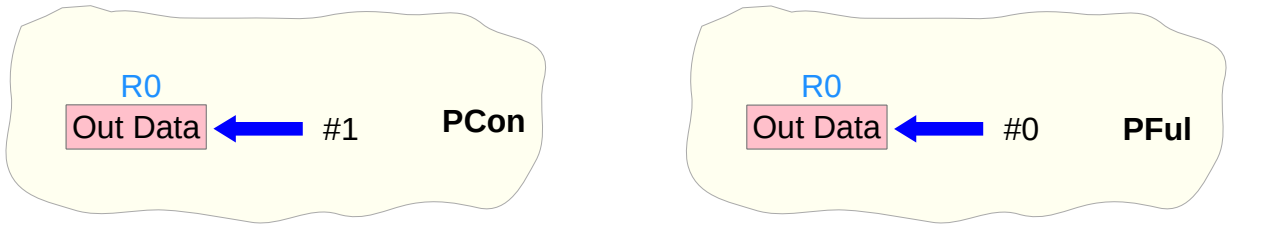
Fifo_Put – detailed view (3)

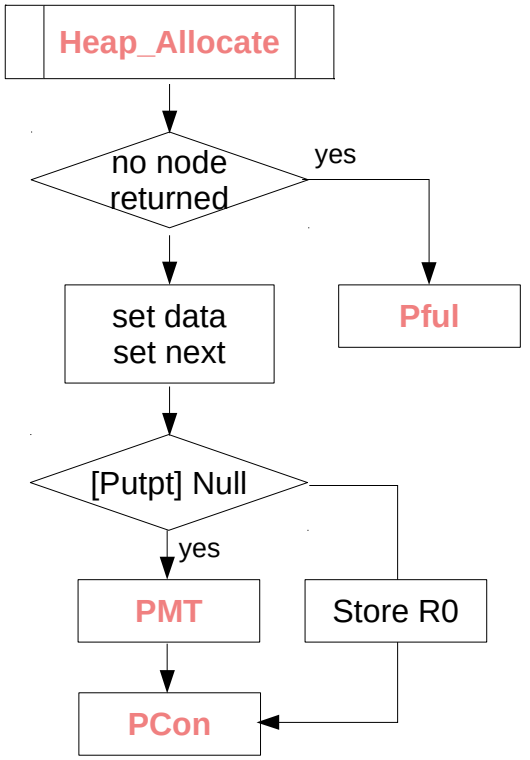
```
PMT     LDR   R1, =GetPt    ; address GetPt     ; R1 ← GetPt (address)
        STR   R0, [R1]      ; Get node address  ; R0 → [GetPt] (content)
PCon    STR   R0, [R2]      ; Points to newst   ; R0 → [PutPt]
                            ; Now one entry
```



Fifo_Put – detailed view (4)

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





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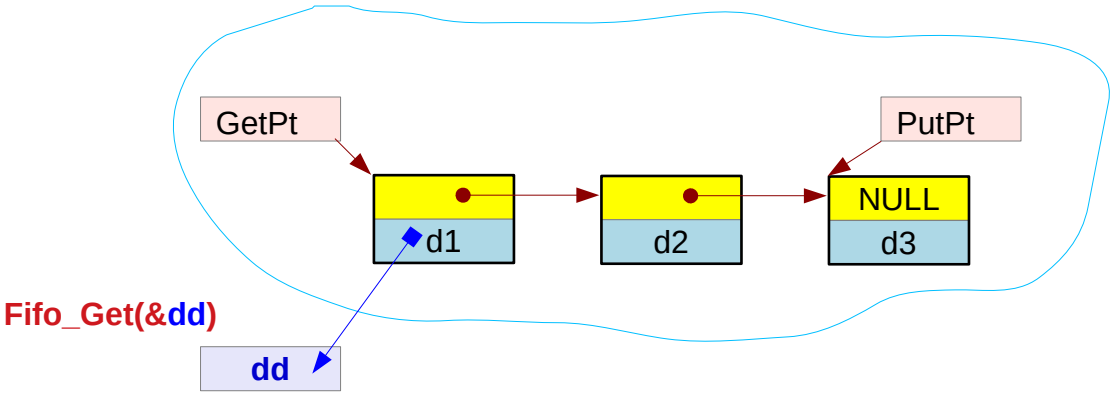
Fifo_Get

