## 0.1 Smooth scrolling

Performing a full-screen redraw per frame would kill the CPU, as it would need to update all pixels of all four EGA planes. There is no way to maintain a 60Hz framerate while refreshing the whole screen. If we were to run the following code, which simply fills all memory banks, it would run at 5 frames per seconds.

```
# define SC_INDEX   0x3C4
# define SC_DATA    0x3C5
# define SC_MAPMASK 0x02

char far *EGA = (unsigned char far*)0xA0000000L;

void selectPlane (int plane) {
  outp ( SC_INDEX , SC_MAPMASK );
  outp ( SC_DATA , 1 << plane );
}

void WriteScreen(void){
  int i, bank_id;

  for (bank_id = 0 ; bank_id < 4 ; bank_id++) {
    selectPlane(bank_id);
    for (i = 0; i < 40 * 200; i++) {
      EGA[i] = 0x00;
  }
}
```

So how did they create a smooth scrolling game with these limitations? By using some EGA hardware tricks and by changing only that part of the screen that has changed.

### 0.1.1 EGA Virtual Screen and Pel Panning

The EGA adds a powerful twist to linear addressing: the logical width of the virtual screen in VRAM memory need not to be the same as the physical width of the screen display. The programmer is free to define a virtual screen width of up to 4096 pixels and then use the physical screen as a window onto any part of the virtual screen. What's more, a virtual screen can have any logical height up to the capacity of the VRAM memory. The code below illustrates how to change the logical width.

```
CRTC_INDEX  = 03D4h
CRTC_OFFSET = 19

;==============
;
; set wide virtual screen
;
;==============

mov dx,CRTC_INDEX
mov al,CRTC_OFFSET
mov ah,[BYTE PTR width]  ;screen width in bytes
shr ah,1                 ;register expresses width
                         ;in word instead of byte
out dx,ax
```

The area of the virtual screen displayed at any given time is selected by setting the display memory address at which to begin fetching video data. This is set by way of the CRTC Start Address register. The default address is `A000:0000h`, but the offset can be changed to any other number.

```
CRTC_INDEX   = 03D4h
CRTC_STARTHIGH   = 12

;==============
;
; VW_SetScreen
;
;==============

  cli                        ;disable interrupts

  mov   cx,[crtc]            ;[crtc] is start address
  mov   dx,CRTC_INDEX        ;set CRTR register
  mov   al,CRTC_STARTHIGH    ;start address high register
  out   dx,al
  inc   dx                   ;port 03D5h
  mov   al,ch
  out   dx,al                ;set address high
  dec   dx                   ;set CRTR register
  mov   al,0dh               ;start address low register
  out   dx,al
  mov   al,cl
  inc   dx                   ;port 03D5h
  out   dx,al                ;set address low

  sti                        ;enable interrupts

  ret
```

Panning down a scan line requires only that the CRTC start address is increased by the logical width. Horizontal panning is possible by increasing the start address by one byte. In EGA's planar graphics modes, the eight bits in each byte of video RAM correspond to eight consecutive pixels on-screen. That means the screen moves horizontally in steps of 8 pixels, which is coarse, not smooth scrolling. Luckily there is another register we can use to resolve this.

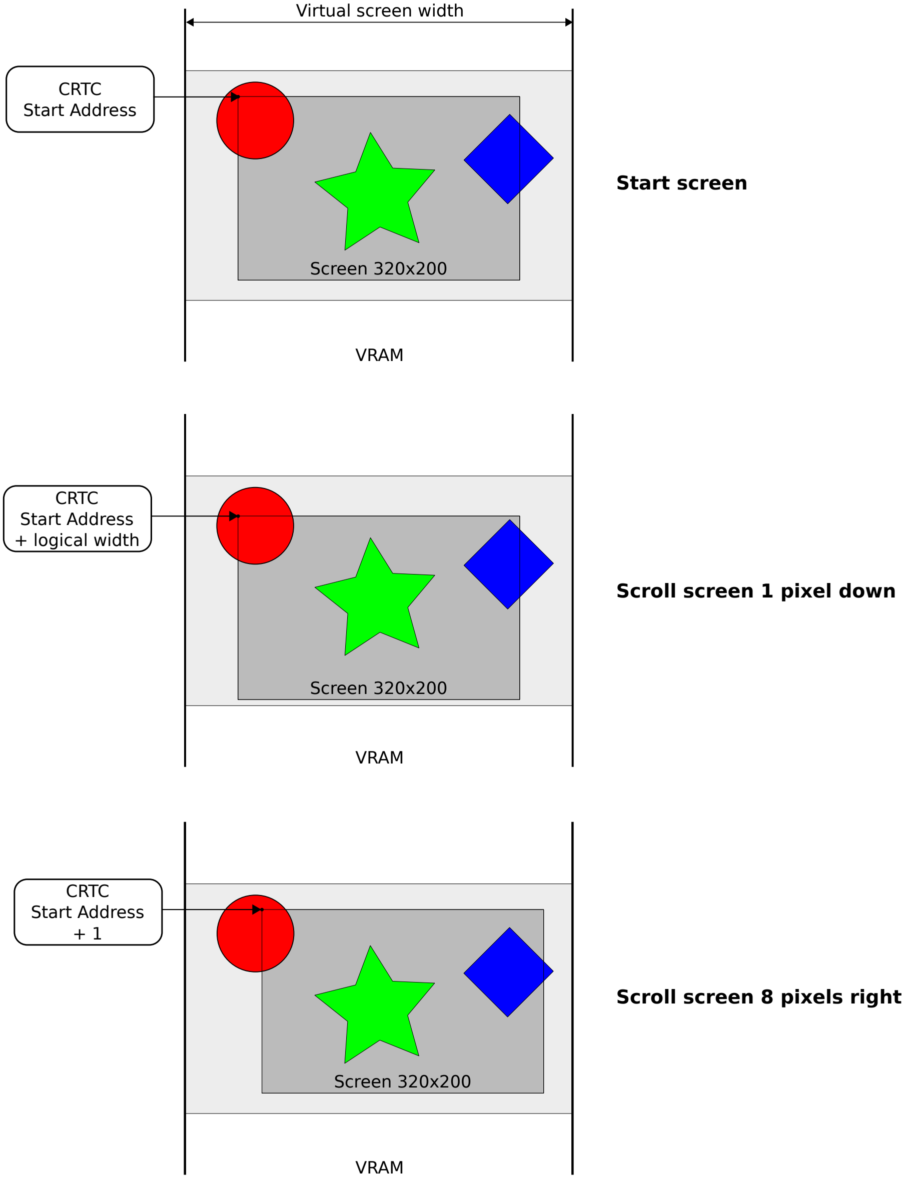



***Figure 1:*** EGA screen scrolling by updating the CRTC Start Address.

### 0.1.2 Horizontal Pel Panning

Smooth horizontal pixel scrolling of the screen is provided by the "Horizontal Pel Panning" register in the Attribute Controller (ATC). Up to 7 pixels' worth of single pixel panning of the displayed image to the left is performed by increasing the register from 0 to 7.

There is one annoying quirk about programming the Attribute Controller: when the ATC Index register is set, only the lower five bits (bits 0-4) are used as the internal index. The next most significant bit, bit 5, controls the source of the video data send to the monitor by the EGA card. When bit 5 is set to 1, the output of the color palette controls the displayed pixels; this is normal operation. When bit 5 is 0, video data doesn't come from the color palette, and the screen becomes a solid color. To ensure the ATC index register is restored to normal video, we must set bit 5 to 1 by writing `20h` to the register.

```
ATR_INDEX = 03C0h
ATR_PELPAN  = 19

;==============
;
; set horizontal panning
;
;==============

  mov dx,ATR_INDEX
  mov al,ATR_PELPAN or 20h ;horizontal pel panning register
                           ;(bit 5 is high to keep palette
                           ;RAM addressing on)
  out dx,al
  mov al,[BYTE pel]        ;pel pan value [0 to 8]
  out dx,al
```

Smooth horizontal on EGA should be viewed as adjusting the CRTC Start Address and fine horizontal adjustments in the 8-pixel range. The scrolling is achieved by the following steps:

- calculate the panning in pixels for both x- and y-direction
- the smooth y-panning is defined by adding `logical width * y` to the CRTC start address
- increase the CRTC start address width `x/8` bytes for coarse horizontal scrolling.
- the horizontal fine tuning is then adjusted by `x mod 8` using horizontal pel panning

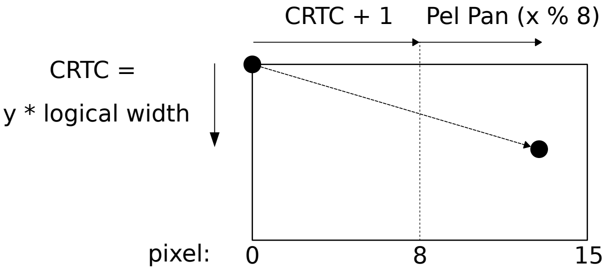



***Figure 2:*** Smooth scrolling in EGA.

## 0.2 Adaptive Tile Refreshment

So far, we have built a virtual screen in VRAM allowing smooth one pixel moves in both axes using only EGA registers. But once it reaches an edge, the virtual screen must be reset. And it cannot be a full screen redraw because it would drop the framerate to 5fps.

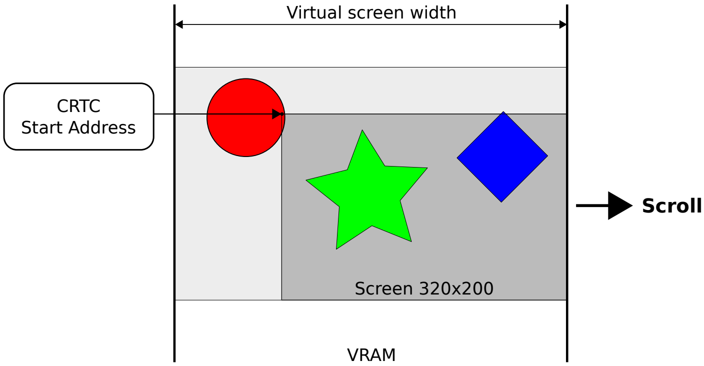



***Figure 3:*** Screen reaching the edge of virtual screen.

An option to resolve screen refresh is loading the entire level into VRAM memory and setting the logical width to the level width. By simply updating the CRTC Start Address and Horizontal Pel Panning registers, the game scrolls smoothly through the virtual screen. Unfortunately, a level won't fit into the VRAM. The first level, *Horsh Radish Hill*, is 2176 pixels wide and 592 pixels high, which means a total of 2176*592/2 = 644KB is required to store the entire level in VRAM. Since we only have 256KB available, this is not a feasible option.

**Trivia :** At the time of writing this book, most video cards contain more than 1GB VRAM, sufficient to store all Commander Keen levels at once in VRAM.

This is where John Carmack's invention starts. The scrolling engine is based on a simple yet powerful technology called *Adaptive Tile Refreshment (ATR)*. The core idea is to refresh only those areas of the screen that need to change. The screen is divided into tiles of 16x16 pixels. On a screen with 320x200 pixels, it means a grid of 20x13 tiles (actually it is 12.5 tiles high, but we round to full tiles).

Let's look at *Commander Keen 1: Marooned on Mars* in Figure 4. This is the first level of Marooned, immediately to the right of the crashed Bean-with-Bacon Megarocket. The first figure is the start of the level, the second figure is after Keen has scrolled one tile (16 pixels) to the right through the world. They look almost identical to the naked eye, don't they?

