

ECE 220

Lecture x0013 - 11/04

Linked data structures & C to LC3

Recap & reminders

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 - Start early though ... this one can be rough.
 - MT2 scores to be released by tonight
 - Regrades will open on Thursday at 4.00 pm.
 - The deadline to submit is Sunday midnight.

Lesson objectives

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- Understand how structs are laid out in memory, specifically LC-3.
- Be able to translate C code using structs and pointers to equivalent LC-3 code in conjunction with LC-3 calling convention and Run-Time stack protocol.
- Be able to understand and reason about common operations involving linked lists and extend ideas to other kinds of linked lists (doubly linked list, circularly linked list, etc.).

Structs in LC3

Memory allocation

Memory allocation

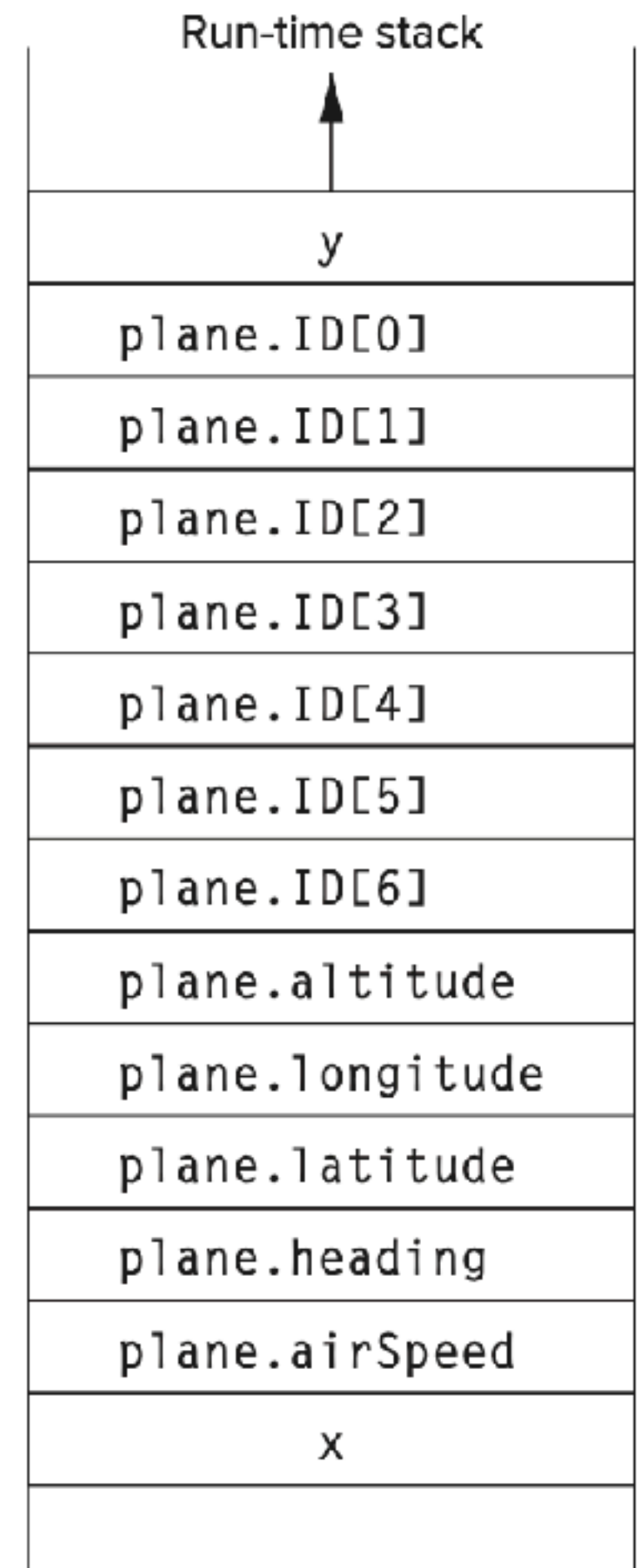
```
struct flightType {  
    char ID[7];           // Max 6 characters  
    int altitude;         // in meters  
    int longitude;        // in tenths of degrees  
    int latitude;         // in tenths of degrees  
    int heading;          // in tenths of degrees  
    double airSpeed;      // in kilometers/hour  
};
```

