6502 Stack

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c64 emulator

PEEK and POKE

- POKE: directly write into memory
- PEEK: directly read memory value
- Example: write into screen memory
  - POKE 1024,1
    writes letter A into top left corner
  - PRINT PEEK(1024)
    returns 1

Character Encoding in Screen Memory

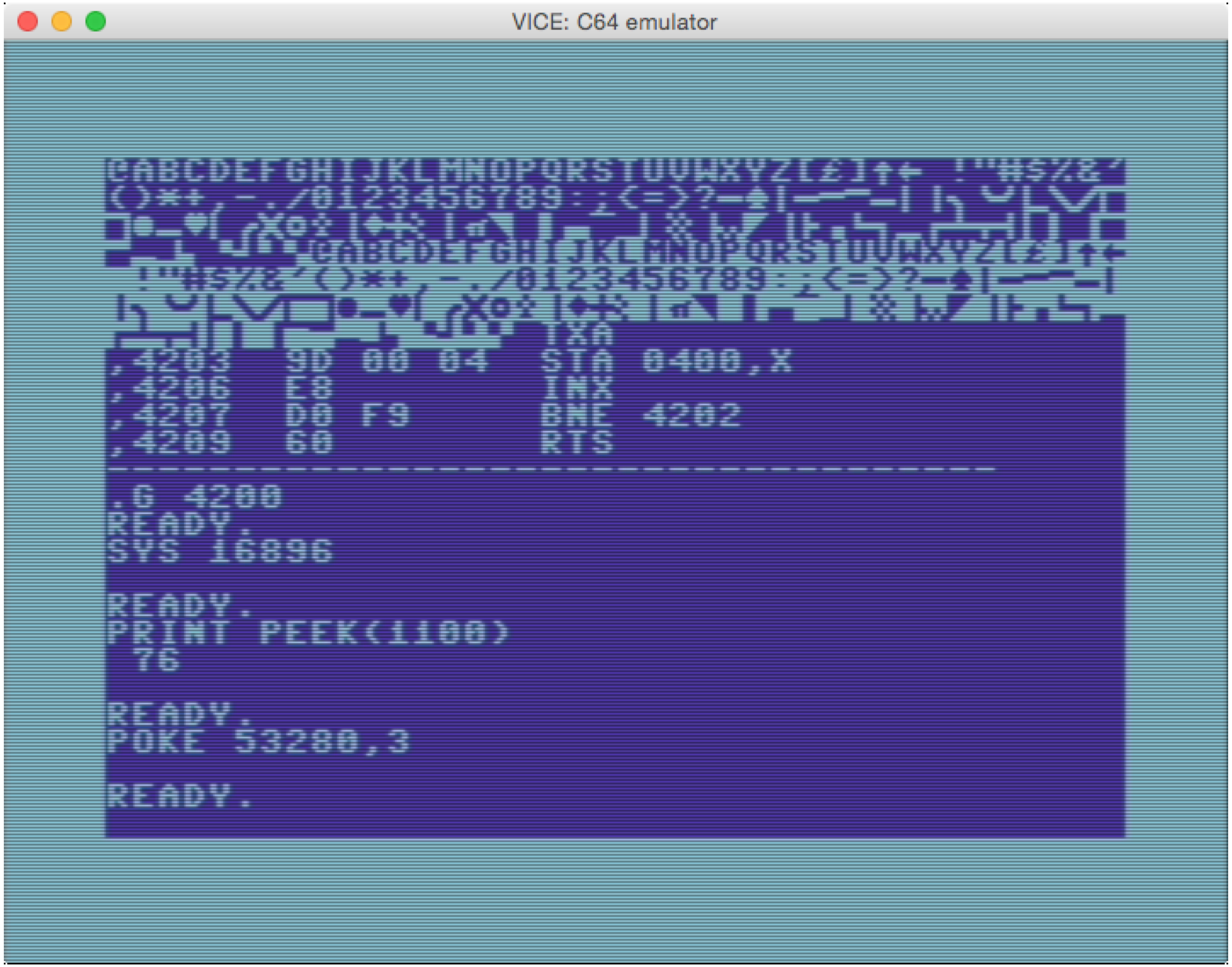
- What is the character encoding in screen memory?