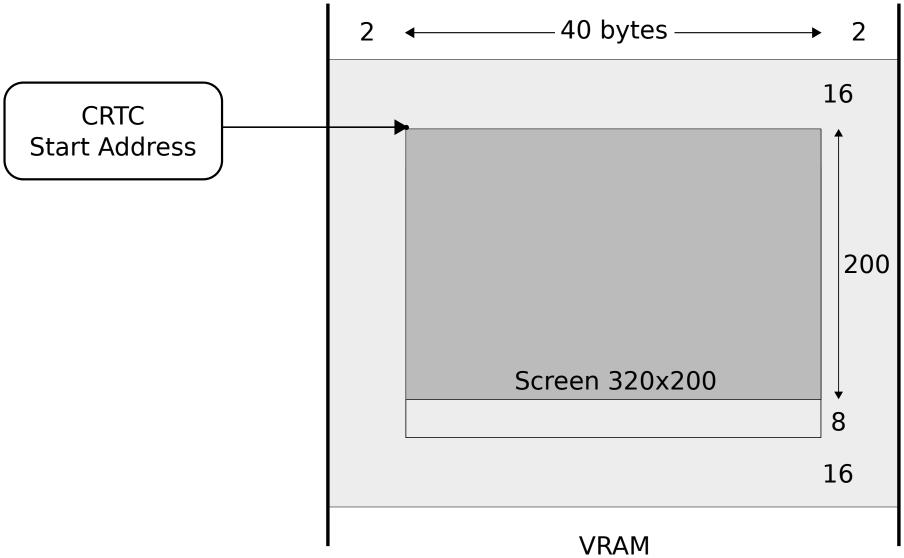
Now, if we perform a difference on both images, you can see which tiles need to be changed upon screen refresh. The trick behind the scrolling is to only redraw tiles that actually changed after panning 16 pixels (one tile). For matching tiles there is nothing to do and they are skipped entirely. In Figure 4.21, there are large swathes of constant background tiles. In total, only 69 tiles out of the 260 tiles need to be refreshed, which is 27% of the screen!

***Figure 4:*** Start of the world, moved one tile to the right and difference.

## 0.3 ATR in action: Commander Keen 1-3

This section explains how ATR is working for the first three episodes of Commander Keen. Since there is no source code released for the first three episodes of Commander Keen, ATR will be explained based without code examples. The later versions of Commander Keen, including Keen Dreams, used a different, improved engine which will be explained in the next section[1].

The EGA screen in mode `0xD` has a resolution of 320x200 pixels, which is 40x200 bytes. Let's extend the height by 8 bytes to have a height of 208 pixels, so the screen fits nicely in 20x13 tiles of 16x16 pixels. By making the virtual screen one tile higher (16 bytes) and one wider (2 bytes) on each side of the screen, the engine can scroll up to 16 pixels to any direction of the screen without any tile refresh, by simply adjusting the CRTC Start Address and Pel Pan registers.




Now, let's have a closer look at the EGA VRAM setup. The video memory is organized into three virtual screens:

- Page 0 and 1, which are used to switch between buffer and visible screen. The idea between two pages (double buffer) is that the code can draw in the second buffer while the first buffer is being shown on screen, which is then switched out during screen refresh. This ensures that no frame is ever displayed mid-drawing, which yields smooth, flicker-free animation.

[1] https://retrocomputing.stackexchange.com/questions/22175/what-is-adaptive-tile-refresh-in-the-context-of-commander-keen

- A master page containing a static page, which is copied to the second buffer when performing the screen refresh.

Each virtual screen has a size of 44*240=10,560 bytes per memory bank, which totals to 42KB. So within a 256KB EGA card there is enough VRAM available to keep all three virtual screens in memory. The page that is actually displayed at any given time is selected by setting the CRTC Start Address register at which to begin fetching video data.

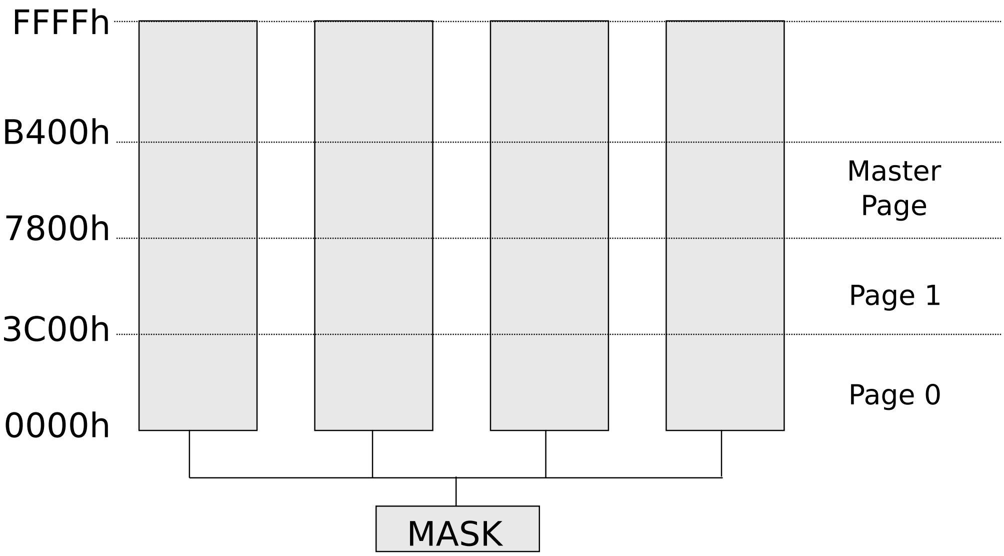



***Figure 5:*** Virtual screen layout on EGA card.

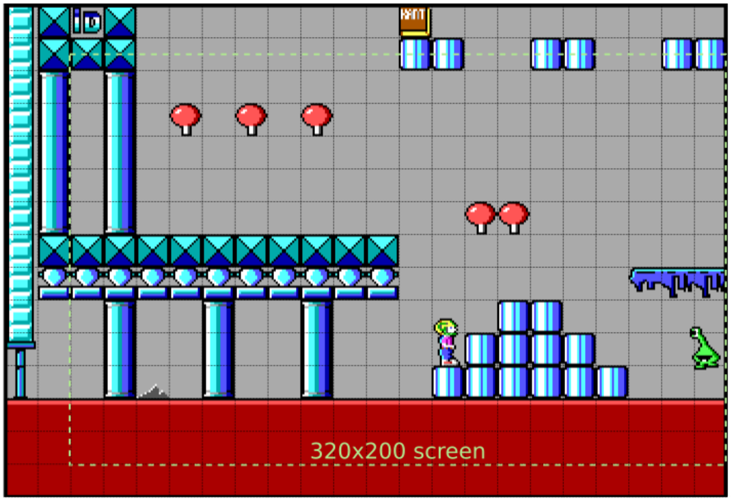
For both the buffer and visible screen a tile index array is created to maintain which tiles are changed since last refresh.

```
byte   update[2][UPDATESIZE];
```

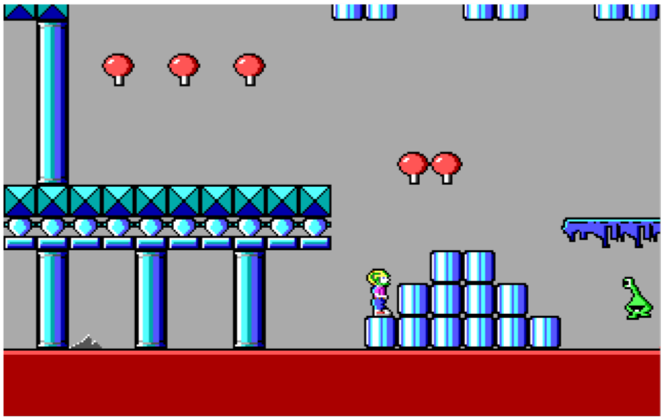
The steps to refresh the screen are as follows:

1. Check if the player has moved one tile in any direction.
2. Validate which tiles have changed and copy these respective tiles to the master page and mark the tiles in both tile index arrays.
3. Refresh the buffer page by scanning the tile index array. If a tile is marked, copy the tile from the master page to the buffer page.
4. Switch the view and buffer page by adjusting the CRTC Start Address and Pel Panning registers.

For now let's ignore sprites on the screen, that will be explained in the next section. In the next four screenshots, we take you step-by-step through each of the stages. The player has reached the edge of the virtual screen and moves further to the right.




Virtual Screen



Display

***Figure 6:*** Start: Need to scroll screen to the right

The engine keeps track of which tile IDs are in the virtual screen. Since the engine only refresh at tiles size granularity, it can determine extremely fast what has changed on the screen by comparing tile IDs. If the tile number has changed, the tile is updated by copying tiles from RAM into the VRAM master page. The changed tiles are marked with a '1' in both tile arrays, which means it needs to be updated upon next refresh.

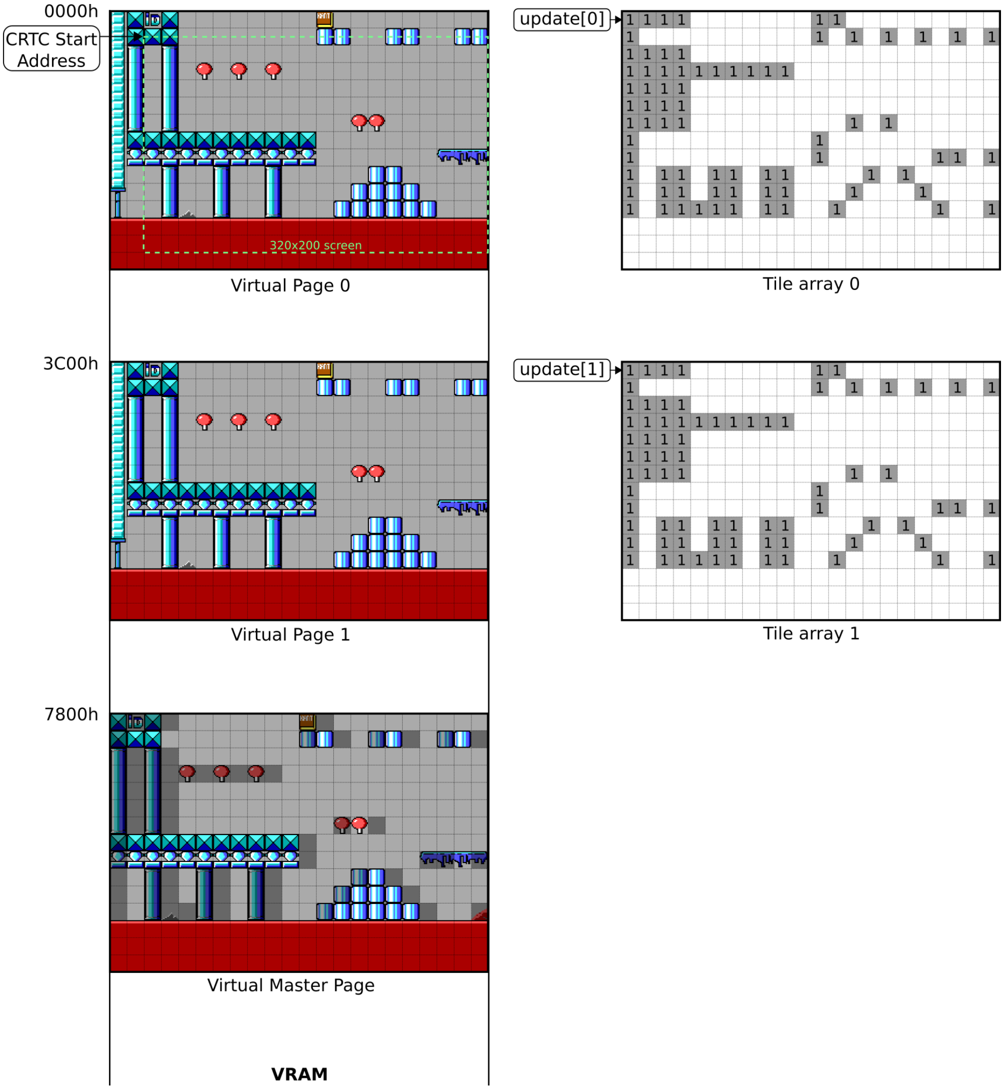



***Figure 7:*** Update tiles in master page and update both tile arrays.

The next step is to scan all tiles in tile array 1 and for each tile marked ’1’, copy the corresponding tile from master to virtual page 1 page.