C code

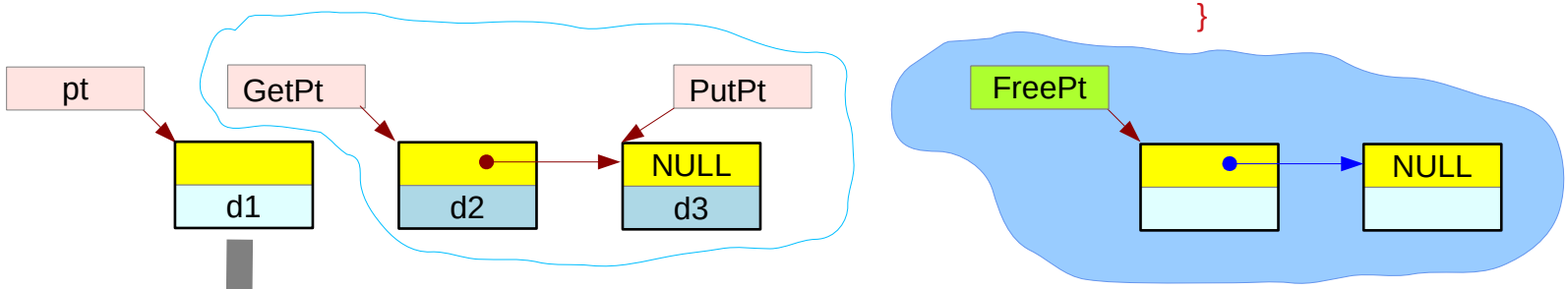
```
Int Fifo_Get(int32_t *datapt) {
        NodeType *pt;

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

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

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

        Heap_Release((int32_t *) pt);

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

Fifo_Get Examples (1)

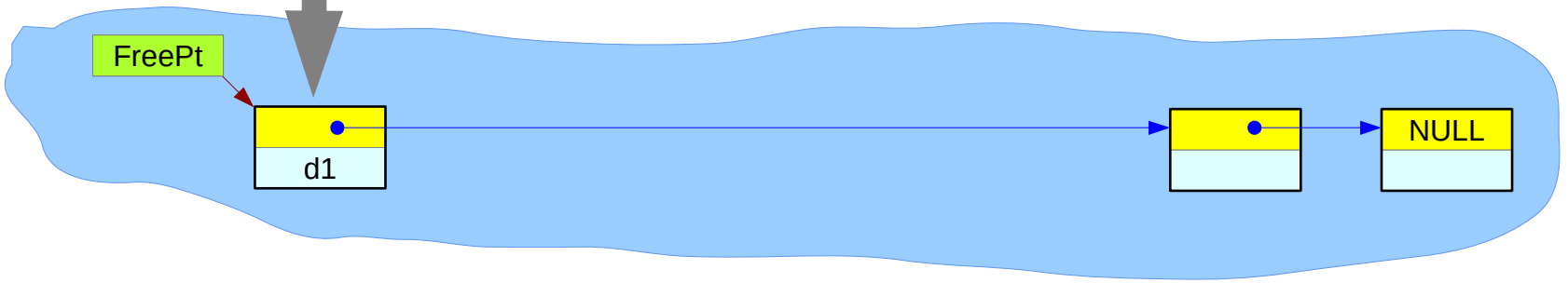
C code




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



Heap_Release((int32_t *) pt);



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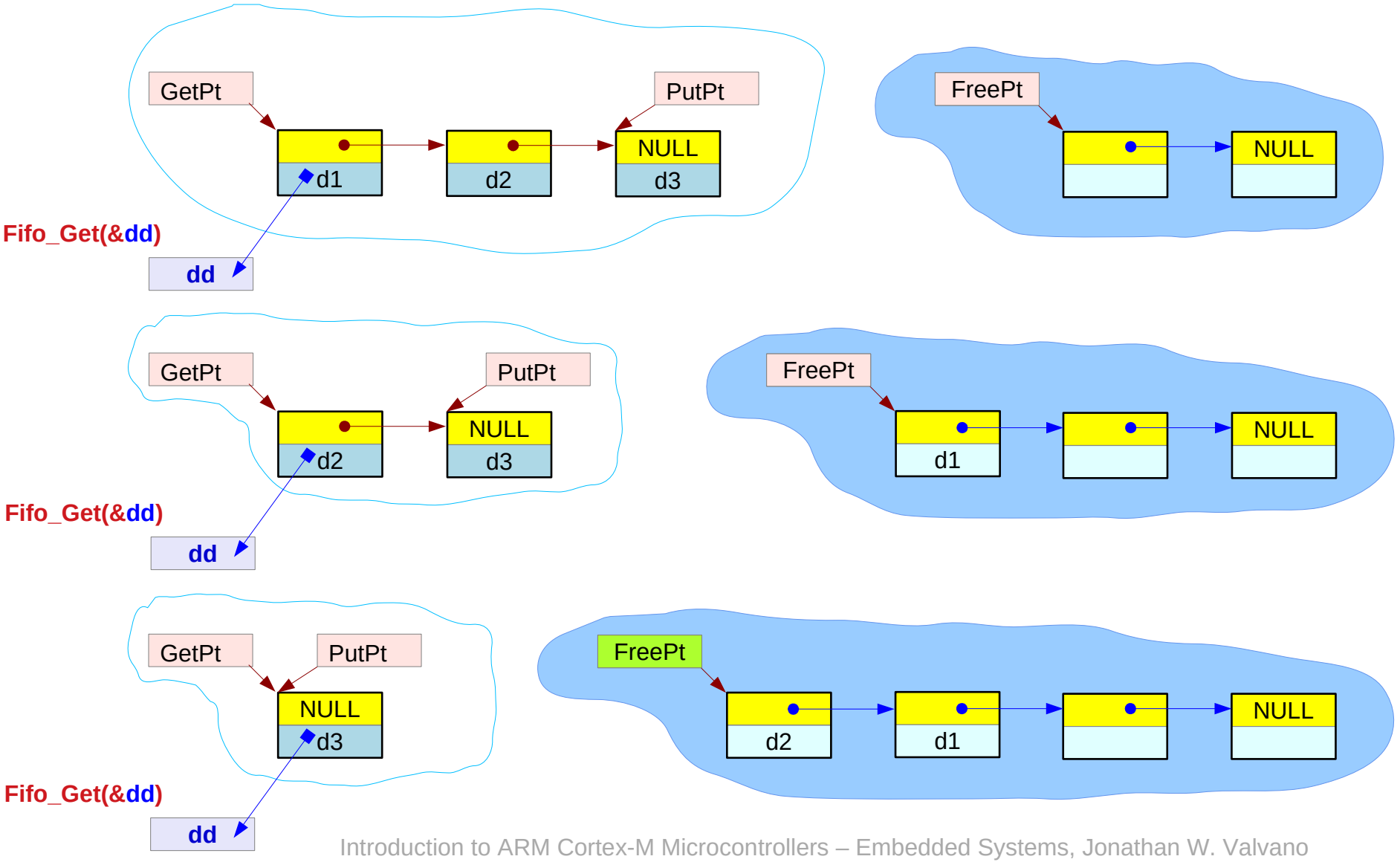
Fifo_Get Examples (2)

C code



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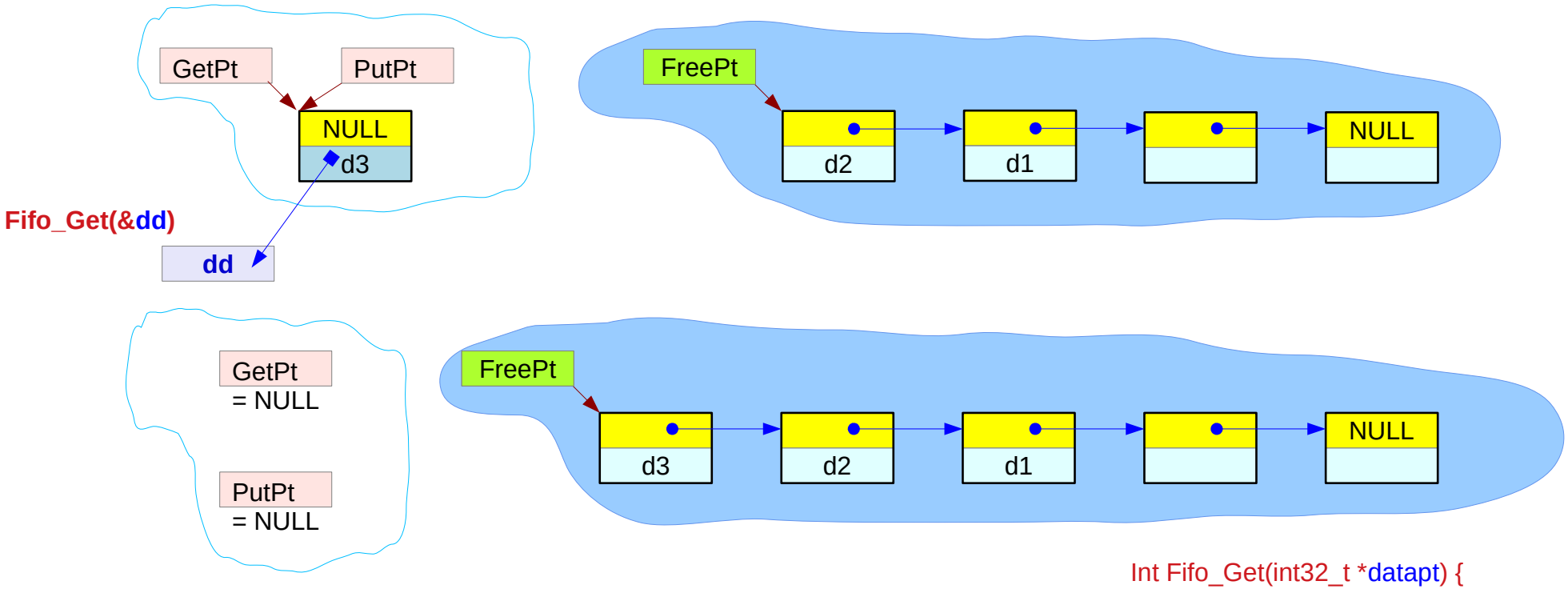
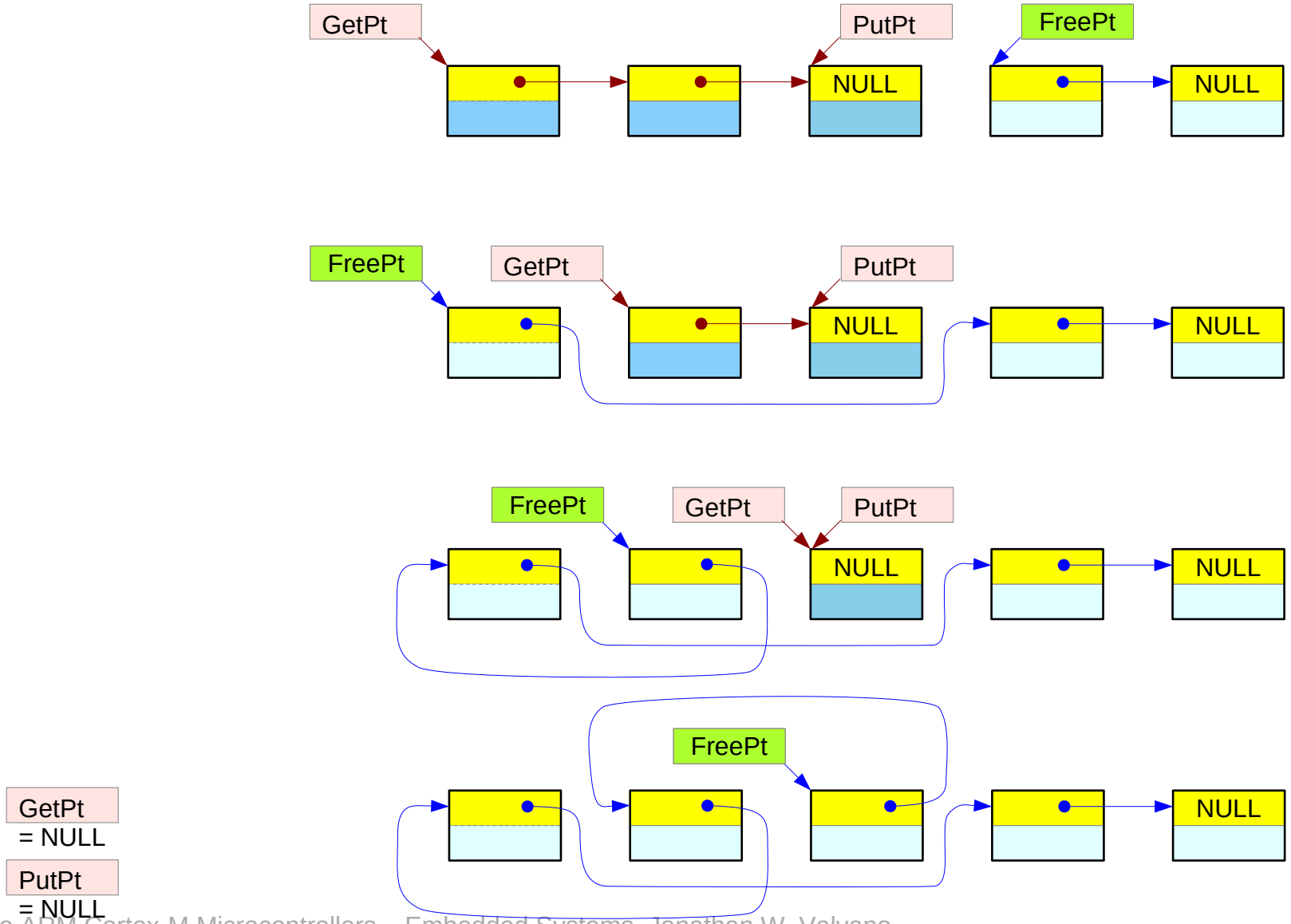
Fifo_Get Examples (3)

C code




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

Fifo_Get



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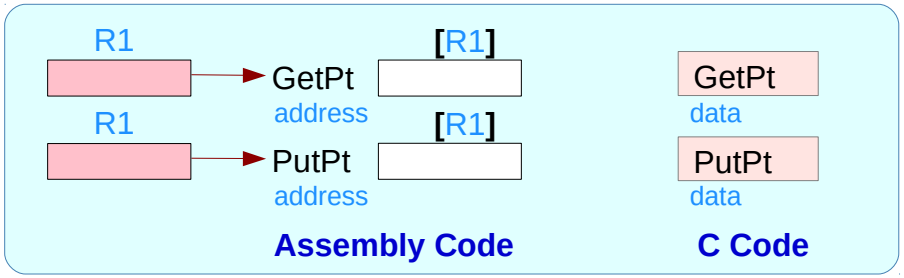
Fifo_Get – overview