Memory allocation

```
struct flightType {  
    char ID[7];           // Max 6 characters  
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    int latitude;         // in tenths of degrees  
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};  
  
int x;  
struct flightType plane;  
int y;
```


Memory allocation

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struct flightType {  
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};  
  
int x;  
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```



Memory representation

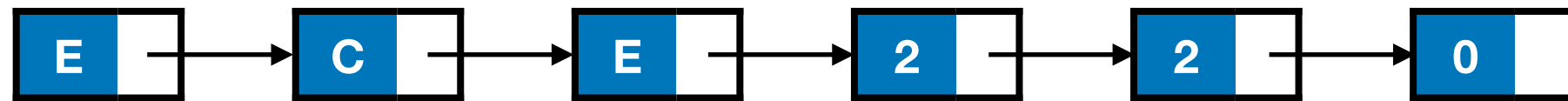
```
typedef struct Node{  
    char symbol;  
    struct Node *next;  
}node;
```

```
int main(){  
    node N3, N2, N1;  
    N1.symbol = 'E'  
    N2.symbol = 'C'  
    N3.symbol = 'E'  
  
    N1.next = &N2;  
    N2.next = &N3;  
    N3.next = NULL;  
}
```

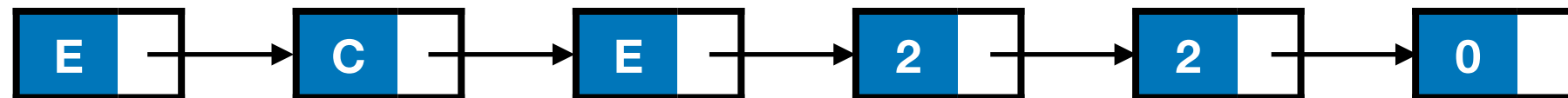
	Address	Value	Symbol
N1	x6000	E	N1.symbol
	x6001	x6002	N1.next
N2	x6002	C	N2.symbol
	x6003	x6004	N2.next
N3	x6004	E	N3.symbol
	x6005	NULL	N3.next

Printing a linked list

Printing a linked list



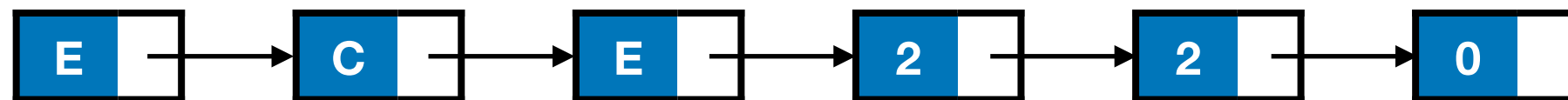
Printing a linked list



```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```


Printing a linked list



```
typedef struct Node{
    char symbol;
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        printf("%c", cursor->symbol);
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    }
}
```

```
.ORIG x3000
```

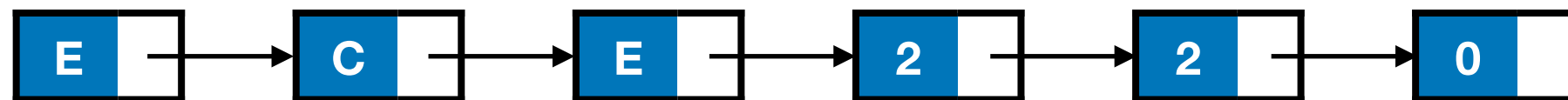
```
MAIN
```

```
LD R5, RSTACK
LD R6, RSTACK
LD R0, HEAD
STR R0, R6, #0 ; push argument onto stack
ADD R6, R6, #-1
JSR PRINT_LIST
ADD R6, R6, #2 ; caller teardown (pop retval & args)
HALT
```