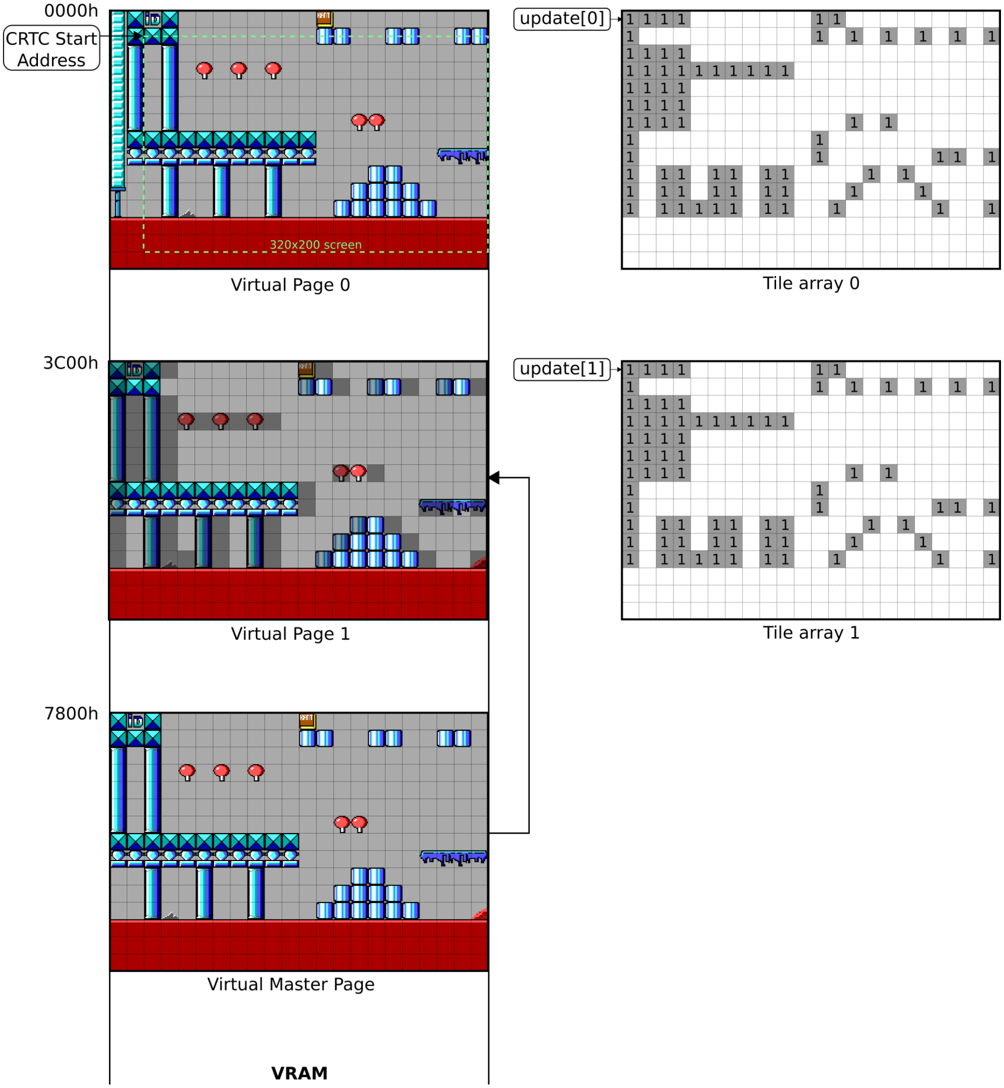



***Figure 8:*** Copy changes tiles from virtual master page to page 1.

In the last step, point the visible screen to virtual page 1 by updating the CRTC start address. Finally, tile array 1 is cleared to '0'. Now the first step is repeated, but this time virtual page 0 acts as the buffer screen. Note that after swapping, tile array 0 keeps marked tiles from last update. This makes sense, as the current buffer page is not yet refreshed since it was displayed in the previous refresh cycle.

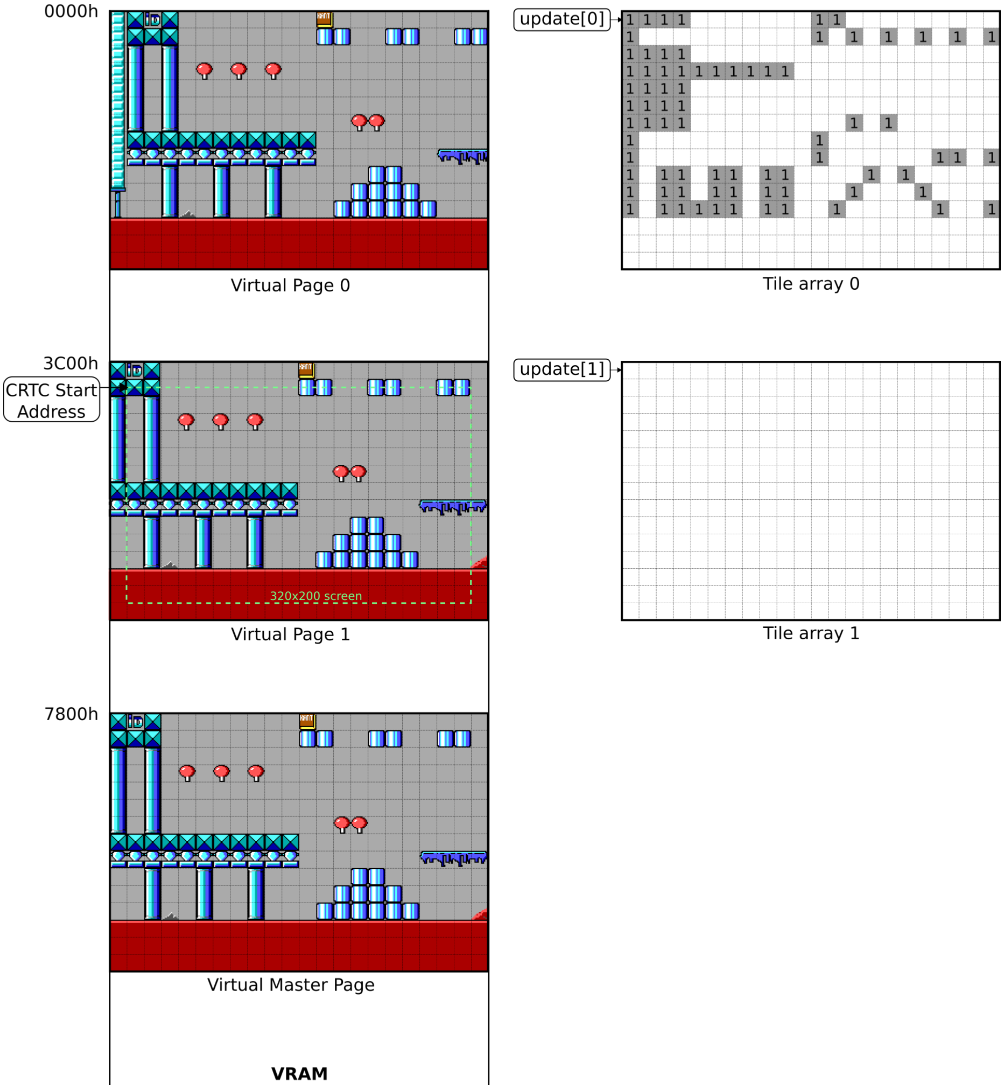



***Figure 9:*** Update CRTC Start Address to virtual page 1 and empty tile array 1.

Now the buffer is refreshed and the CRTC address is updated, the final step is fine adjustment using the Pel Panning register.

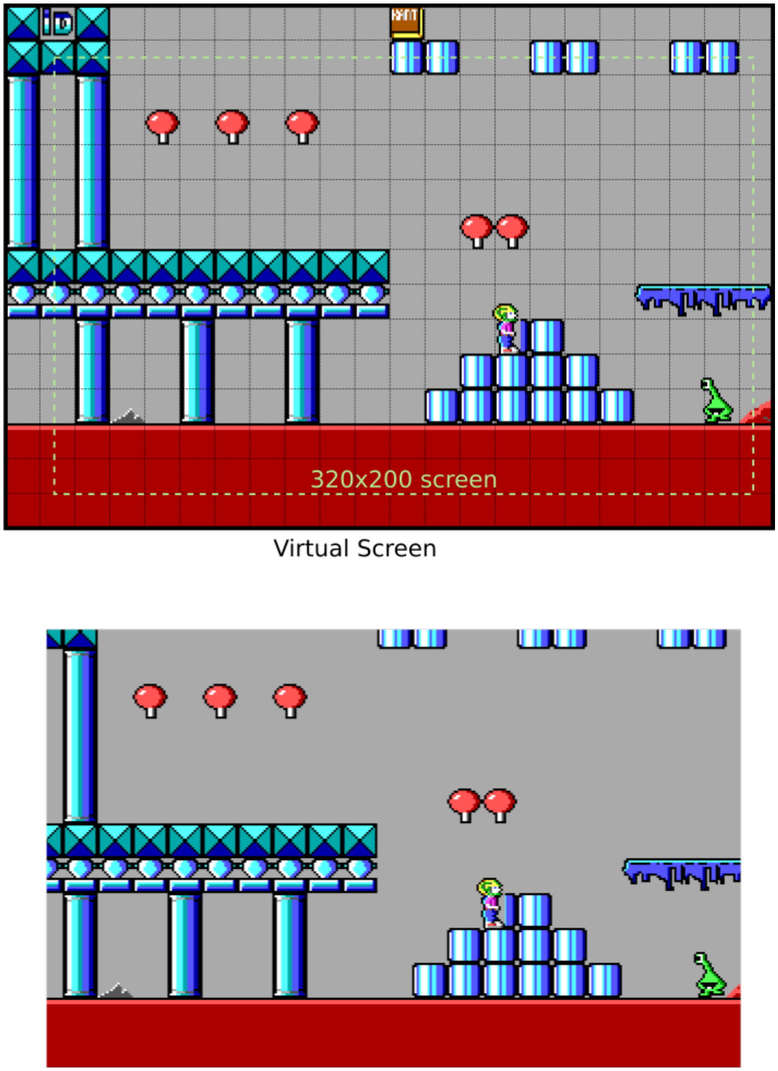



***Figure 10:*** End: Screen is refreshed and scrolled to the right.

### 0.3.1 Wrap around the EGA Memory

John Carmack explored what would happen if you push the virtual screen over the 64kB border (address `0xFFFF`) in video memory. It turned out that the EGA continues the virtual screen at `0x0000`. This means you could wrap the virtual screen around the EGA memory and only need to add a stroke of tiles on one of the edges when Commander Keen moves more than 16 pixels.

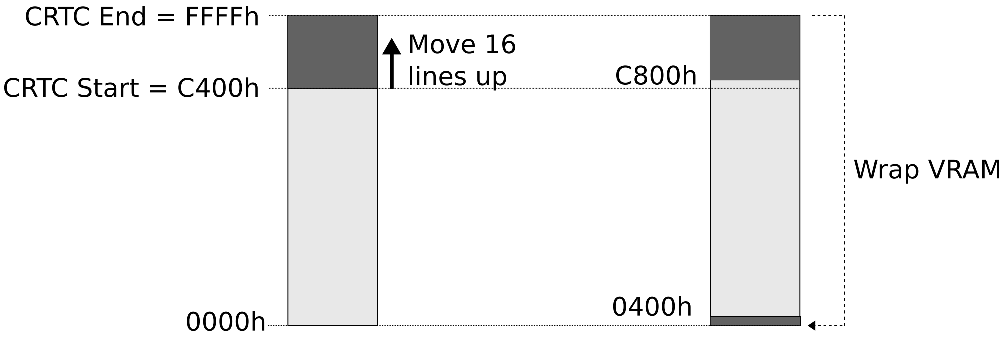



***Figure 11:*** Wrap virtual screen around the EGA memory

> I finally asked what actually happens if you just go off the edge [OF THE VRAM]?
>
> If you take your [CRTC] start and you say OK, I can move over and I get to what should be the bottom of the memory window. [...] What happens if I start at 0xFFFE at the very end of the 64k block? It turns out it just wraps back around to the top of the block.
>
> I'm like oh well this makes everything easy. You can just scroll the screen everywhere and all you have to draw is just one new line of tiles.
>
> It just works. We no longer had the problem of having fields of similar colors. It doesn't matter what you're doing, you could be having a completely unique world and you're just drawing the new strip.
>
> **John Carmack**[2]

[2] An explanation further elaborated during an interview with Lex Fridman in 2022.

There was however an issue with the introduction of Super VGA cards, which had typically more than 256kB RAM[3]. This resulted in crippled backwards compatibility and the wrapping around `0xFFFF` did not work anymore on these cards.