```
; 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 *datapt)
              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)
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}
```

```
int Fifo_Get(int32_t *datapt) {
        NodeType *pt;

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

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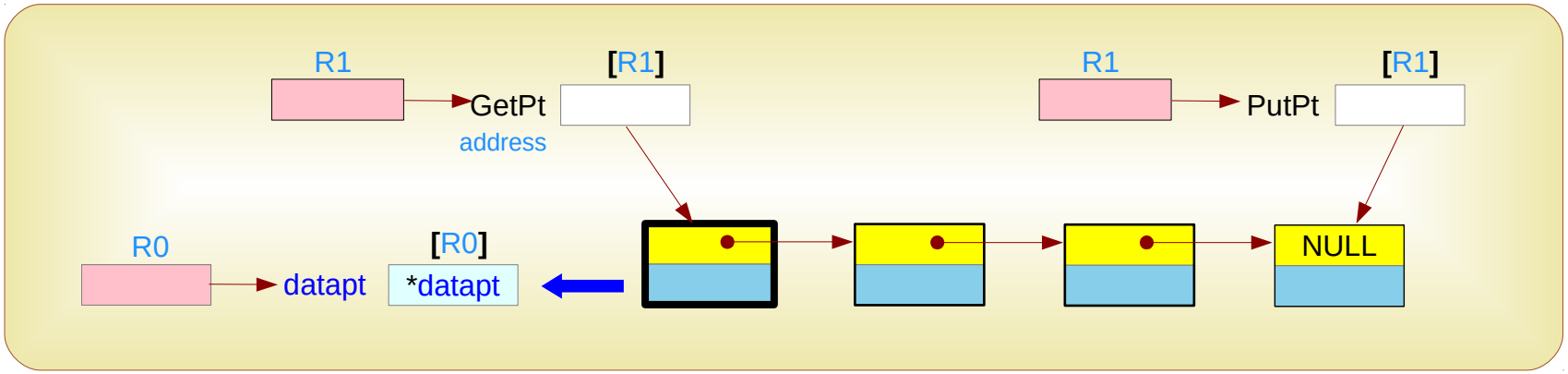
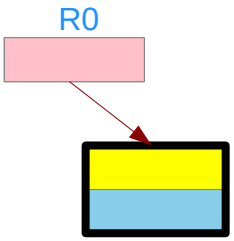
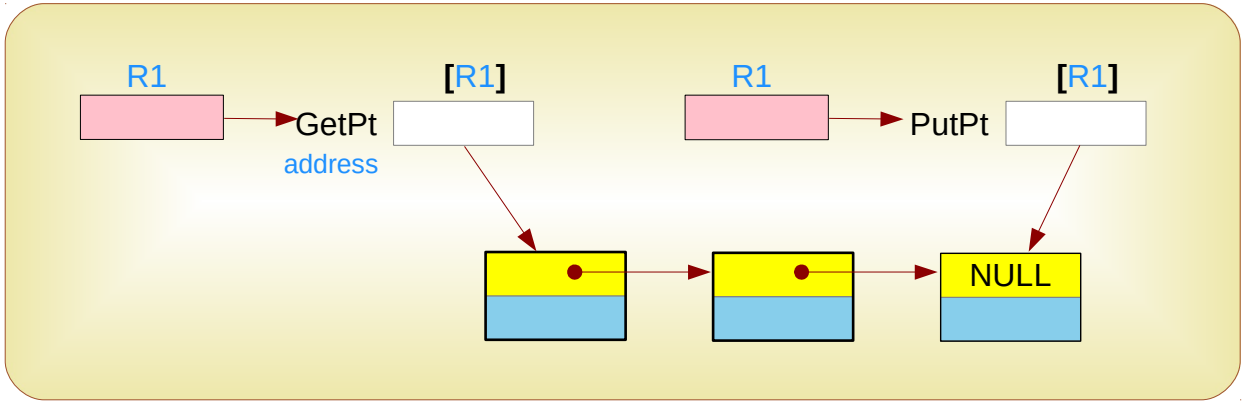
Fifo_Get – get operation