- Let's write a program

Address	Bytes	Command
4200	A2 00	LDX #00
4202	8A	TXA
4203	9D 00 04	STA 0400,X
4206	E8	INX
4207	D0 F9	BNE 4202
4209	60	RTS

- Run from BASIC: SYS 16896

Screenshot


VICE: C64 emulator
TXA
,4203 9D 00 04 STA 0400,X
,4206 E8 INX
,4207 D0 F9 BNE 4202
,4209 60 RTS
.G 4200
READY.
SYS 16896
READY.
PRINT PEEK(1100)
76
READY.
POKE 53280,3
READY.

stack

Stack

- Useful data structure

Stack

- Useful data structure

- LIFO: Last in, first out
  - PUSH 5

Stack

- Useful data structure
- LIFO: Last in, first out
  - PUSH 5
  - PUSH 2

Stack

- Useful data structure

- LIFO: Last in, first out
  - PUSH 5
  - PUSH 2
  - PULL $\rightarrow$ 2

Stack

- Useful data structure
- LIFO: Last in, first out
  - PUSH 5
  - PUSH 2
  - PULL $\rightarrow$ 2
  - PULL $\rightarrow$ 5

6502 Stack in Memory

- 2nd page in memory reserved
  ("page" = 256 bytes)

- Stack pointer
  - current free position
  - an address, e.g., 01FF
  - register in CPU

⇒	01FF	
	01FE	
	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A

⇒ 01FF	
01FE	
01FD	
01FC	
01FB	
01FA	
01F9	
01F8	
01F7	
01F6	
01F5	
01F4	
01F3	
01F2	
...	...
0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE

	01FF	0A
⇒	01FE	
	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE

- PUSH 55

	01FF	0A
⇒	01FE	
	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE

- PUSH 55
  - store 55 to 01FE
  - decrease stack pointer to 01FD

	01FF	0A
	01FE	55
$\Rightarrow$	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE
- PUSH 55
  - store 55 to 01FE
  - decrease stack pointer to 01FD
- PULL

	01FF	0A
	01FE	55
⇒	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE
- PUSH 55
  - store 55 to 01FE
  - decrease stack pointer to 01FD
- PULL
  - increase stack pointer to 01FE
  - retrieve 55 from 01FE

	01FF	0A
⇒	01FE	55
	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE
- PUSH 55
  - store 55 to 01FE
  - decrease stack pointer to 01FD
- PULL
  - increase stack pointer to 01FE
  - retrieve 55 from 01FE
- PUSH 42

	01FF	0A
⇒	01FE	55
	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- PUSH 0A
  - store 0A to 01FF
  - decrease stack pointer to 01FE
- PUSH 55
  - store 55 to 01FE
  - decrease stack pointer to 01FD
- PULL
  - increase stack pointer to 01FE
  - retrieve 55 from 01FE
- PUSH 42
  - store 42 to 01FE
  - decrease stack pointer to 01FD

	01FF	0A
	01FE	42
⇒	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

6502 stack instructions

Basic Stack Manipulation

- Accumulator
  - PHA: push accumulator to stack
  - PLA: pull accumulator from stack

Basic Stack Manipulation

- Accumulator
  - PHA: push accumulator to stack
  - PLA: pull accumulator from stack
- Processor status (flags)
  - PHP: push processor status to stack
  - PLP: pull processor status from stack

Example

- Stack is a good place to safely store register values
- Example

```
PHA
TXA
PHA
TYA
PHA
(some code that changes registers)
PLA
TAY
PLA
TAX
PLA
(all registers back to original state)
```

Stack Pointer Instructions

- Read out stack pointer
- TSX: transfer stack pointer to X register
- TXS: transfer X register to stack pointer

Warning

- Stack is not very big (256 bytes)
- Too heavy use may lead to stack overflow

sub routines

Subroutines

- Subroutines are small programs that do common things
  - for instance: write a character at current cursor position
  - this is in the C64 kernel at address FFD2

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  - for instance: write a character at current cursor position
  - this is in the C64 kernel at address FFD2

- Naive usage

```
LDA #41
JMP FFD2
```

- Why won't that work?

Subroutines

- Subroutines are small programs that do common things
  - for instance: write a character at current cursor position
  - this is in the C64 kernel at address FFD2

- Naive usage

```
LDA #41
JMP FFD2
```

- Why won't that work?

  Subroutine does not know where to return to

Solution

- Use the stack!

Solution

- Use the stack!
- Jump to subroutine
  - store current program counter to stack
  - jump to subroutine address

Solution

- Use the stack!