There is a simple way to resolve this issue. As you can see in Figure 5 on page 10, the space between `0xB400` and `0xFFFF` is not used and contains enough space for another virtual screen. Each screen buffer has a size of `0x3C00` in each memory bank. In case the start address is between `0xC400` and `0xFFFF` the corresponding screen is copied to the opposite end of the buffer, as illustrated in Figure 12.

> I was in a tough position. Do I have to track every single one of these [SUPER VGA CARDS] and it was a madhouse back then with 20 different video card vendors with all slightly different implementations of their non-standard functionality. Either I needed to natively program all of the cards or I kind of punt. I took the easy solution of when you finally did run to the edge of the screen I accepted a hitch and just copied the whole screen up.
>
> **John Carmack**

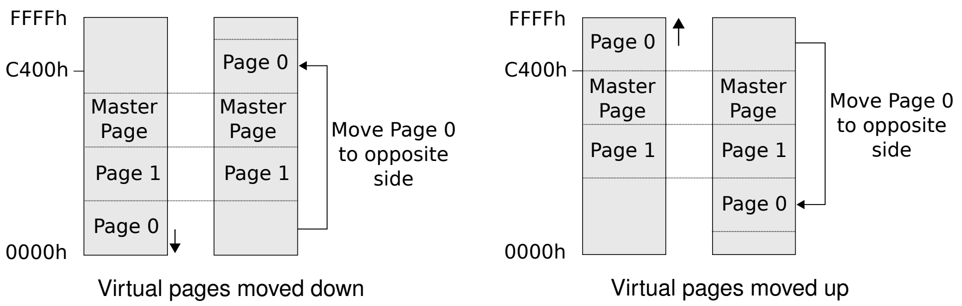



***Figure 12:*** Move screen to opposite end of VRAM buffer

[3]In 1989 the VESA consortium standardized an API to use Super VGA modes in a generic way. One of the first modes was 640x480 at 256 colors requiring at least 256kB RAM, which from a hardware constraint resulted in 512kB.

```
#define SCREENSPACE    (SCREENWIDTH*240)
#define FREEEGAMEM     (0x10000l-3l*SCREENSPACE)

screenmove = deltay*16*SCREENWIDTH + deltax*TILEWIDTH;
for (i=0;i<3;i++)
{
  screenstart[i]+= screenmove;
  if (compatability && screenstart[i] > (0x10000l-
   SCREENSPACE) )
  {
    //
    // move the screen to the opposite end of the buffer
    //
    screencopy = screenmove>0 ? FREEEGAMEM : -FREEEGAMEM;
    oldscreen = screenstart[i] - screenmove;
    newscreen = oldscreen + screencopy;
    screenstart[i] = newscreen + screenmove;
    // Copy the screen to new location
    VW_ScreenToScreen (oldscreen,newscreen,
       PORTTILESWIDE*2,PORTTILESHIGH*16);

    if (i==screenpage)
      VW_SetScreen(newscreen+oldpanadjust,oldpanx &
   xpanmask);
  }
}
```

But how can we copy four VRAM planes fast enough, without noticing any performance hit? As explained in Section **??** each pixel is encoded by four bits, which are spread across the four EGA banks. Since all write operations are one byte wide, it is not hard to imagine the difficulty in plotting a single pixel without changing the others stored in the same byte. One would have to do four read, four xor, and four writes.

Since the designers of the EGA were not complete sadists, they added some circuitry to simplify this operation. For each bank, they created a latch placed in front of a configurable ALU.

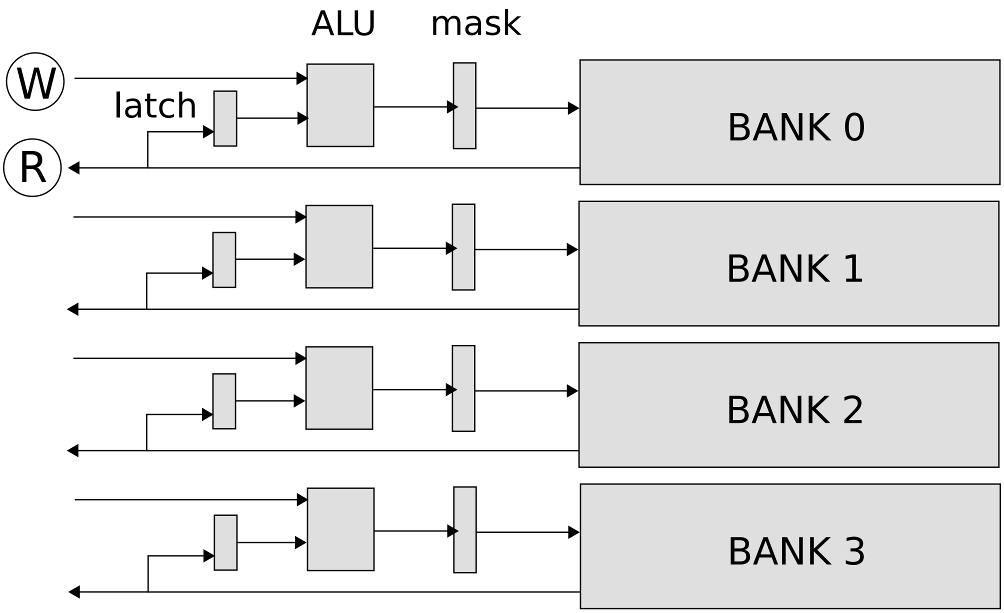



***Figure 13:*** Latches memorize read operations from each bank. The memorized value can be used for later writes.

With this architecture, each time the VRAM is read (R), the latch from the corresponding bank is loaded with the read value. Each time a value is written to the VRAM (W), it can be composited by the ALU using the latched value and the written value. This design allowed mode `0Dh` programmers to plot a pixel easily with one read, one ALU setup, and one write instead of four reads, 4 xors, and 4 writes.

By getting a little creative, the circuitry can be re-purposed. The ALU in front of each bank can be setup to use only the latch for writing. With such a setup, upon doing one read, four latches are populated at once and four bytes in the bank are written with only one write to the RAM. This system allows transfer from VRAM to VRAM 4 bytes at a time. Now it is possible to copy the entire buffer fast enough, without notifying any performance impact.

```
GC_INDEX    =   0x3CE    ;Graphics Controller register
GC_MODE     =   5        ;mode register
SC_INDEX    =   0x3C4    ;Sequence register
SC_MAPMASK  =   2        ;map mask register

;==============
;
; Set EGA mode to read/write from latch
;
;==============

cli                      ;interrupts disabled
mov dx,GC_INDEX          ;mode 1, each memory plane is
mov ax,GC_MODE+256*1     ;written with the content of
out dx,ax                ;the latches only

mov dx,SC_INDEX          ;enable writing to all 4 planes
mov ax,SC_MAPMASK+15*256 ;at once
out dx,ax

sti                      ;interrupts enabled
```

To take full advantage of this optimization, the refresh algorithm maintains a list of tiles that are already copied on the master page via `tilecache` variable. If a tile is already on the master page the algorithm copies the tile from that location to its destination instead of the RAM location in memory, saving the four separated writes to each memory plane.

### 0.3.2 Adaptive tile refreshment in Commander Keen in Keen Dreams

The EGA memory wrapping results in an improved, more simplified Adaptive Tile Refreshment algorithm. The following six steps take place, where `*screenstart[]` are pointers to the starting address (upper-left pixel) of the viewports in VRAM and `*updatestart[]` are pointers to the tile view and buffer arrays.

1. Check if the player has moved one tile in any direction.
2. In case the player moved one tile, move the `*screenstart[]` and `*update[]` pointers accordingly and copy the new column or row of tiles to the master page and flag this new column/row of tiles to be updated in the next refresh for both pages.
3. Refresh the buffer page by scanning all tiles in the tile buffer array. If a tile is flagged for update, copy the tile from the master page to the buffer page.
4. Iterate through the sprite removal list and copy corresponding image block from master page to buffer page.
5. Iterate through the sprite list and copy corresponding sprite image block from RAM to buffer page.
6. Switch the view and buffer page by adjusting the CRTC Start Address and Pel Panning register.

As you can see, only step 2 is different from Commander Keen 1-3, the rest of the steps are the same. In the example below the screen is forced to scroll to the left.

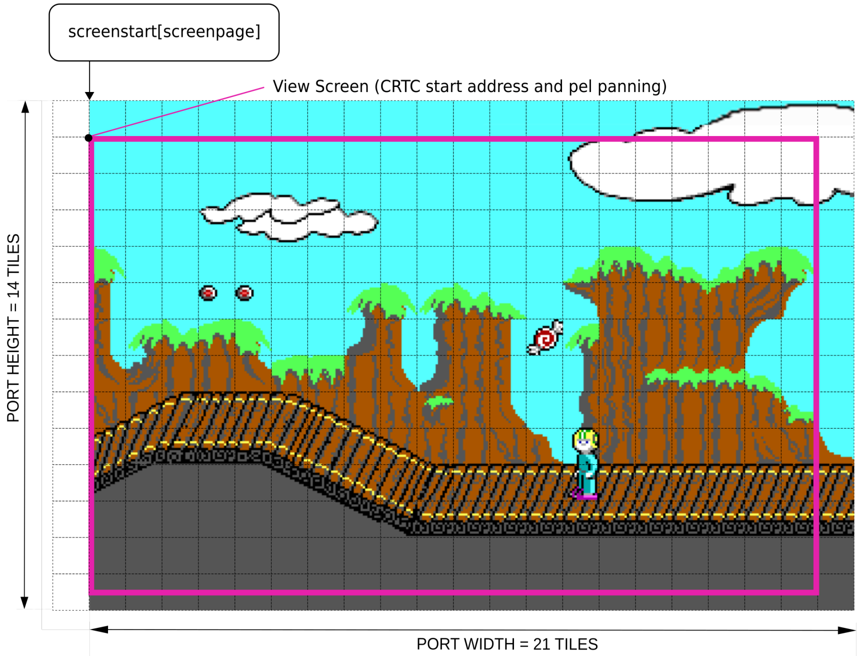



***Figure 14:*** Step 1: Scroll screen to the left

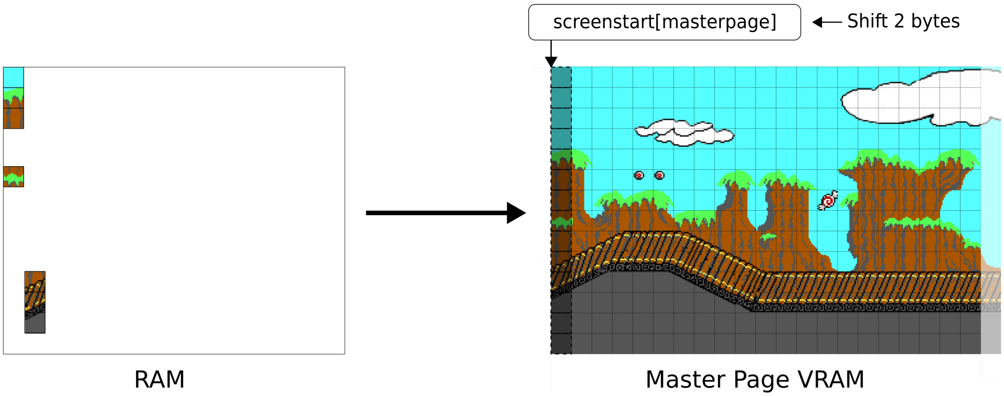



***Figure 15:*** Step 2 and 3: Shift screen pointer and add column to VRAM

First decrease the `*screenstart[]` pointers by 2 bytes (1 tile). Then copy a left-column of new tiles from RAM to the master page.

In parallel both tile array pointers are decreased by one byte and each tile on the left border in both buffer arrays is marked with '1', so it is updated upon the next refresh. Finally, the most right column (which is now outside the view port) is marked with a '0'.