argument : a release node address



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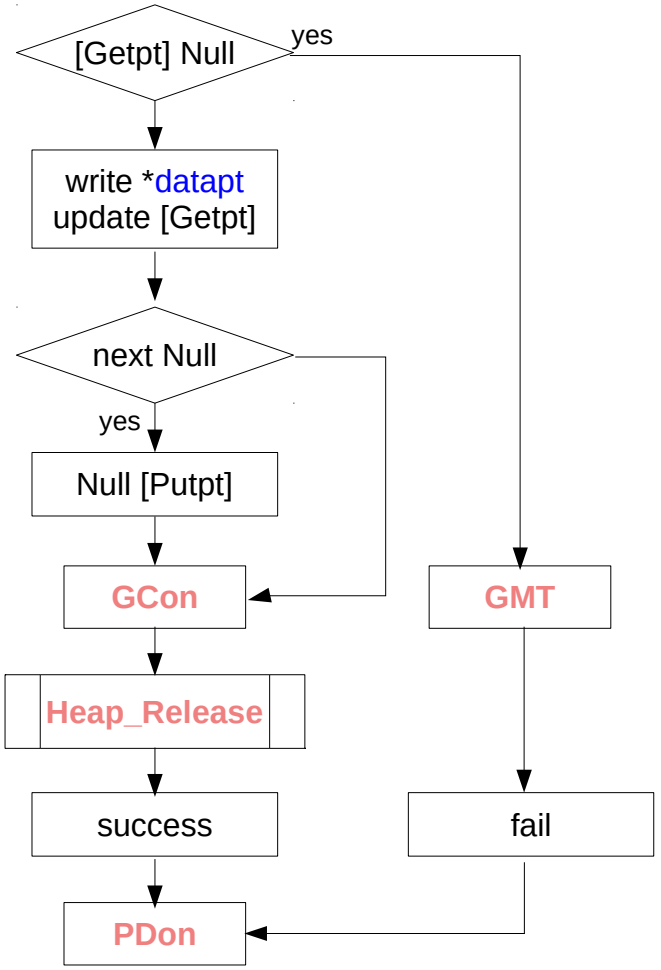
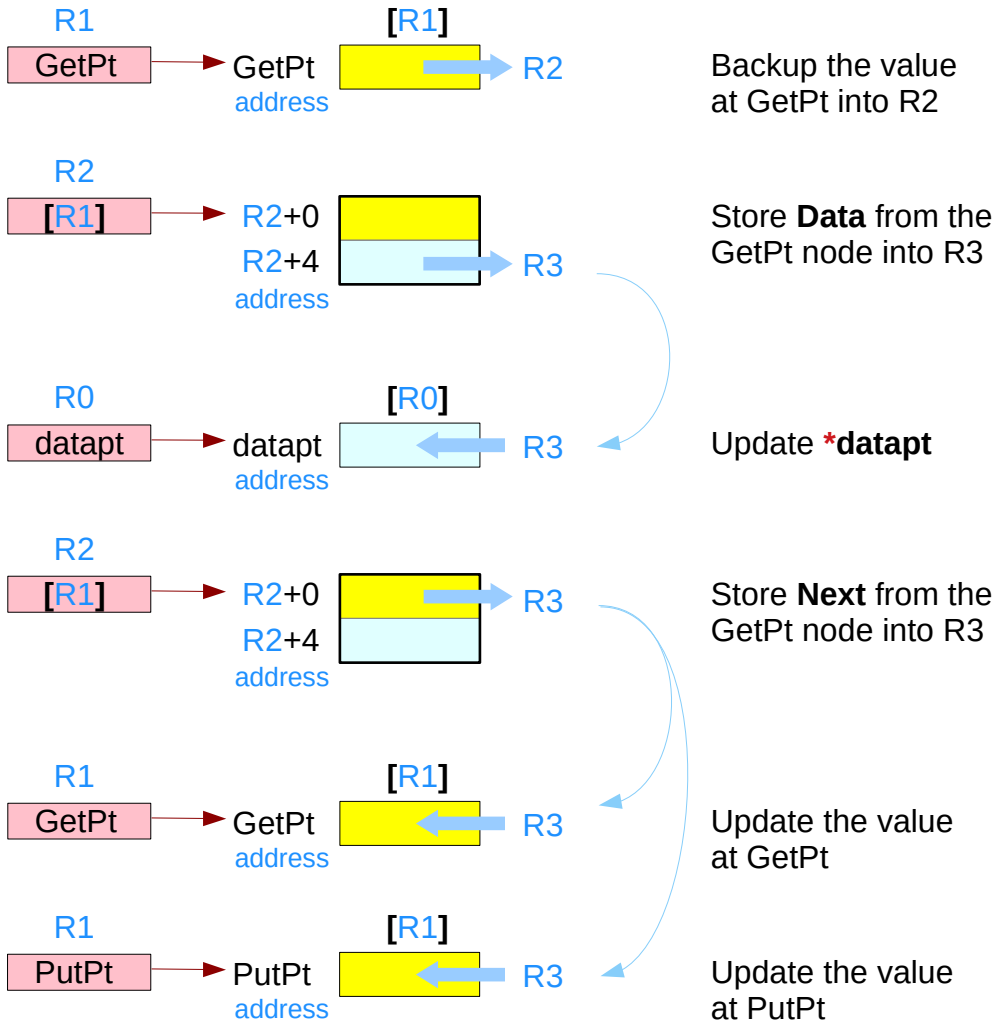
Fifo_Get – flow char view

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



Fifo_Get – load and store view

```
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}
```



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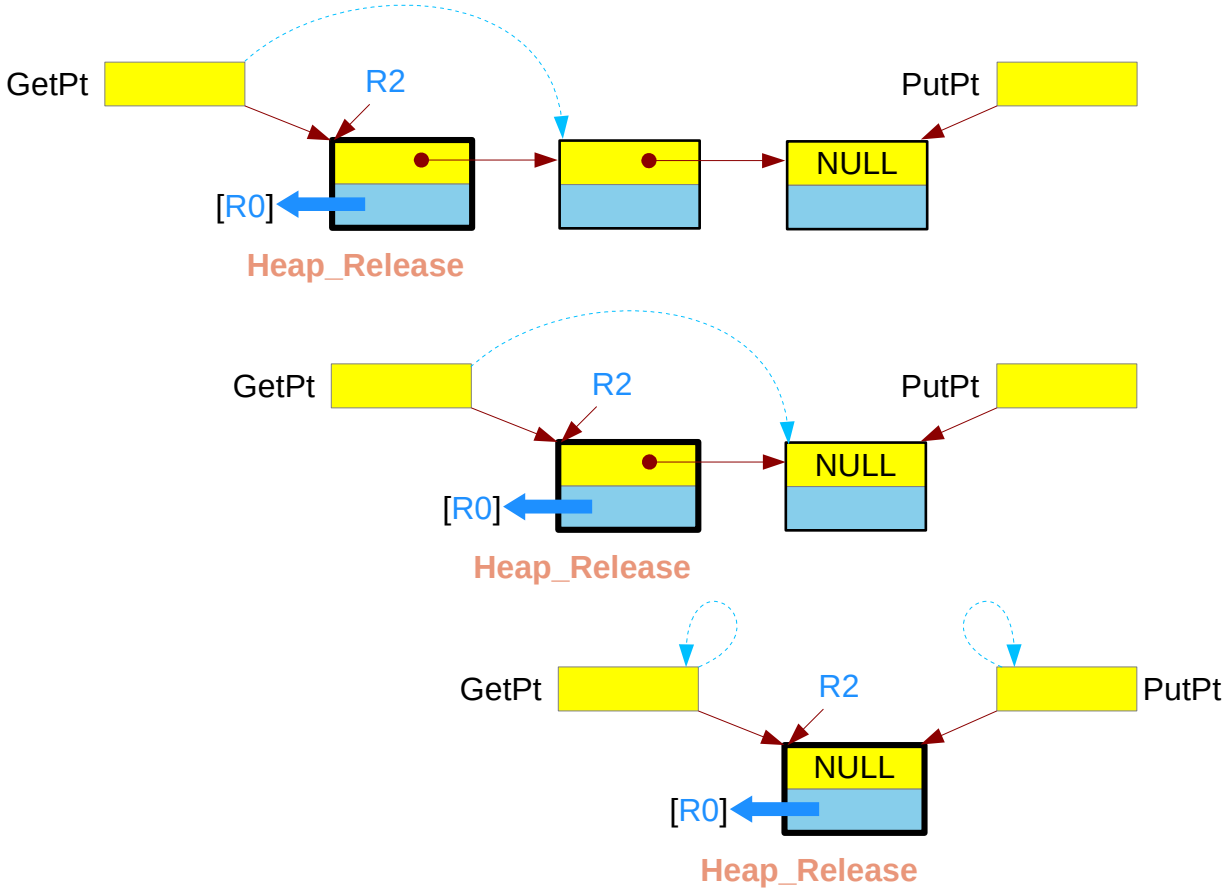
Fifo_Get – example cases