```
HEAD .FILL x4004
```

```
RSTACK .FILL x7000
```

Printing a linked list



What is at memory location x4004?

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

```
.ORIG x3000
```

```
MAIN
```

```
LD R5, RSTACK
LD R6, RSTACK
LD R0, HEAD
STR R0, R6, #0 ; push argument onto stack
ADD R6, R6, #-1
JSR PRINT_LIST
ADD R6, R6, #2 ; caller teardown (pop retval & args)
HALT
```

```
HEAD .FILL x4004
RSTACK .FILL x7000
```



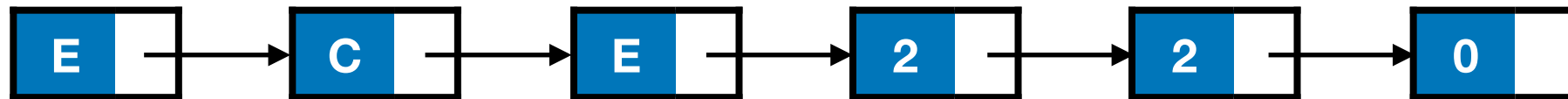
```

typedef struct Node{
    char symbol;
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}node;

void print_list(node *cursor){
    if (cursor==NULL)
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        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}

```

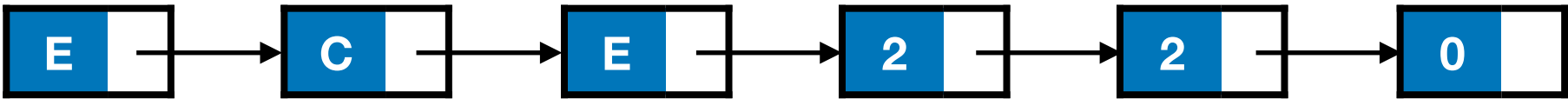
Printing a linked list



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Printing a linked list

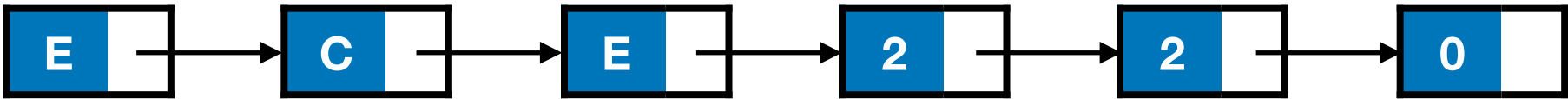


x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...

```
typedef struct Node{
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    }
}
```

Printing a linked list

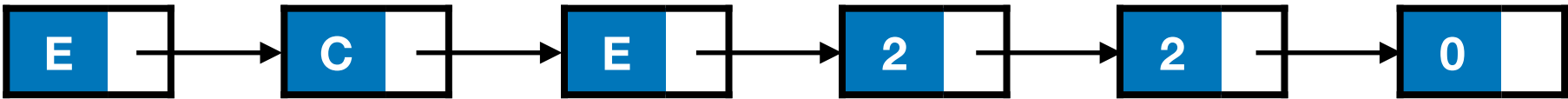


Head pointer	→	x4004	69	x0045
		x4005	16390	x4006
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		...	...	...

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Printing a linked list



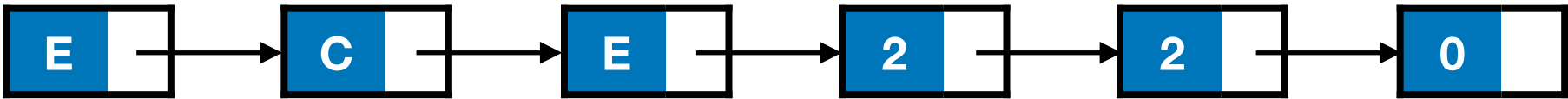
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		x400B	16396	x400C
		x400C	50	x0032
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		x400E	48	x0030
		...	...	...

What is at memory location x7000?


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
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}
```

Printing a linked list



Head pointer

—————>	x4004	69	x0045
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	x4008	69	x0045
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	x400C	50	x0032
	x400D	16398	x400E
	x400E	48	x0030
	...	...	...