- Jump to subroutine
  - store current program counter to stack
  - jump to subroutine address

- Return from subroutine
  - retrieve return address from stack
  - jump to retrieved address

6502 Subroutine Instructions

- JSR: Jump to subroutine

- RTS: Return from subroutine

Example

- 4400 LDA #41
- 4402 JSR FFD2

	01FF	0A
	01FE	55
⇒	01FD	
	01FC	
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store program counter

01FF	0A
01FE	55
01FD	44
01FC	05
⇒ 01FB	
01FA	
01F9	
01F8	
01F7	
01F6	
01F5	
01F4	
01F3	
01F2	
...	...
0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter

01FF	0A
01FE	55
01FD	44
01FC	05
⇒ 01FB	
01FA	
01F9	
01F8	
01F7	
01F6	
01F5	
01F4	
01F3	
01F2	
...	...
0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter
- FFD2 JMP (0326)

	01FF	0A
	01FE	55
	01FD	44
	01FC	05
⇒	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter
- FFD2 JMP (0326)
- F1CA ...

	01FF	0A
	01FE	55
	01FD	44
	01FC	05
$\Rightarrow$	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter
- FFD2 JMP (0326)
- F1CA ...
- F207 RTS

	01FF	0A
	01FE	55
	01FD	44
	01FC	05
⇒	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter
- FFD2 JMP (0326)
- F1CA ...
- F207 RTS

	01FF	0A
	01FE	55
	01FD	44
	01FC	05
⇒	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter
- FFD2 JMP (0326)
- F1CA ...
- F207 RTS
  - retrieve program counter from stack
  - jump to retrieved address

	01FF	0A
	01FE	55
⇒	01FD	44
	01FC	05
	01FB	
	01FA	
	01F9	
	01F8	
	01F7	
	01F6	
	01F5	
	01F4	
	01F3	
	01F2	
	...	...
	0100	

Example

- 4400 LDA #41
- 4402 JSR FFD2
  - program counter is 4405
  - store programm counter
- FFD2 JMP (0326)
- F1CA ...
- F207 RTS
  - retrieve program counter from stack
  - jump to retrieved address
- 4405 ...

01FF	0A
01FE	55
⇒ 01FD	44
01FC	05
01FB	
01FA	
01F9	
01F8	
01F7	
01F6	
01F5	
01F4	
01F3	
01F2	
...	...
0100	

example

Recursion

- Recursively calling subroutines

- Canonical example: Fibonacci numbers

$$f(x) = f(x-1) + f(x-2)$$

0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, ...

- $\lim_{x \to \infty} \frac{f(x+1)}{f(x)}$ is Golden Ratio

Code

```
START   TXA
        BNE M01       ; f(0) = 0?  no, continue
        RTS           ; yes
```

Code


```
START   TXA
        BNE M01     ; f(0) = 0?  no, continue
        RTS         ; yes
---------------------------------------------
M01     DEX         ; prepare for f(x-1) call
        BNE M02     ; f(1) = 1?  no, continue
        RTS         ; yes
```

Code

```
START   TXA
        BNE M01     ; f(0) = 0?  no, continue
        RTS         ; yes
-------------------------------------------------
M01     DEX         ; prepare for f(x-1) call
        BNE M02     ; f(1) = 1?  no, continue
        RTS         ; yes
-------------------------------------------------
M02     TXA         ; save X on stack
        PHA
        JSR START
```

Code


```
START   TXA
        BNE M01        ; f(0) = 0?  no, continue
        RTS            ; yes
--------------------------------------------------
M01     DEX            ; prepare for f(x-1) call
        BNE M02        ; f(1) = 1?  no, continue
        RTS            ; yes
--------------------------------------------------
M02     TXA            ; save X on stack
        PHA
        JSR START      ; result of f(x-1) in accumulator
        TAY            ; let's put f(x-1) aside
```

Code


```
START   TXA
        BNE M01     ; f(0) = 0?  no, continue
        RTS         ; yes
----------------------------------------------------
M01     DEX         ; prepare for f(x-1) call
        BNE M02     ; f(1) = 1?  no, continue
        RTS         ; yes
----------------------------------------------------
M02     TXA         ; save X on stack
        PHA
        JSR START   ; result of f(x-1) in accumulator
        TAY         ; let's put f(x-1) aside
        PLA         ; get X back from stack
        TAX
```