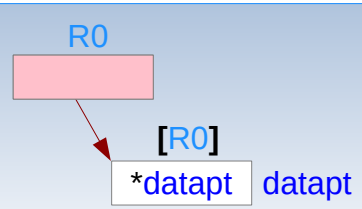
```
Fifo_Get
        PUSH {R4, LR}
        LDR  R1, =GetPt
        LDR  R2, [R1]
        CMP  R2, #NULL
        BEQ  GMT
        LDR  R3, [R2, #Data]
        STR  R3, [R0]
        LDR  R3, [R2, #Next]
        STR  R3, [R1]
        CMP  R3, #NULL
        BNE  GCon
        LDR  R1, =PutPt
        STR 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

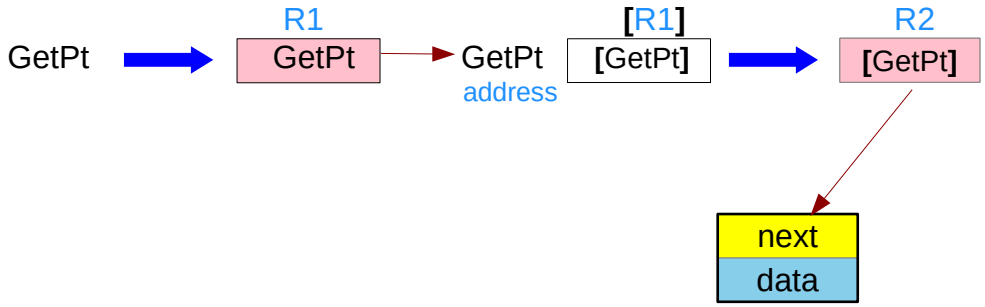


Fifo_Get – detailed view (1)

```
; 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)
```

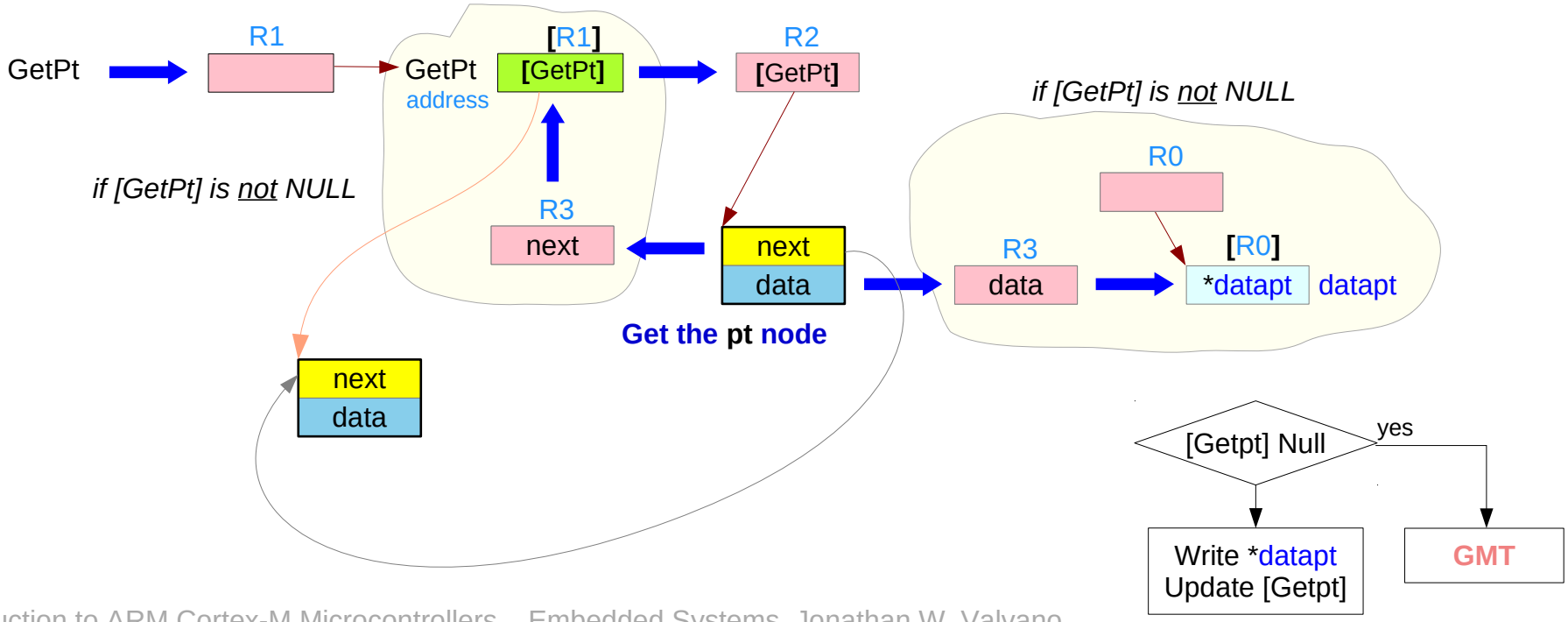




Get the pt node

Fifo_Get – detailed view (2)

```
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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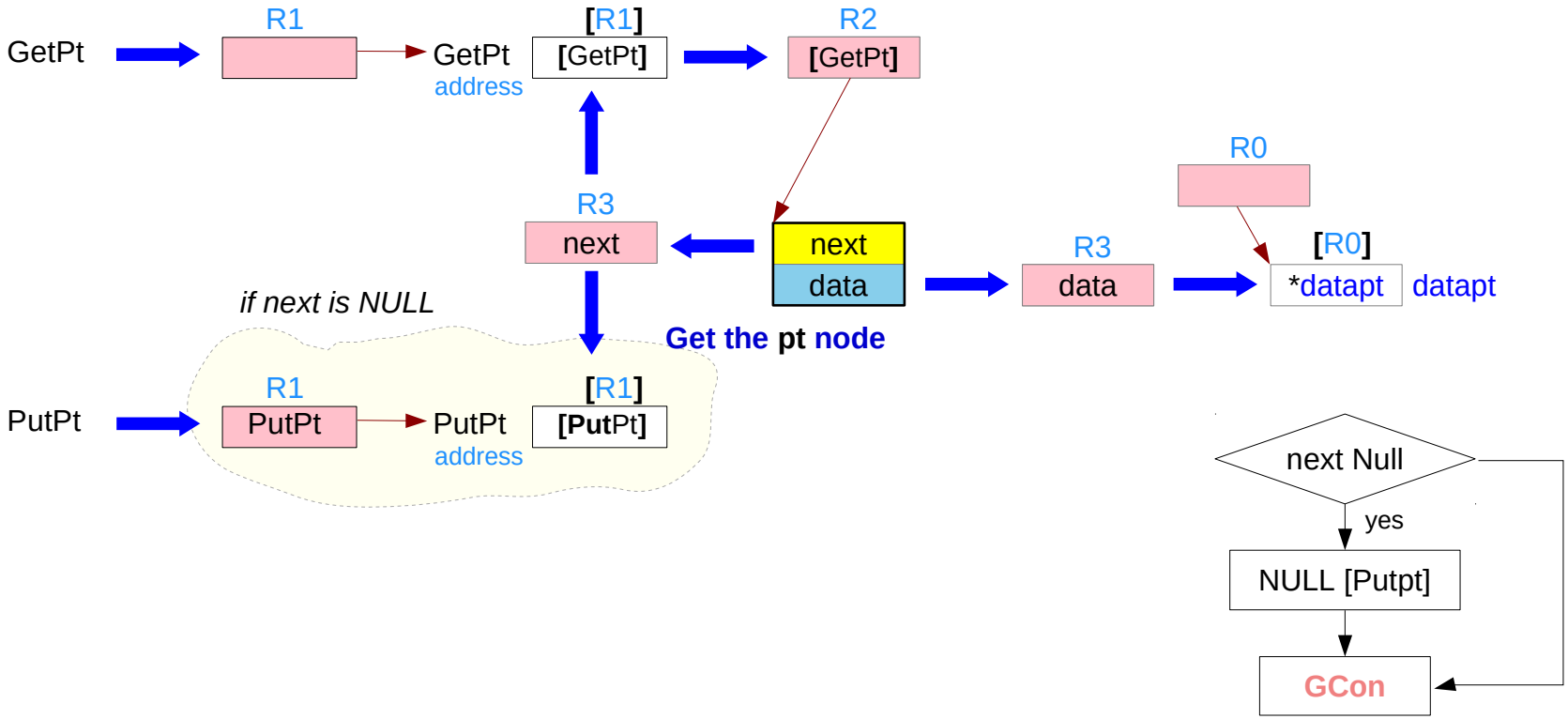
Fifo_Get – detailed view (3)

```
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)
```