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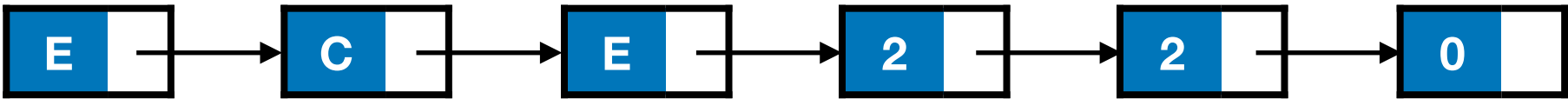
Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	

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		x400E	48	x0030
		...	...	...

What is at memory location x7000?

.ORIG x3000

MAIN

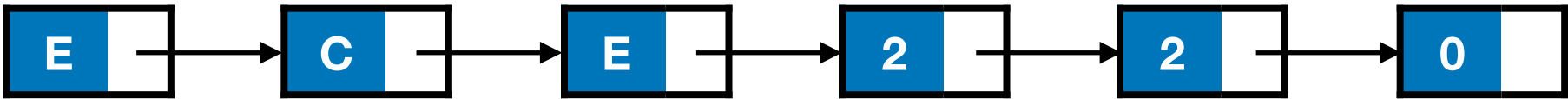
Runtime stack

...	
x6FF5	
x6FF6	
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x6FFC	
x6FFD	
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	...	...	...

What is at memory location x7000?

```
.ORIG x3000

MAIN
    LD R5, RSTACK
```

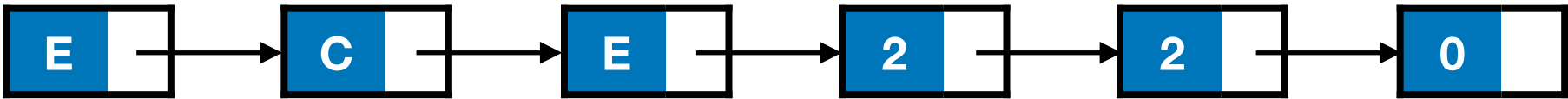
R5 →

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	


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```

Printing a linked list



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		x400B	16396	x400C
		x400C	50	x0032
		x400D	16398	x400E
		x400E	48	x0030
		...	...	...

What is at memory location x7000?

```
.ORIG x3000

MAIN
    LD R5, RSTACK
    LD R6, RSTACK
```

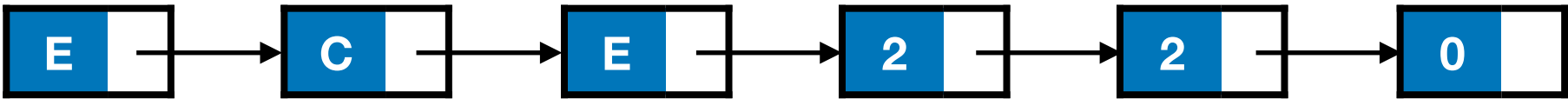
R5 —> R6 —>

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	

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		x400B	16396	x400C
		x400C	50	x0032
		x400D	16398	x400E
		x400E	48	x0030
		...	...	...

What is at memory location x7000?

```
.ORIG x3000

MAIN
    LD R5, RSTACK
    LD R6, RSTACK
    LD R0, HEAD
```

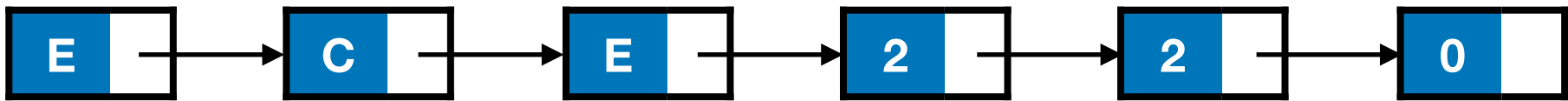
R5 —> R6 —>

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	

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	x400D	16398	x400E
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	...	...	...