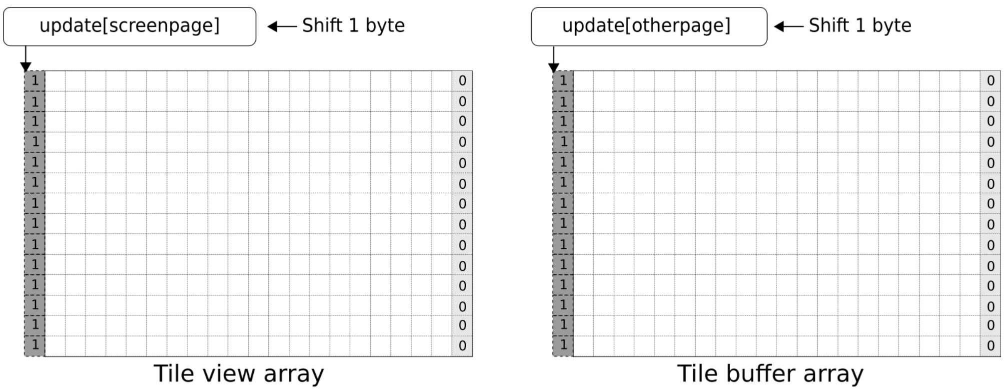



***Figure 16:*** Mark new column in both tile buffer and display array.

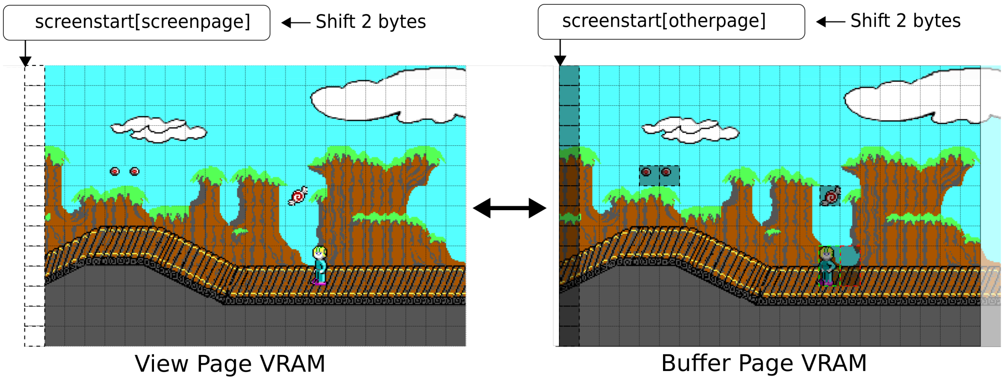



***Figure 17:*** Step 3 to 6: Update buffer page with tile animations and sprites

Just like before, we copy the animated tiles from RAM to master page and mark them as '1' in both tile arrays. Then we scan all '1' and copy those tiles from master to buffer page. The remaining steps are the same as before, meaning erasing and copying sprites to the buffer page and finally swap the buffer and view pages.

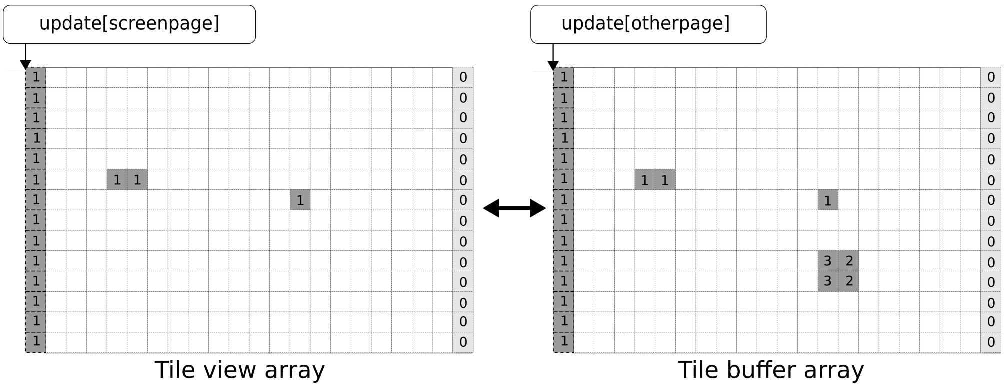



***Figure 18:*** Final tile arrays layout after buffer page is updated.

**<u>Trivia :</u>** The removal blocks which are marked '2' in the tile buffer array are nowhere used in the engine.

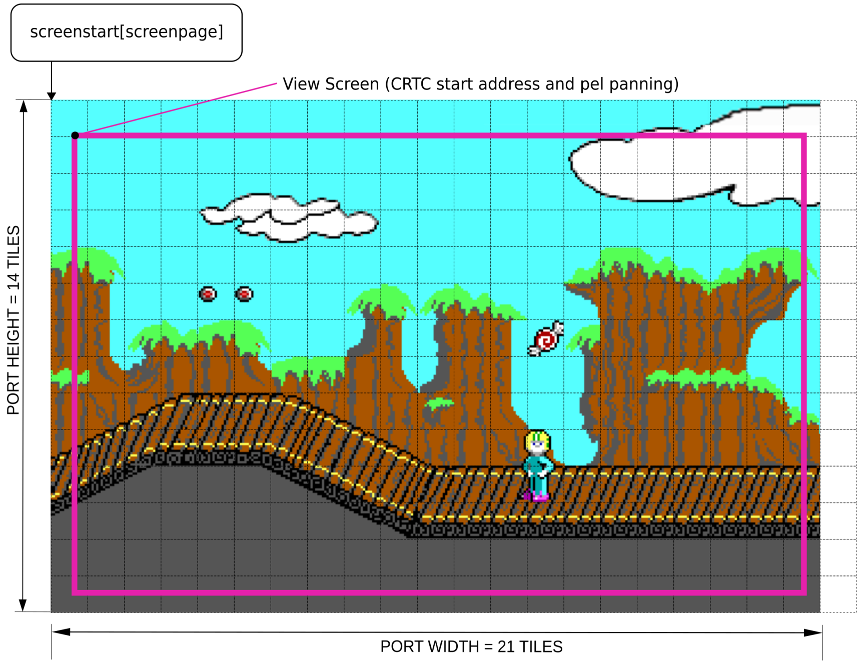



***Figure 19:*** Step 7: Updated screen after swapping buffer and screen page

Since we only need to update one border, the engine needed to update only 6% of the screen!

```
void RF_Refresh (void)
{

    updateptr = updatestart[otherpage];

    RFL_AnimateTiles ();// update animated tiles

    // copy newly scrolled and animated tiles
    // from the master to buffer screen
    EGAWRITEMODE(1);
    EGAMAPMASK(15);      // write 4 bytes of VRAM at once
    RFL_UpdateTiles (); // copy from master to buffer page
    RFL_EraseBlocks (); // remove sprites

    // update sprites
    EGAWRITEMODE(0);
    RFL_UpdateSprites ();

    // display the changed screen (swap view and buffer)
    VW_SetScreen(bufferofs+panadjust,panx & xpanmask);

}
```

Now we can also explain why the tile buffer and view arrays are 2 tiles wider on all sides than the view port as illustrated in Figure 31. Let's take the situation where the screen scrolls to the top-left, meaning 1 tile left and 1 tile up as illustrated in Figure 20. Both `*updatestart` pointers are updated and tiles are marked as '1'. After completing all tile refresh steps, the buffer page is updated on places where the tile buffer array is marked '1'.

After the view page is swapped with the buffer page, the `*updatestart[otherpage]` pointer is cleared and the array is reset to '0'. However, the `*updatestart[screenpage]` is not cleared nor reset since we did not update the view page (we only updated the buffer page).

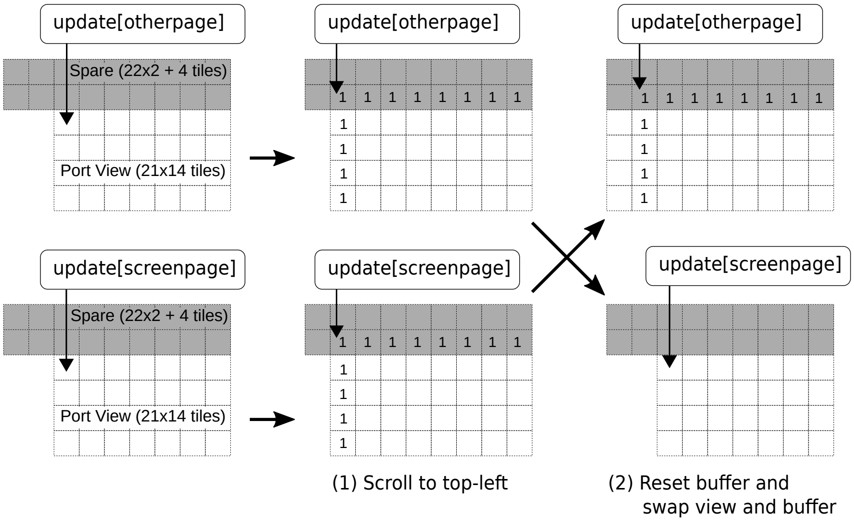



***Figure 20:*** scroll to top-left tile.

Now, if the screen is again scrolling to the top-left one can see why there is a need for the 2nd row in the buffer. After this cycle the `*update[otherpage]` pointer is cleared and reset as shown in the illustration below.

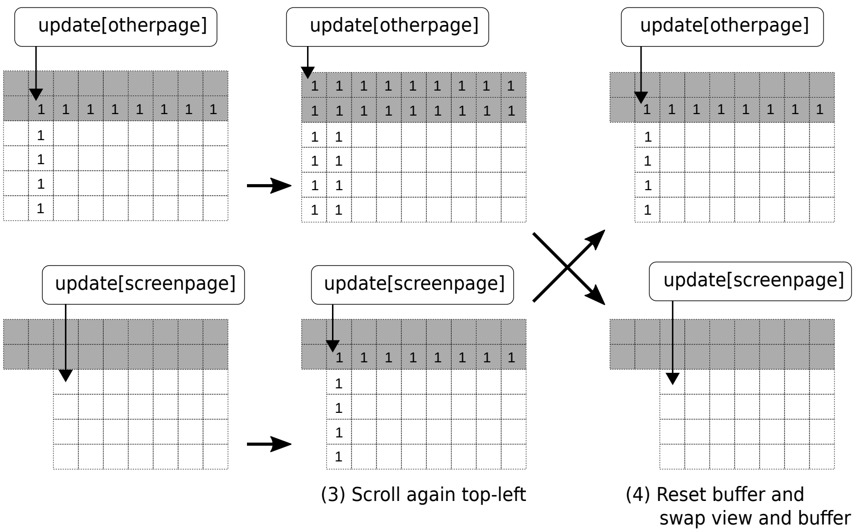
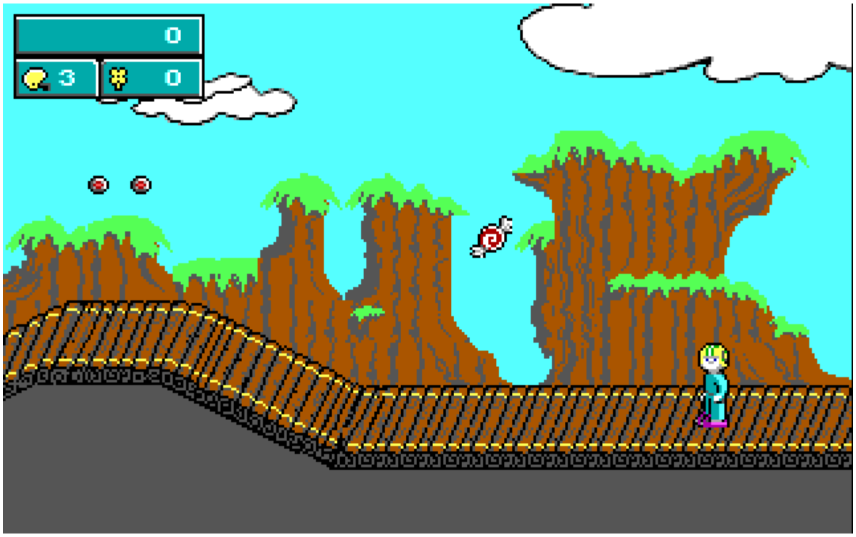


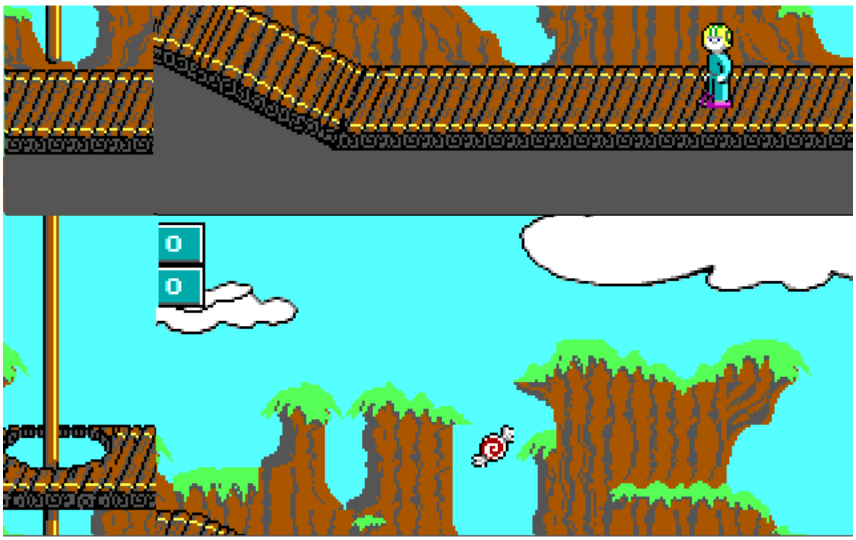

***Figure 21:*** scroll to top-left tile again.

### 0.3.3 Screen refresh

Flipping between the pages is as simple as setting the CRTC start address registers to page 0 or page 1 starting point. However, there is one issue to solve. If you were to run it, every once in a while the expected screen shown below...