Code

```
START   TXA
        BNE M01     ; f(0) = 0?  no, continue
        RTS         ; yes
-----------------------------------------------
M01     DEX         ; prepare for f(x-1) call
        BNE M02     ; f(1) = 1?  no, continue
        RTS         ; yes
-----------------------------------------------
M02     TXA         ; save X on stack
        PHA
        JSR START   ; result of f(x-1) in accumulator
        TAY         ; let's put f(x-1) aside
        PLA         ; get X back from stack
        TAX
        TYA         ; get f(x-1) back
        PHA         ; save that for now on stack
```

Code

```
START   TXA
        BNE M01     ; f(0) = 0?  no, continue
        RTS         ; yes
-----------------------------------------------
M01     DEX         ; prepare for f(x-1) call
        BNE M02     ; f(1) = 1?  no, continue
        RTS         ; yes
-----------------------------------------------
M02     TXA         ; save X on stack
        PHA
        JSR START   ; result of f(x-1) in accumulator
        TAY         ; let's put f(x-1) aside
        PLA         ; get X back from stack
        TAX
        TYA         ; get f(x-1) back
        PHA         ; save that for now on stack
        DEX         ; prepare f(x-2)
        JSR START
```

Code

```
START   TXA
        BNE M01      ; f(0) = 0?  no, continue
        RTS          ; yes
-------------------------------------------------
M01     DEX          ; prepare for f(x-1) call
        BNE M02      ; f(1) = 1?  no, continue
        RTS          ; yes
-------------------------------------------------
M02     TXA          ; save X on stack
        PHA
        JSR START    ; result of f(x-1) in accumulator
        TAY          ; let's put f(x-1) aside
        PLA          ; get X back from stack
        TAX
        TYA          ; get f(x-1) back
        PHA          ; save that for now on stack
        DEX          ; prepare f(x-2)
        JSR START
        STA TEMP     ; store f(x-2) for addition
```

Code


```
START   TXA
        BNE M01     ; f(0) = 0?  no, continue
        RTS         ; yes
-----------------------------------------------
M01     DEX         ; prepare for f(x-1) call
        BNE M02     ; f(1) = 1?  no, continue
        RTS         ; yes
-----------------------------------------------
M02     TXA         ; save X on stack
        PHA
        JSR START   ; result of f(x-1) in accumulator
        TAY         ; let's put f(x-1) aside
        PLA         ; get X back from stack
        TAX
        TYA         ; get f(x-1) back
        PHA         ; save that for now on stack
        DEX         ; prepare f(x-2)
        JSR START
        STA TEMP    ; store f(x-2) for addition
        PLA         ; f(x-1) from stack
```

Code


```
START   TXA
        BNE M01      ; f(0) = 0?  no, continue
        RTS          ; yes
-------------------------------------------------
M01     DEX          ; prepare for f(x-1) call
        BNE M02      ; f(1) = 1?  no, continue
        RTS          ; yes
-------------------------------------------------
M02     TXA          ; save X on stack
        PHA
        JSR START    ; result of f(x-1) in accumulator
        TAY          ; let's put f(x-1) aside
        PLA          ; get X back from stack
        TAX
        TYA          ; get f(x-1) back
        PHA          ; save that for now on stack
        DEX          ; prepare f(x-2)
        JSR START
        STA TEMP     ; store f(x-2) for addition
        PLA          ; f(x-1) from stack
        CLC
        ADC TEMP     ; f(x-1) + f(x-2)
        RTS
```

some more instructions

Logic

- Standard Boolean operations
  - AND: bitwise AND
  - ORA: bitwise OR
  - EOR: bitwise XOR
- Operations impact negative and zero flag
- BIT: bitwise AND, but do not store result

Compare

- Compare register value
  - CMP: compare accumulator
  - CPX: compare X register
  - CPY: compare Y register
- Does not change register value
- Sets flags as in a subtraction
  (e.g., if values match, set zero flag)

some quirky things

Decimal Mode

- Decimal mode: pretend that hex numbers are really decimal numbers

```
LDA #07
CLC
ADC #04
```

- Normally results in 0B

Decimal Mode

- Decimal mode: pretend that hex numbers are really decimal numbers

```
LDA #07
CLC
ADC #04
```

- Normally results in 0B
- But in decimal mode: result 11

Decimal Mode

- Decimal mode: pretend that hex numbers are really decimal numbers

```
LDA #07
CLC
ADC #04
```

- Normally results in 0B
- But in decimal mode: result 11
- Instructions
  - SED: set decimal mode
  - CLD: clear decimal mode

NOP

- NOP: No Operation
- Does nothing
- Useful as filler
  e.g., when deleting instructions