What is at memory location x7000?

```
.ORIG x3000

MAIN
    LD R5, RSTACK
    LD R6, RSTACK
    LD R0, HEAD
    STR R0, R6, #0 ; push argument onto stack
```

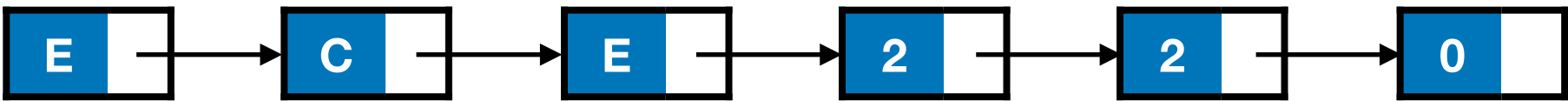
R5 → R6 →

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	x4004

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	...	...	...

What is at memory location x7000?

```
.ORIG x3000

MAIN
    LD R5, RSTACK
    LD R6, RSTACK
    LD R0, HEAD
    STR R0, R6, #0 ; push argument onto stack
    ADD R6, R6, #-1
```

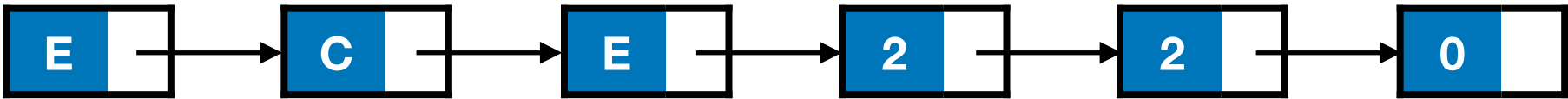
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...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	x4004


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Printing a linked list



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		...	...	...

What is at memory location x7000?

```
.ORIG x3000

MAIN
    LD R5, RSTACK
    LD R6, RSTACK
    LD R0, HEAD
    STR R0, R6, #0 ; push argument onto stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2 ; caller teardown (pop retval & args)
    HALT

HEAD .FILL x4004
RSTACK .FILL x7000
```

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	x4004

```
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}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	x4004

PRINT_LIST
;;Part 1 - callee build up

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
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x400E	48	x0030	
...	...	...	

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}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	
x7000	x4004

PRINT_LIST

;;Part 1 - callee build up

ADD R6, R6, #-1 ;make space for return value

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
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x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →

R5 →


```
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    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	
x6FFF	Ret Val
x7000	x4004

PRINT_LIST

;;Part 1 - callee build up

ADD R6, R6, #-1 ;make space for return value

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →

R5 →

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

```
PRINT_LIST
;;Part 1 - callee build up
    ADD R6, R6, #-1      ;make space for return value
    STR R7, R6, #0       ;push return addr to stack
    ADD R6, R6, #-1
```

Printing a linked list

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →

R5 →

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

PRINT_LIST

```
;;Part 1 - callee build up
ADD R6, R6, #-1      ;make space for return value
STR R7, R6, #0       ;push return addr to stack
ADD R6, R6, #-1
STR R5, R6, #0       ;push caller frame pointer
```

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

PRINT_LIST

```
;;Part 1 - callee build up
ADD R6, R6, #-1      ;make space for return value
STR R7, R6, #0       ;push return addr to stack
ADD R6, R6, #-1
STR R5, R6, #0       ;push caller frame pointer
ADD R5, R6, #-1      ;set new frame pointer
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

PRINT_LIST

;;Part 1 - callee build up

```
ADD R6, R6, #-1      ;make space for return value
STR R7, R6, #0        ;push return addr to stack
ADD R6, R6, #-1
STR R5, R6, #0        ;push caller frame pointer
ADD R5, R6, #-1      ;set new frame pointer
```

;;Part 2 - implement function logic

```
;if(cursor == NULL) skip to the end;
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
	x4004