...would instead appear distorted:



This glitch shows both misalignment and parts of two pages. This problem has to do with the timing between updating the CRTC starting address and screen refresh. The start address is latched by the EGA's internal circuitry exactly once per frame, typically at the start of the vertical retracement. The CRTC starting address is a 16-bit value but the `out` instruction can only write 8 bits at a time.

Now we have the following situation, where the current CRTC start address (Page 0) is pointing to `0x0000` and the buffer (Page 1) to `0x3C00`. We moved one tile to the left and now Page 0 is pointing at 0xFFFE in VRAM and Page 1 is at 0x3BFE. Page 1 is the updated buffer and will be displayed upon next refresh cycle. Poor timing of the vertical retracement and start address update results in the CRTC only picking up the first byte of the address, `0x3B`, and setting the new start address to `0x3B00` instead of `0x3BFE`.

```
CRTC_INDEX   = 03D4h
CRTC_STARTHIGH  = 12

  cli                        ;disable interrupts
  mov  cx,[crtc]             ;[crtc] is start address
  mov  dx,CRTC_INDEX         ;set CRTR register
  mov  al,CRTC_STARTHIGH     ;start address high register
  out  dx,al
  inc  dx                    ;port 03D5h
  mov  al,ch
  out  dx,al                 ;set address high

  ;******** VERTICAL RETRACE STARTS HERE  !!!!!!!  ****
  ;******** AND SHOWS 2 PARTIAL FRAMEBUFFERS **********

  dec  dx                    ;set CRTR register
  mov  al,0dh                ;start address low register
  out  dx,al
  mov  al,cl
  inc  dx                    ;port 03D5h
  out  dx,al                 ;set address low
  sti                        ;enable interrupts

  ret
```

The most obvious solution to this issue is to update the start address when we pick up the vertical retracement signal via the Input Status 1 Register (bit 3 of `0x3DA`). Unfortunately, by the time the vertical retrace status is observed by a program, the start address for the next frame has already been latched, having happened the instant the vertical retrace pulse began.

The trick is to update the start address sufficient far away from when the vertical retracement starts. So we're looking for a signal that tells us it just finished a horizontal or vertical retrace and started a scan line, far enough away from vertical retrace so we can be sure the new start address will get used at the next vertical sync. This signal is provided by the Display Enable status signal via the Input Status 1 Register, where a value of 1 indicates the display is in a horizontal or vertical retracement[4].

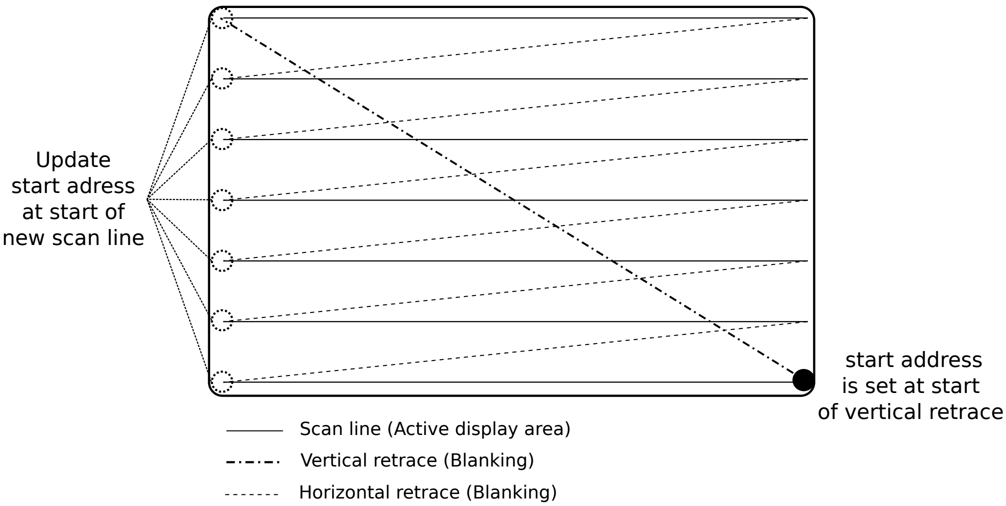



***Figure 22:*** Update CRTC start address at beginning of new scan line.

When the Display Enable status is observed, the program sets the new start address. Once the CRTC start address is updated, the game waits for vertical retrace to happen, sets the new pel panning state, and then continues drawing.

[4] Documentation is a bit unclear here. The IBM technical documentation for VGA explains retrace takes place when bit 0 of the Input Status Register 1 is set to high ('1'). The IBM technical EGA documentation explains the opposite, saying when bit 0 is set low ('0') a retrace is taking place. For now, we assume source code and VGA documentation is correct, retrace takes place on a '1'.

```
;==============
;
; VW_SetScreen
;
;==============

  mov dx,03DAh          ;Status Register 1
;
; wait util the CRTC just starts scaning a diplayed line
; to set the CRTC start
;
  cli

@@waitnodisplay:        ;wait until scan line is finished
  in  al,dx
  test  al,01b
  jz  @@waitnodisplay

@@waitdisplay:          ;wait until retrace is finished
  in  al,dx
  test  al,01b
  jnz @@waitdisplay

endif

; #### set CRTC start address

;
; wait for a vertical retrace to set pel panning
;
  mov dx,STATUS_REGISTER_1
@@waitvbl:
  sti                  ;service interrupts
  jmp $+2
  cli
  in  al,dx
  test  al,00001000b   ;look for vertical retrace
  jz  @@waitvbl

endif

; #### set horizontal panning
```

## 0.4 Actors and sprites

### 0.4.1 A.I.

To simulate enemies, some objects are allowed to "think" and take actions like walking, shooting or emitting sounds. These thinking objects are called "actors". Actors are programmed via a state machine. They can be aggressive (chase you), just running in any direction, or dump (throwing things at you). To model their behavior, all enemies have an associated state:

- Chase Keen
- Smash Keen
- Shoot projectile
- Climb and slide from pole
- Walking around
- Turn into flower
- Special Boss (Boobus)

Each state has associated think, reaction and contact method pointers. There is also a next pointer to indicate which state the actor should transition to when the current state is completed.

```
typedef struct
{
  int     leftshapenum,rightshapenum; // Sprite to render
                                      // on screen
  enum    {step,slide,think,stepthink,slidethink} progress;
  boolean skippable;
  boolean pushtofloor;  // Make sure sprites stays
                        // connected with ground
  int tictime;          // How long stay in that state
  int xmove;
  int ymove;
  void (*think) ();
  void (*contact) ();
  void (*react) ();
  void *nextstate;
} statetype;
```

All actors have a state chain, as example the tater trooper.

```
statetype s_taterwalk1 = {TATERTROOPWALKL1SPR,TATERTROOPWALKR1SPR, step ,
    false , true ,10 , 128,0, TaterThink , NULL, WalkReact , &s_taterwalk2 };
statetype s_taterwalk2 = {TATERTROOPWALKL2SPR,TATERTROOPWALKR2SPR, step ,
    false , true ,10 , 128,0, TaterThink , NULL, WalkReact , &s_taterwalk3 };
statetype s_taterwalk3 = {TATERTROOPWALKL3SPR,TATERTROOPWALKR3SPR, step ,
    false , true ,10 , 128,0, TaterThink , NULL, WalkReact , &s_taterwalk4 };
statetype s_taterwalk4 = {TATERTROOPWALKL4SPR,TATERTROOPWALKR4SPR, step ,
    false , true ,10 , 128,0, TaterThink , NULL, WalkReact , &s_taterwalk1 };

statetype s_taterattack1 = {TATERTROOPLUNGEL1SPR,TATERTROOPLUNGER1SPR,
    step , false , false ,12 , 0 ,0 , NULL, NULL, BackupReact , &s_taterattack2 };
statetype s_taterattack2 = {TATERTROOPLUNGEL2SPR,TATERTROOPLUNGER2SPR,
    step , false , false ,20 , 0 ,0 , NULL, NULL, DrawReact , &s_taterattack3 };
statetype s_taterattack3 = {TATERTROOPLUNGEL1SPR,TATERTROOPLUNGER1SPR,
    step , false , false ,8 , 0 ,0 , NULL, NULL, DrawReact , &s_taterwalk1 };
```

All types of enemies (including Boobus) have their own state machine. They often share the same reactions (e.g. WalkReact and ProjectileReact), but often have their own thinking state.

### 0.4.2 Drawing Sprites

Once the state of the actor is updated, it is time to render the actor on the screen. This is done using sprites and contains the following steps:

1. Update the state and move actors within the active region.
2. Determinate if a actor has changed or moved
3. Update the actor by removing and drawing sprites to it's new position

Unlike many game consoles such as Nintendo, the concept of sprites did not exists on the EGA card, so again the team needs to write their own solution. As explained in Section **??** (Page 34, table 1) each sprite asset contains additional information which is illustrated in Figure 23.

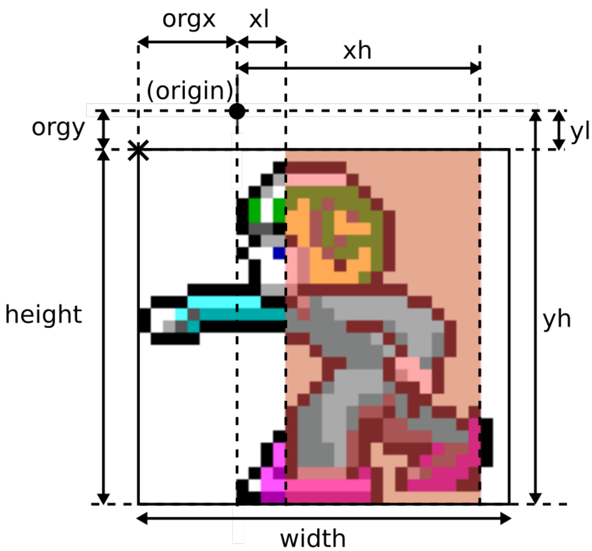



***Figure 23:*** sprite structure

All global movement takes place from the origin. The origin is offset by `(orgx, orgy)` from the top-left location of the sprite. The parameters `(xl, xh, yl, yh)` define the hit box of the sprite, which is used to detect collisions.

| index | width | height | orgx | orgy | xl | yl | xh | yh | shift |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 3 | 24 | 0 | 0 | 0 | 0 | 368 | 368 | 4 |
| 1 | 3 | 32 | 0 | 0 | 64 | 0 | 304 | 496 | 4 |
| 2 | 3 | 30 | 0 | 16 | 64 | 0 | 304 | 496 | 4 |
| 3 | 3 | 30 | 0 | 32 | 64 | 48 | 304 | 496 | 4 |
| 4 | 3 | 32 | 0 | 0 | 64 | 0 | 304 | 496 | 4 |
| 5 | 3 | 30 | 0 | 32 | 64 | 48 | 304 | 496 | 4 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 296 | 12 | 103 | -128 | 0 | 256 | 128 | 752 | 1648 | 4 |

***Table 1:*** content of spritetable[] in the `KDREAMS.EGA` asset file.

Once the new state and movement of the actor is calculated from the state machine, the engine needs to first remove the current sprite from the buffer and then redraw the sprite on the new location.