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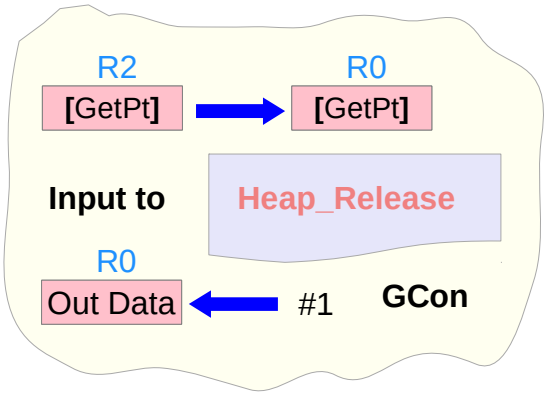
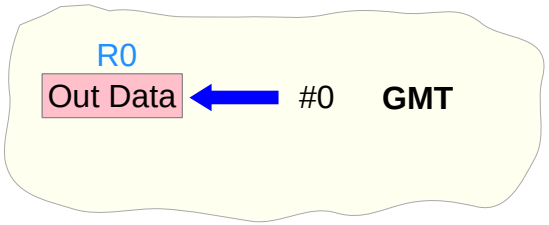
Fifo_Get – detailed view (4)

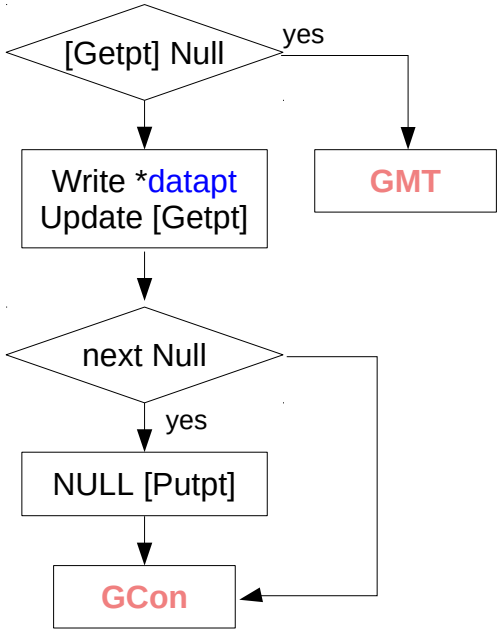
```
GCon    MOV   R0, R2          ; old data      ; R0 ← [GetPt]  ; input arg
        BL    Heap_Release
        MOV   R0, #1          ; success
        B     GDon
GMT     MOV   R0, #0          ; failure, empty
GDon    POP   {R4, PC}
```

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

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

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

byte matrix uint8_t M[2][3];

Base → (0,0)
Base + (3*i + j) → (0,2)

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

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

halfword matrix uint16_t M[2][3];

Base → (0,0)
Base + 2*(3*i + j) → (0,2)

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

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

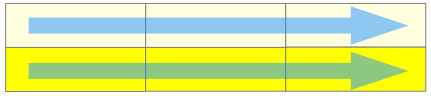
word matrix uint32_t M[2][3];

Base → (0,0)
Base + 4*(3*i + j) → (0,2)

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

row major order vs column major order

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



uint8_t M[2][3];

byte matrix – row major order

Base → (0,0)

(0,1)

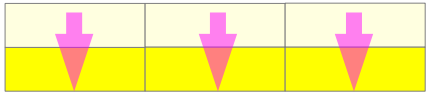
Base + (3*i + j) → (0,2)

(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 – column major order

Base → (0,0)

(1,0)

(0,1)

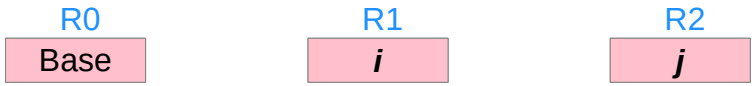
(1,1)

Base + (2*j + i) → (0,2)

(1,2)

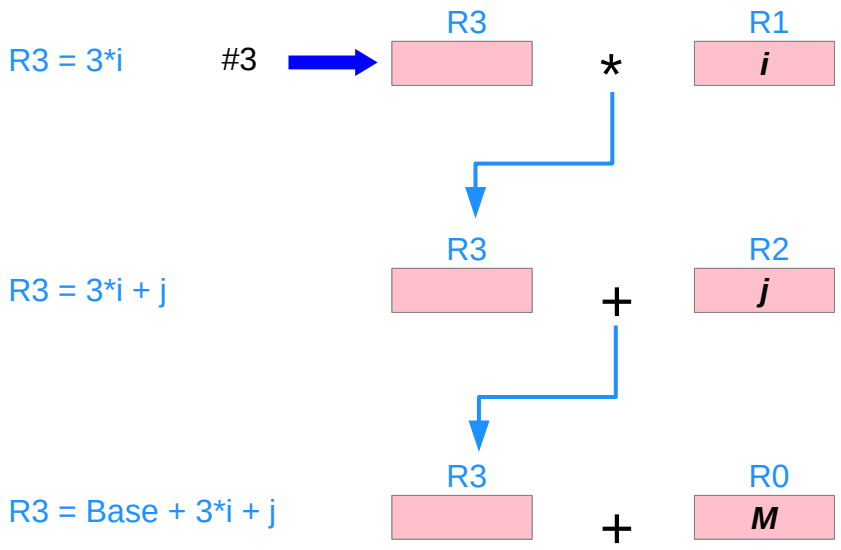
Matrix

```
; 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
```