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

PRINT_LIST

```
;;Part 1 - callee build up
    ADD R6, R6, #-1      ;make space for return value
    STR R7, R6, #0       ;push return addr to stack
    ADD R6, R6, #-1
    STR R5, R6, #0       ;push caller frame pointer
    ADD R5, R6, #-1      ;set new frame pointer

;;Part 2 - implement function logic

;if(cursor == NULL) skip to the end;
    LDR R1, R5, #4       ;load head to R1
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
	x4004

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

PRINT_LIST

;;Part 1 - callee build up

```
ADD R6, R6, #-1      ;make space for return value
STR R7, R6, #0        ;push return addr to stack
ADD R6, R6, #-1
STR R5, R6, #0        ;push caller frame pointer
ADD R5, R6, #-1      ;set new frame pointer
```

;;Part 2 - implement function logic

```
;if(cursor == NULL) skip to the end;
LDR R1, R5, #4        ;load head to R1
BRz TEAR_DOWN        ;if head null, nothing to do
;
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4004

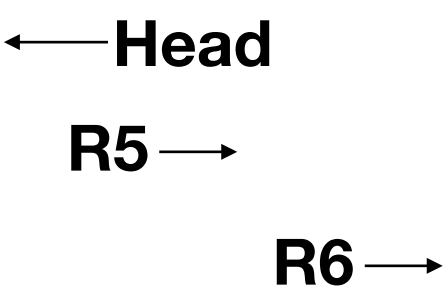
PRINT_LIST

```
;;Part 1 - callee build up
    ADD R6, R6, #-1      ;make space for return value
    STR R7, R6, #0       ;push return addr to stack
    ADD R6, R6, #-1
    STR R5, R6, #0       ;push caller frame pointer
    ADD R5, R6, #-1      ;set new frame pointer

;;Part 2 - implement function logic

;if(cursor == NULL) skip to the end;
    LDR R1, R5, #4       ;load head to R1
    BRz TEAR_DOWN        ;if head null, nothing to do
;
;else printf("%c", cursor->symbol);
    LDR R0, R1, #0       ;load cursor->symbol to R0
    OUT
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...



Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4004

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	R6 →
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4004

```
;print_list(head->next);
LDR R1, R1, #1    ;load head->next to R1
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
    LDR R1, R1, #1    ;load head->next to R1
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	R6 →
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
LDR R1, R1, #1      ;load head->next to R1
ADD R6, R6, #-1
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 → R6 →
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

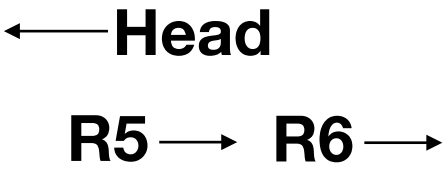
void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
LDR R1, R1, #1      ;load head->next to R1
ADD R6, R6, #-1
STR R1, R6, #0      ;push head->next to the stack
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...



Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

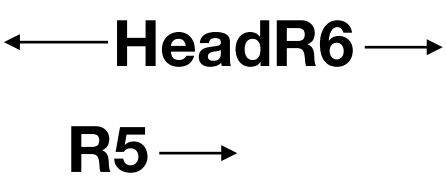
void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
LDR R1, R1, #1      ;load head->next to R1
ADD R6, R6, #-1
STR R1, R6, #0      ;push head->next to the stack
ADD R6, R6, #-1
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...



Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
LDR R1, R1, #1      ;load head->next to R1
ADD R6, R6, #-1
STR R1, R6, #0      ;push head->next to the stack
ADD R6, R6, #-1
JSR PRINT_LIST
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...