Erasing sprites from the buffer page is done by maintaining a list of erase blocks. Each erase block contains the screen (x,y) location, width and height of the sprite to be erased.

Instead of copying each variable one-by-one, it makes smartly use of `memcpy` function.

```
typedef struct spriteliststruct
{
    //This is the same structure as eraseblocktype
    int     screenx,screeny;
    int     width,height;
    //----------------------------------------------

    unsigned  grseg,sourceofs,planesize;
    [...]
} spritelisttype;


typedef struct
{
    int     screenx,screeny;
    int     width,height;
} eraseblocktype;


//
// post an erase block to both pages by copying
// screenx,screeny,width,height
// both pages may not need to be erased if the sprite
// just changed last frame (updatecount = 2)
//
if (sprite->updatecount<2)
{
    if (!sprite->updatecount)
        memcpy (eraselistptr[otherpage]++,sprite,
            sizeof(eraseblocktype));
    memcpy (eraselistptr[screenpage]++,sprite,
        sizeof(eraseblocktype));
}
```

The engine is maintaining two list of erase blocks; one for the view page and one for the buffer page. As explained before, each erase block is copying from the (static) master page to the buffer page.

As each sprite can float freely over the screen, also here bitshifted sprites are used to position the sprite on a byte-aligned memory layout (as explained in section **??** on page **??**). The value in the shift column defines the amount of steps the sprite has to be shifted within 8 pixels. A shift value of 4 means the sprite is shifted in 4 steps with a 2 pixel interval.

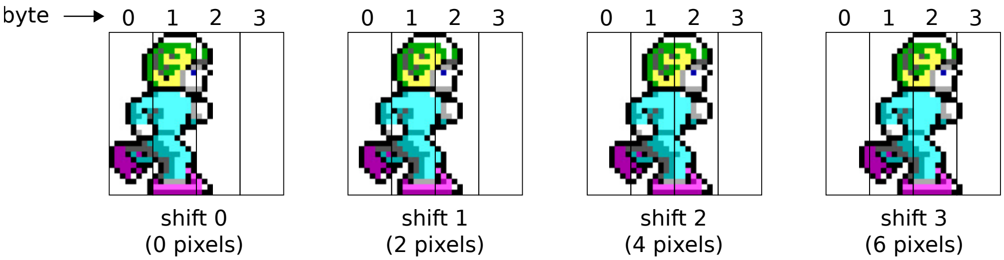


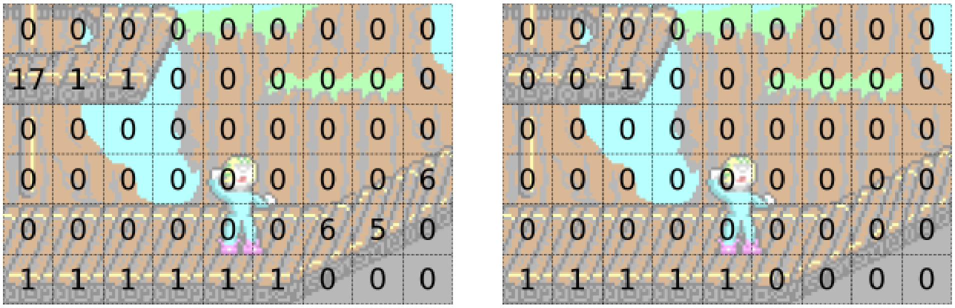

***Figure 24:*** Sprite shifted in 4 steps.

Displaying the correct shifted sprite is as simple as below.

```
//Set x,y to top-left corner of sprite
y+=spr->orgy>>G_P_SHIFT;
x+=spr->orgx>>G_P_SHIFT;

shift = (x&7)/2;  // Set sprite shift
```

### 0.4.3 Clipping

Before drawing a sprite on the screen, the engine determines if the boundaries of a sprite are hitting a wall or floor. This is called clipping and ensures an actor doesn't fall through a floor or walks through a vertical wall. To define whether a tile is a wall or floor, a tile is enriched with tile information, as explained in section **??** on page **??**. Each foreground tile contains a `NORTHWALL`, `SOUTHWALL`, `EASTWALL` and `WESTWALL`, as explained in section **??**. A number greater than 0 means the tile is a wall or floor when approaching from a given direction.




***(a)*** Wall type map NORTHWALL ***(b)*** Wall type map EASTWALL

***Figure 25:*** Foreground tile clipping information.

As example, when a sprite, moving from right to left, is hitting a wall on the left side, it will update the sprite movement to ensure the sprite clips to the east wall of the left tile as illustrated in Figure 26. The east/west wall clipping logic is covered by `ClipToEastWalls()` and `ClipToWestWalls()` functions.

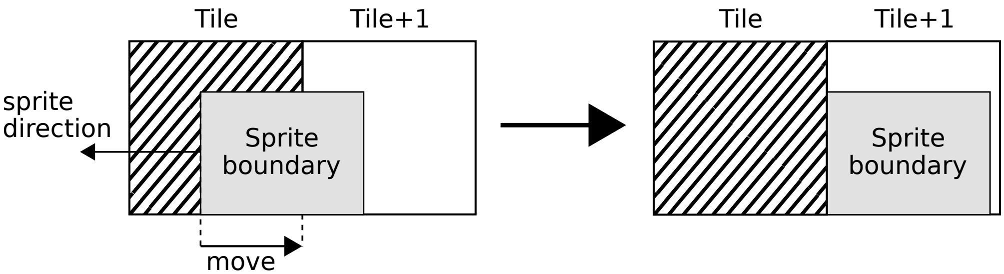



***Figure 26:*** Clipping to east wall when moving from the west.

```
void ClipToEastWalls (objtype *ob)
{
    ...

  for (y=top;y<=bottom;y++)
  {
    map = (unsigned far *)mapsegs[1] +
      mapbwidthtable[y]/2 + ob->tileleft;

    //Check if we hit EAST wall
    if (ob->hiteast = tinf[EASTWALL+*map])
    {
      //Clip left side actor to left side
      //of next right tile
      move = ( (ob->tileleft+1)<<G_T_SHIFT ) - ob->left;
      MoveObjHoriz (ob,move);
      return;
    }
  }
}
```

For clipping top and bottom the engine also needs to take clipping to slopes into account. After the sprite is clipped to the top or bottom of the wall tile, an offset can be applied to move a sprite up or down a slope. The offset is defined by a lookup table, where the midpoint of the sprite and the wall type from the foreground tile defines the offset.

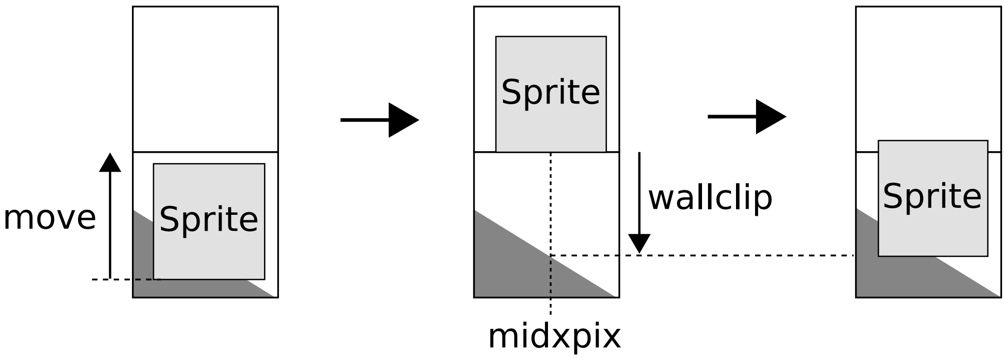



***Figure 27:*** Clipping north wall with slope.

```
// walltype / x coordinate (0-15)

int wallclip[8][16] = {      // the height of a given point in a tile
{ 256, 256, 256, 256, 256, 256, 256, 256, 256, 256, 256, 256, 256, 256, 256, 256},
{   0,   0,   0,   0,   0,   0,   0,   0,   0,   0,   0,   0,   0,   0,   0,   0},
{   0,0x08,0x10,0x18,0x20,0x28,0x30,0x38,0x40,0x48,0x50,0x58,0x60,0x68,0x70,0x78},
{0x80,0x88,0x90,0x98,0xa0,0xa8,0xb0,0xb8,0xc0,0xc8,0xd0,0xd8,0xe0,0xe8,0xf0,0xf8},
{   0,0x10,0x20,0x30,0x40,0x50,0x60,0x70,0x80,0x90,0xa0,0xb0,0xc0,0xd0,0xe0,0xf0},
{0x78,0x70,0x68,0x60,0x58,0x50,0x48,0x40,0x38,0x30,0x28,0x20,0x18,0x10,0x08,   0},
{0xf8,0xf0,0xe8,0xe0,0xd8,0xd0,0xc8,0xc0,0xb8,0xb0,0xa8,0xa0,0x98,0x90,0x88,0x80},
{0xf0,0xe0,0xd0,0xc0,0xb0,0xa0,0x90,0x80,0x70,0x60,0x50,0x40,0x30,0x20,0x10,   0}
};
```

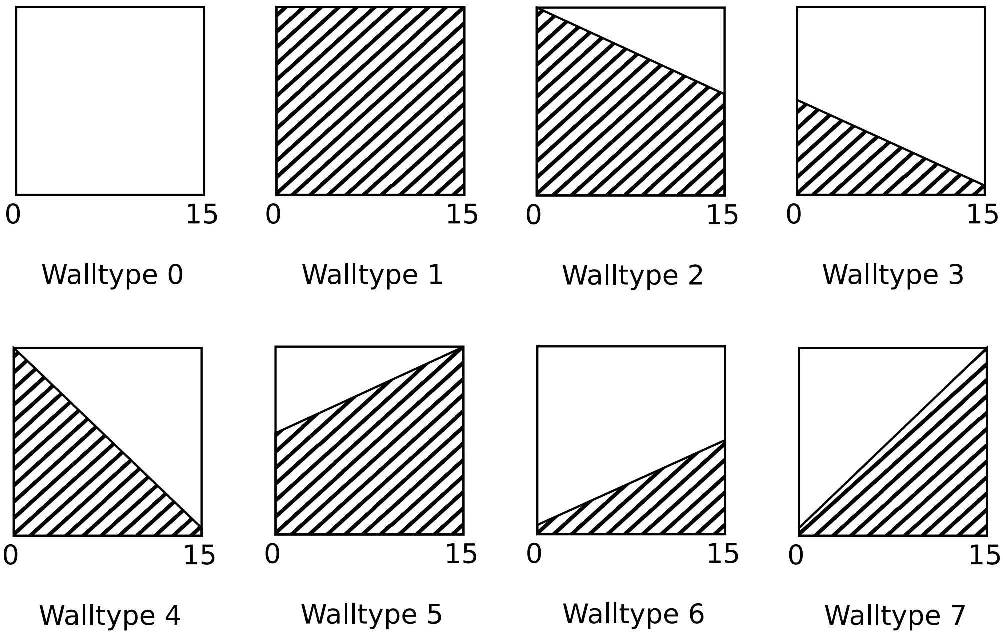



***Figure 28:*** Eight different walltypes (slopes) defined.

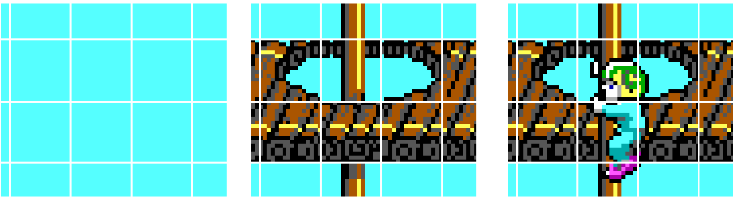
```
void ClipToEnds (objtype *ob)
{
  ...

  //Get midpoint of sprite [0-15]
  midxpix = (ob->midx&0xf0) >> 4;

  map = (unsigned far *)mapsegs[1] +
    mapbwidthtable[oldtilebottom-1]/2 + ob->tilemidx;
  for (y=oldtilebottom-1 ; y<=ob->tilebottom ; y++,map+=
   mapwidth)
  {
    //Do we hit a NORTH wall
    if (wall = tinf[NORTHWALL+*map])
    {
      //offset from tile border clip
      clip = wallclip[wall&7][midxpix];
      //Clip bottom side actor to top side tile + offset-1
      move = ( (y<<G_T_SHIFT)+clip - 1) - ob->bottom;
      if (move<0 && move>=maxmove)
      {
        ob->hitnorth = wall;
        MoveObjVert (ob,move);
        return;
      }
    }
  }
```

### 0.4.4 Priority of tiles and sprites on screen

The normal screen build is as follows:

1. Draw the background tiles.
2. Draw the masked foreground tiles.
3. Draw the sprites on top of both the background and foreground tiles.