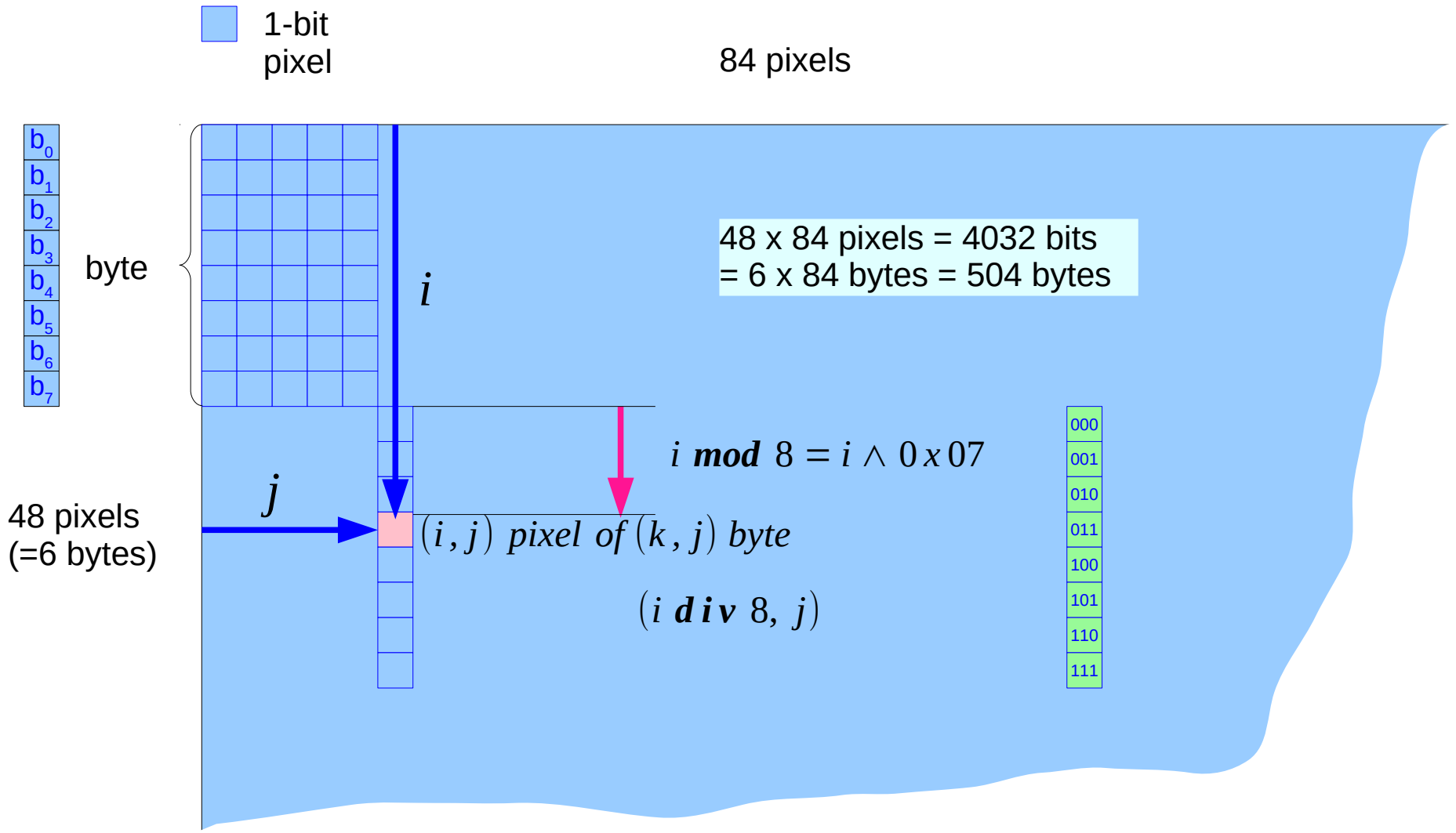


Matrix

```
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
```

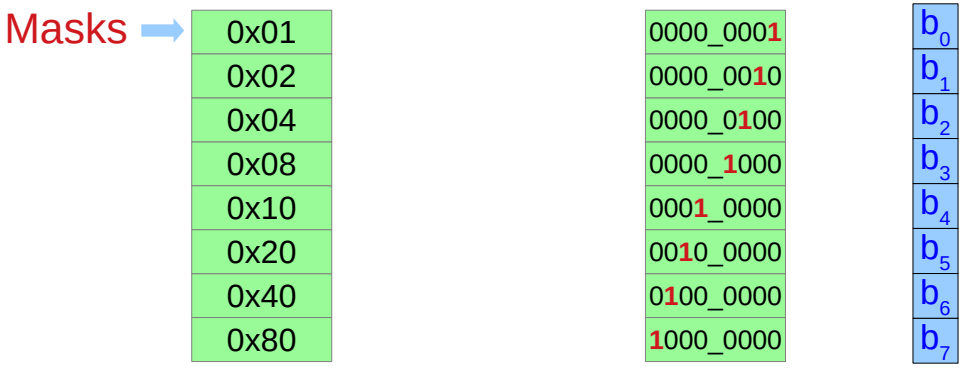


48 x 84 B/W Image



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

fcb 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>)

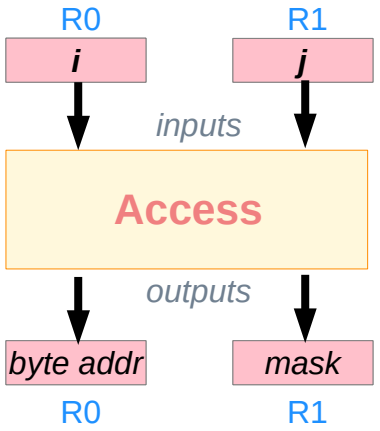
The FCB directive may have one or more operands separated by commas. The value of each operand is truncated to eight bits, and is stored in a single byte of the object program. Multiple operands are stored in successive bytes. The operand may be a numeric constant, a character constant, a symbol, or 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 delimitors 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

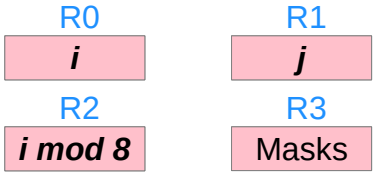


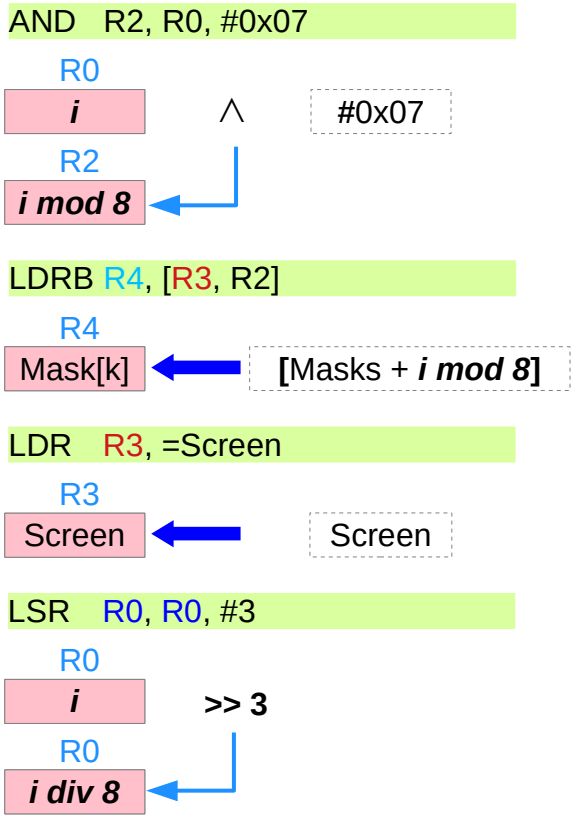

```
; Input :   R0 the row index i (0 to 47 in this case), Y-coordinate
;          R1 the column index j (0 to 83 in this case), X-coordinate
; Output:  R0 points to the byte of interest
          R1 the Mask to access that 1-bit pixel

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 >> 3 (i div 8)
          MOV   R2, #84
          MUL   R2, R0, R2      ; R2 = 84 * (i >> 3)
          ADD   R0, R2, R3      ; R0 = Screen + 84 * (i >> 3)   (pointer)
          ADD   R0, R0, R1      ; R0 = Screen + 84 * (i >> 3) + j     (pointer)
          MOV   R1, R4          ; R1 is Masks[i mod 8]
          BX    LR
```

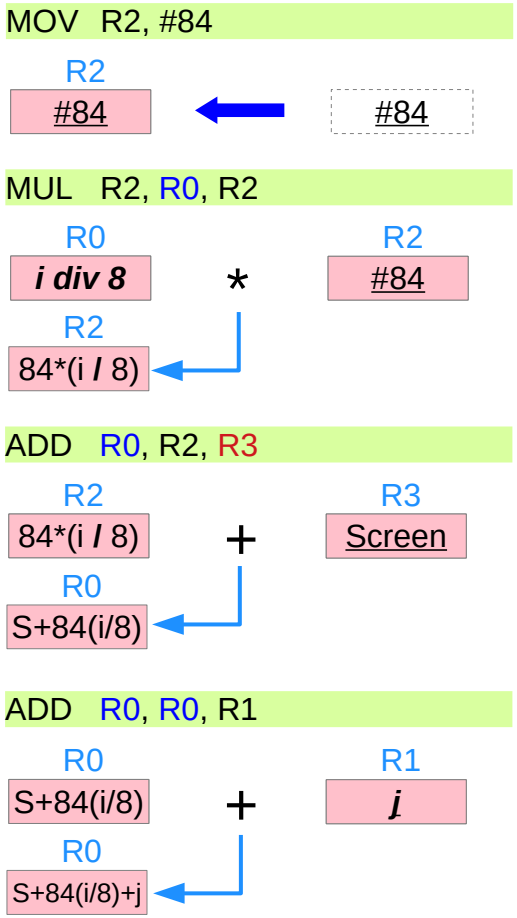
Matrix

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
```

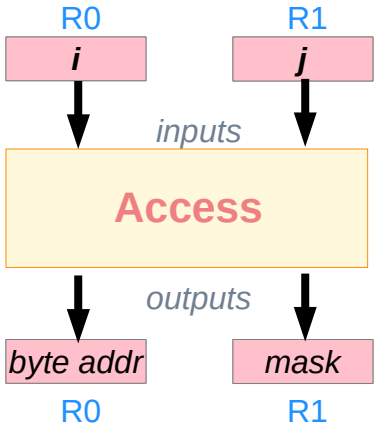


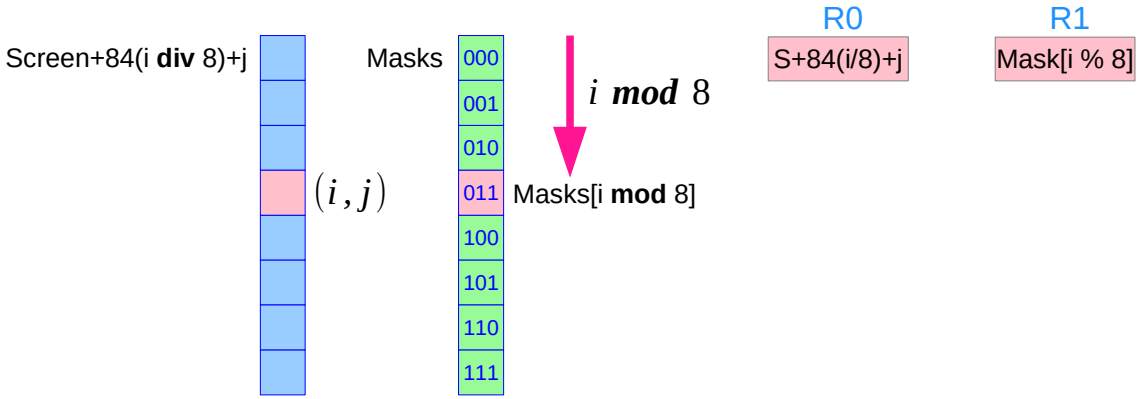




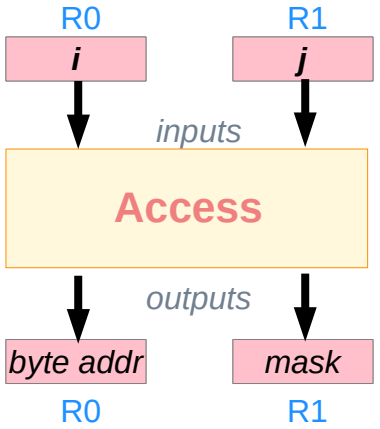
Clear a pixel