← **HeadR6** →
R5 →

Runtime stack	
...	...
x6FF5	...
x6FF6	Ret Addr
x6FF7	Ret Val
x6FF8	x4008
x6FF9	CFP
x6FFA	Ret Addr
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

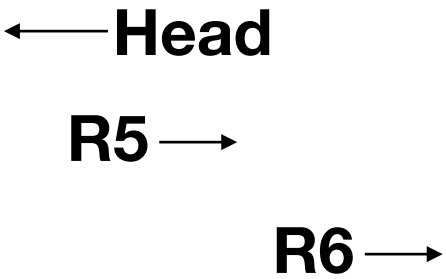
void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
LDR R1, R1, #1      ;load head->next to R1
ADD R6, R6, #-1
STR R1, R6, #0      ;push head->next to the stack
ADD R6, R6, #-1
JSR PRINT_LIST
ADD R6, R6, #2      ; caller stack tear down
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...



Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

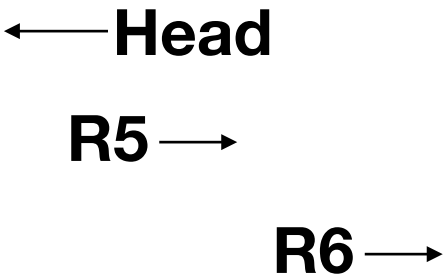
void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
LDR R1, R1, #1      ;load head->next to R1
ADD R6, R6, #-1
STR R1, R6, #0      ;push head->next to the stack
ADD R6, R6, #-1
JSR PRINT_LIST
ADD R6, R6, #2      ; caller stack tear down
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...



Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	R6 →
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004


```
typedef struct Node{
    char symbol;
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}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

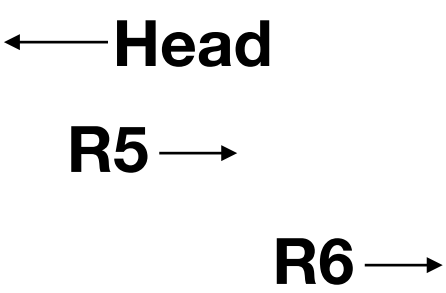
R0	R1
69	x4006

R5	R7

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
```

x4004	69	x0045
x4005	16390	x4006
x4006	67	x0043
x4007	16392	x4008
x4008	69	x0045
x4009	16394	x400A
x400A	50	x0032
x400B	16396	x400C
x400C	50	x0032
x400D	16398	x400E
x400E	48	x0030
...	...	...



Runtime stack	
...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

R0	R1
69	x4006

R5	R7

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
TEAR_DOWN
```

x4004	69	x0045	← Head
x4005	16390	x4006	R5 →
x4006	67	x0043	R6 →
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004


```
typedef struct Node{
    char symbol;
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void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

R0	R1	R5	R7
69	x4006	CFP	

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
TEAR_DOWN
    LDR R5, R6, #0      ;Restore old frame pointer
```

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	


```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

R0	R1	R5	R7
69	x4006	CFP	

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
TEAR_DOWN
    LDR R5, R6, #0      ;Restore old frame pointer
    ADD R6, R6, #1
```

x4004	69	x0045	← Head
x4005	16390	x4006	
x4006	67	x0043	
x4007	16392	x4008	
x4008	69	x0045	
x4009	16394	x400A	R5 →
x400A	50	x0032	
x400B	16396	x400C	
x400C	50	x0032	
x400D	16398	x400E	
x400E	48	x0030	
...	...	...	

R6 →

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
TEAR_DOWN
    LDR R5, R6, #0      ;Restore old frame pointer
    ADD R6, R6, #1
    LDR R7, R6, #0      ;Restore return address
```

R0		R1		R5		R7	
69		x4006		CFP		Ret Addr	
x4004	69	x0045	← Head	x4005	16390	x4006	R6 →
x4006	67	x0043		x4007	16392	x4008	
x4008	69	x0045	R5 →	x4009	16394	x400A	
x400A	50	x0032		x400B	16396	x400C	
x400C	50	x0032		x400D	16398	x400E	
x400E	48	x0030					
...	...	...					

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
TEAR_DOWN
    LDR R5, R6, #0      ;Restore old frame pointer
    ADD R6, R6, #1
    LDR R7, R6, #0      ;Restore return address
    ADD R6, R6, #1
```

R0		R1		R5		R7	
69		x4006		CFP		Ret Addr	
x4004	69	x0045	← Head	x4005	16390	x4006	
x4006	67	x0043		x4007	16392	x4008	
x4008	69	x0045		x4009	16394	x400A	
x400A	50	x0032		x400B	16396	x400C	
x400C	50	x0032		x400D	16398	x400E	
x400E	48	x0030		...			

R6 →
R5 →

```
typedef struct Node{
    char symbol;
    struct Node *next;
}node;

void print_list(node *cursor){
    if (cursor==NULL)
        /* List empty; do nothing */
        return;
    else{
        /* Print and recurse */
        printf("%c", cursor->symbol);
        print_list(cursor->next);
    }
}
```

Printing a linked list

Runtime stack

...	
x6FF5	
x6FF6	
x6FF7	
x6FF8	
x6FF9	
x6FFA	
x6FFB	Ret Val
x6FFC	x4006
x6FFD	CFP
x6FFE	Ret Addr
x6FFF	Ret Val
x7000	x4004

```
;print_list(head->next);
    LDR R1, R1, #1      ;load head->next to R1
    ADD R6, R6, #-1
    STR R1, R6, #0      ;push head->next to the stack
    ADD R6, R6, #-1
    JSR PRINT_LIST
    ADD R6, R6, #2      ; caller stack tear down

;skip here if head is null
;;Part 3 - callee tear down (preparing to return)
TEAR_DOWN
    LDR R5, R6, #0      ;Restore old frame pointer
    ADD R6, R6, #1
    LDR R7, R6, #0      ;Restore return address
    ADD R6, R6, #1

RET

.END
```

R0		R1		R5		R7	
69		x4006		CFP		Ret Addr	
x4004	69	x0045	← Head	x4005	16390	x4006	
x4006	67	x0043		x4007	16392	x4008	
x4008	69	x0045		x4009	16394	x400A	
x400A	50	x0032		x400B	16396	x400C	
x400C	50	x0032		x400D	16398	x400E	
x400E	48	x0030		...			

R6 →

R5 →

Linked Lists Practice

More linked lists

- Exercise(s)
 - Given two already sorted linked lists, merge them.
 - Result should still be sorted!
 - Reverse a singly linked list.
 - Implement a doubly linked list.

Sorted merging

- Given two lists of commanders-in-chiefs, merge the list while maintaining their sorted property
 - (Reagan, 1911)→(Nixon, 1913)→(Trump, 1946)→(Bush, 1946)→NULL
 - (Carter, 1924)→(Biden, 1942)→(Clinton, 1946)→(Obama, 1961)→NULL
- What should the merged list look like?

```
typedef struct person{  
    char *name;  
    unsigned int byear;  
    struct person *next;  
}node;
```


Reverse a singly-linked list

- Given the list, generate a ***new*** (not just print) linked list where the nodes are linked in ***reverse*** order.
 - (Reagan, 1911)->(Nixon, 1913)->(Carter, 1924)->(Biden, 1942)->(Trump, 1946)->(Bush, 1946)->(Clinton, 1946)->(Obama, 1961)->NULL
 - (Obama, 1961)->(Clinton, 1946)->(Bush, 1946)->(Trump, 1946)->(Biden, 1942)->(Carter, 1924)->(Nixon, 1913)->(Reagan, 1911)->NULL

Doubly linked lists

- How many pointers to maintain?
 - Head pointer? Tail pointer?



- How should insertion/deletion work?

Left as exercise!

- At head, middle, tail.
- We will just do an autosorted one using strcmp

```
typedef struct person{
    char *name;
    struct person *next;
    struct person *prev;
}node;
```

More practice? Okey doke!

More practice? Okey doke!

- Practicing on linked lists:

More practice? Okey doke!

- Practicing on linked lists:
 - Stanford's [Linked List Question Bank](#)

More practice? Okey doke!

- Practicing on linked lists:
 - Stanford's [Linked List Question Bank](#)
 - Also good practice for technical interviews!