```
; 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          ; get pointer to pixel to change
        LDRB    R3, [R0]        ; R3 = [R0] = read 8 pixels
        BIC     R3, R3, R1      ; R3 = R3 & ~R1     clear proper pixel
        STRB    R3, [R0]        ; [R0] = R3 = write 8 pixels
        POP     {PC}
```

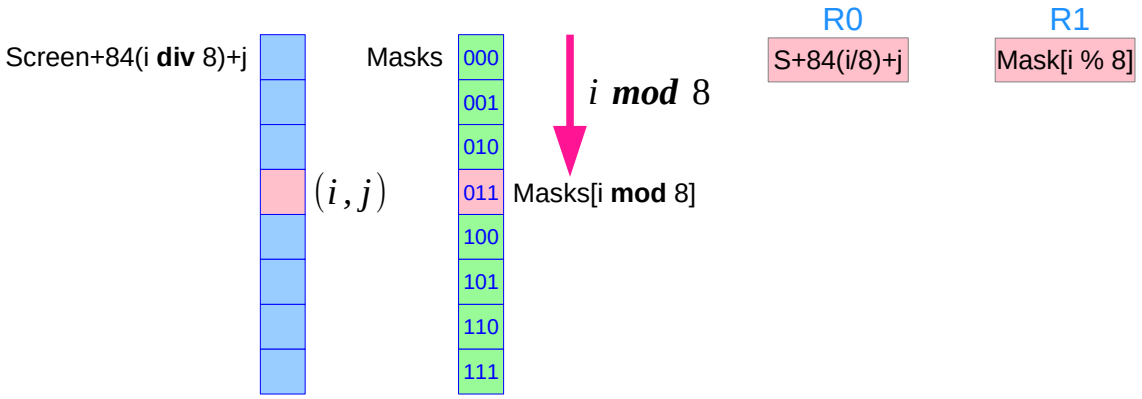




Set a pixel




```
; 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}
```

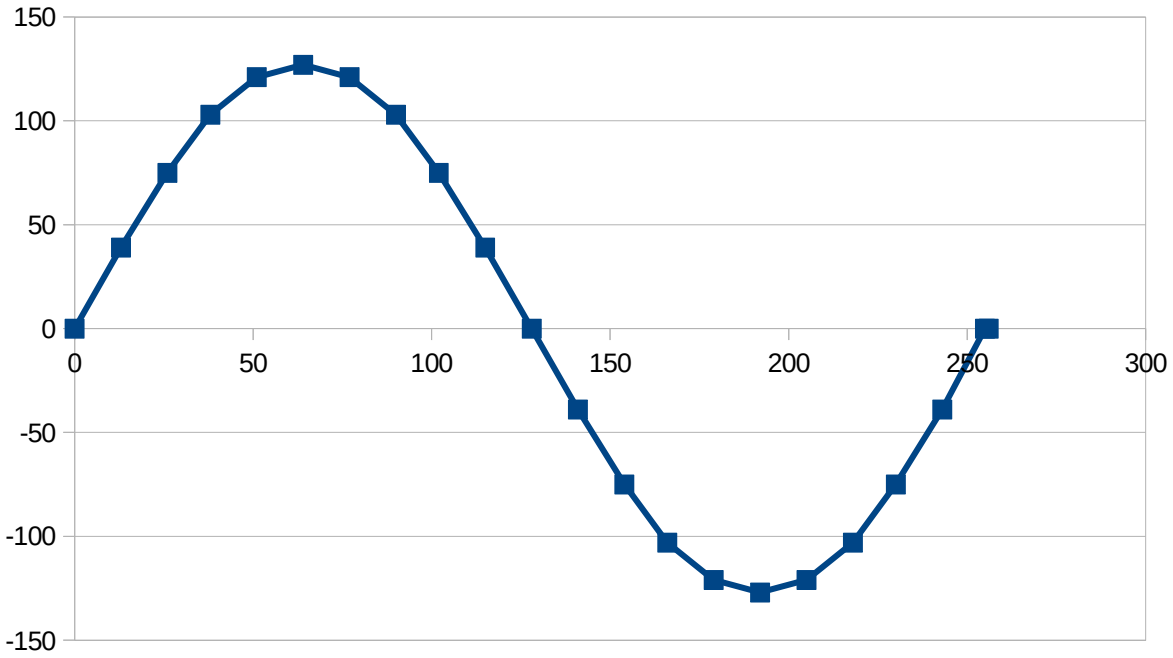


Table

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

```
IxTabl    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

IyTabl    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
```

Table




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

	IxTabl	IyTabl
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

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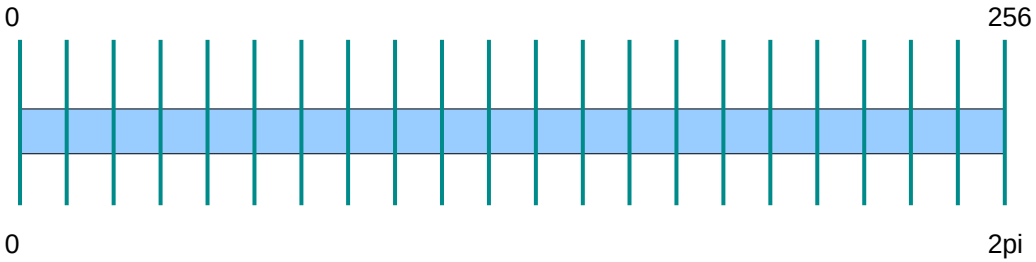
Table

=ROUND(256*(A2-1)/21)

256 * i / (22-1)




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

	IxTabl	IyTabl		
1	0	0		0
2	13	39		12
3	26	75		24
4	38	103		37
5	51	121		49
6	64	127		61
7	77	121		73
8	90	103		85
9	102	75		98
10	115	39		110
11	128	0		122
12	141	-39		134
13	154	-75		146
14	166	-103		158
15	179	-121		171
16	192	-127		183
17	205	-121		195
18	218	-103		207
19	230	-75		219
20	243	-39		232
21	255	0		244
22	256	0		256

Table

```
// Ix is 0 to 255 (pi/128)
// Iy is -127 to +127 (1/256)

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

        while (Ix >= IxTab(i+1)) {
                i++;
        }
        x1 = IxTab[i];
        x2 = IxTab[i+1];
        y1 = IyTab[i];
        y2 = IyTab[i+1];

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

Table

```
; Input :    R0 is 0 to 255, Ix
; Output:   R1 is -127 to +127, Iy

Sin         PUSH    {R4-R6, LR}
            LDR     R1, =IxTab          ; find x1 <= Ix < x2
            LDR     R2, =IyTab
Lookx1      LDR     R6, [R1, #4]        ; x2
            CMP     R0, R6              ; check Ix < x2
            BLO     found               ; R1 >= x1
            ADD     R1, #4
            ADD     R2, #4
            B       lookx1
```

Table

```
Found   LDR   R4, [R1]      ; x1
        SUB   R4, R0, R4     ; Ix-x1
        LDR   R5, [R2, #4]   ; y2
```

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