If multiple sprites are displayed on the same tile, each sprite is given a priority 0-3 to define the order of drawing. A sprite with a higher priority number is always displayed on top of lower priority sprites. As sprites are always displayed on top of tiles, this is causing unnatural situation when Commander Keen is climbing through a hole as illustrated in Figure 29.



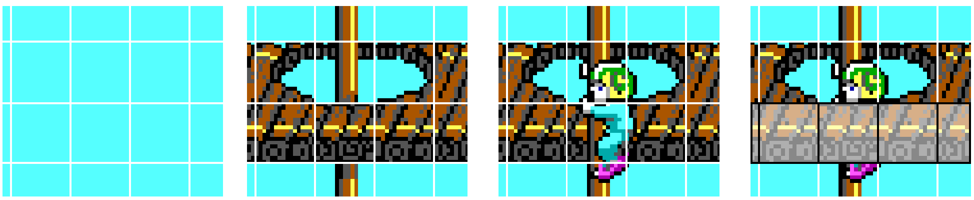
***(a)*** Background tile. ***(b)*** Foreground tile. ***(c)*** Sprite on top.

***Figure 29:*** Unnatural situation where Commander Keen is in front of a hole.

To draw sprites 'inside' a foreground tile, a small trick is used by introducing a priority foreground tile. As explained in section **??** each foreground tile is enriched with INTILE ('inside tile') information. If the highest bit (`80h`) of INTILE is set, this foreground tile has a higher priority than sprites with a priority 0, 1 or 2. So when drawing the tiles and sprites the following drawing order is applied:

1. Draw the background tile.
2. Draw the masked foreground tile.
3. Draw sprites with priority 0, 1 and 2 (in that order) and mark the corresponding tile in the tile buffer array with '3' as illustrated in Figure 35 on page 48.
4. Scan the tile buffer array for tiles marked with '3'. If the corresponding foreground INTILE high bit (`80h`) is set, redraw the masked foreground tile.
5. Finally, draw sprites with priority 3. These sprites are always on top of everything.

The priority foreground tiles are updated in the `RFL_MaskForegroundTiles()` function.



***(a)*** Background tile. ***(b)*** Foreground tile. ***(c)*** Sprite on top. ***(d)*** Redraw masked foreground tile.

***Figure 30:*** Draw sprite inside a tile, by redrawing foreground tile.

```
  jmp SHORT @@realstart   ; start the scan
@@done:
;============
; all tiles have been scanned
;============
  ret

@@realstart:
  mov di,[updateptr]
  mov bp,(TILESWIDE+1)*TILESHIGH+2
  add bp,di          ; when di = bx,
  push di            ; all tiles have been scanned
  mov cx,-1          ; definately scan the entire thing
;============
; scan for a 3 in the update list
;============
@@findtile:
  mov ax,ss
  mov es,ax          ; scan in the data segment
  mov al,3           ; check for tiles marked as '3's
  pop di             ; place to continue scanning from
  repne scasb
  cmp di,bp
  je  @@done
;============
; found a tile, see if it needs to be masked on
;============
  push  di
  sub di,[updateptr]
  shl di,1
  mov si,[updatemapofs-2+di]  ; offset from originmap
  add si,[originmap]
  mov es,[mapsegs+2]      ; foreground map plane segment
  mov si,[es:si]          ; foreground tile number
  or  si,si
  jz  @@findtile          ; 0 = no foreground tile
  mov bx,si
  add bx,INTILE           ; INTILE tile info table
  mov es,[tinf]
  test [BYTE PTR es:bx],80h ; high bit = masked tile
  jz  @@findtile

; mask the tile
```

### 0.4.5 Manage refresh timing

After each screen refresh a certain amount of time, which we call ticks, has passed. The amount of ticks depends on several factors like amount of tiles refreshed and waiting time for a screen vertical retrace. Since all game actions and reactions rely on the amount of ticks between two refreshes, it is important to keep the tick interval consistent.

Without controlling the tick interval, the state and speed of actors could become unreliable, they could run faster and even can "warp" to an unexpected location. To control refresh intervals, a minimum and maximum number of tics is defined in the refresh loop.

```
#define MINTICS          2
#define MAXTICS          6

void RF_Refresh (void)
{
    [...]

//
// calculate tics since last refresh for adaptive timing
//
    do
    {
        newtime = TimeCount;
        tics = newtime-lasttimecount;
    } while (tics<MINTICS);
    lasttimecount = newtime;

    if (tics>MAXTICS)
    {
        TimeCount -= (tics-MAXTICS);
        tics = MAXTICS;
    }
}
```

The game and all actors are defined in a global coordinate system, which is scaled to 16 times a pixel. The higher resolution enables more precision of movements and better simulation of movement acceleration. Conversion between global and pixel coordinatess can be easily performed by bit shift operations.

## 0.5 use later

```
#define G_P_SHIFT 4   // global >> ?? = pixels

void RFL_CalcOriginStuff (long x, long y)
{
  originxglobal = x;
  originyglobal = y;
  [...]

  //panning 0-15 pixels
  panx = (originxglobal>>G_P_SHIFT) & 15;
  //move CRTC + 1 when move >7 pixels
  pansx = panx & 8;
  pany = pansy = (originyglobal>>G_P_SHIFT) & 15;
  //Start location in VRAM
  panadjust = panx/8 + ylookup[pany];
}
```

## 0.6 ATR

In the file `id_vw.h` the virtual screen in VRAM is defined by SCREENSPACE, which is set to 512x240 pixels (64x240 = 15,360 bytes). This is more than sufficient since the visible screen in mode `0x0D` is 320x200 pixels.

Since one screen only uses 15,360 bytes of VRAM (which is 3,840 bytes per plane), there is more than enough space to store more than two full screens of video data.
Before explaining the scrolling algorithm, let's first explain how the tile layout is organized. The EGA screen in mode `0xD` has a resolution of 320x200 pixels. Translated in 16x16 pixel tiles, the screen view has a size of 20x13 tiles (actually 12.5 tiles high, but we round up to 13 tiles). By making the port view one tile higher and wider than the screen, the engine can scroll the screen up to 16 pixels to the right or bottom side of the screen without any tile refresh, by means of adjusting the CRTC Start Address and Pel Pan registers. Finally, the buffer must have enough space to float the view port up to two tiles in all directions (This is

required for later versions of Commander Keen, which will be explained in Section 0.3.2). In total two tile arrays are maintained; one for the view screen and one for the buffer screen.

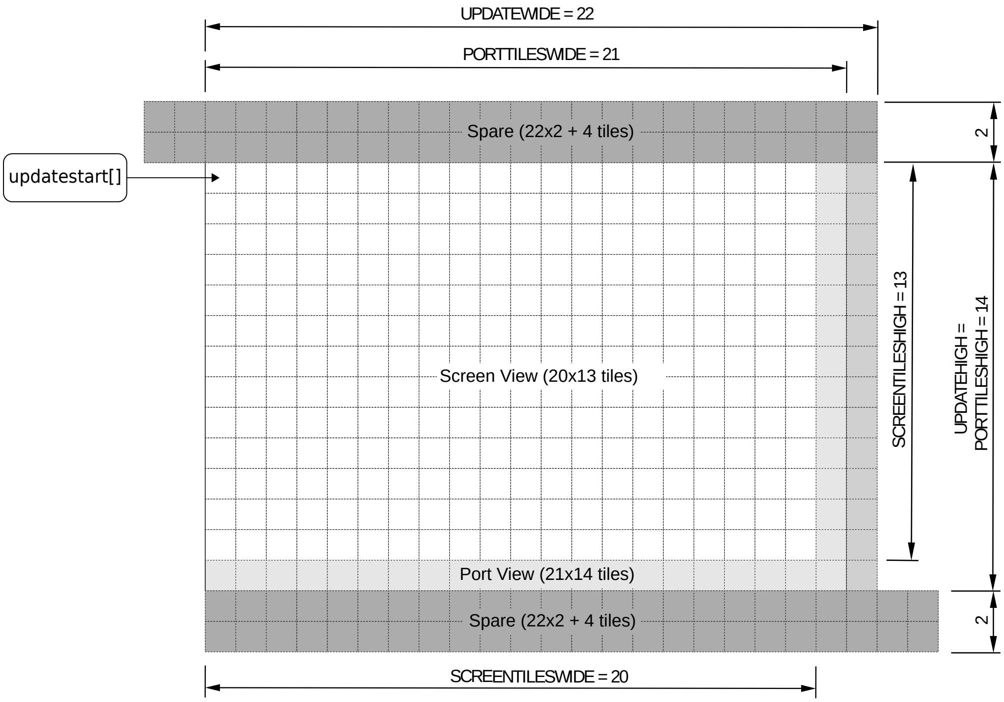



***Figure 31:*** Tile view and tile buffer layout.

### 0.6.1 Adaptive tile refreshment in Commander Keen 1-3

In the this section we explain how the first 3 versions of the game are working[5]. Six stages are involved in drawing a 2D scene:

1. Check if the player has moved one tile in any direction.
2. Validate which tiles have changed (both from scrolling and animated tiles), copy these respective tiles to the master page and mark the tiles in both tile arrays (view and buffer tile arrays).
3. Refresh the buffer page by scanning all tiles. If a tile needs to be updated, copy the tile from the master page to the buffer page.

[5]We can only explain how the algorithm is working without code examples, since the only released code is Keen Dreams which is using the improved algorithm.

4. Iterate through the sprite removal list and copy corresponding image block from the master page to buffer page.

5. Iterate through the sprite list and copy corresponding sprite image block from RAM to buffer page.

6. Switch the view and buffer page by adjusting the CRTC Start Address and Pel Panning registers.

In the next six screenshots, we take you step-by-step through each of the stages. The player has moved and forces the screen to scroll one tile to the right.

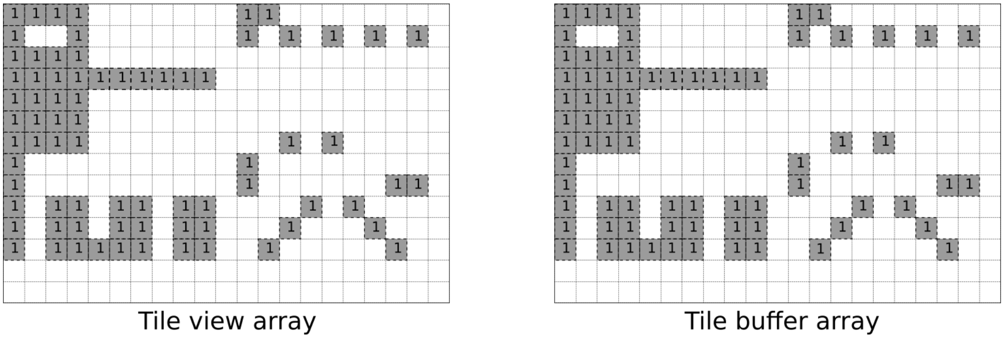



***Figure 32:*** Mark all changed tiles with ’1’ in both tile buffer and tile view array.

If a sprite has moved or disappeared, the latest sprite location is added to the block erase list. For each block in this erase list, erase the sprite by copying the width and height of the sprite block (marked in green in Figure **??**) from the master to the buffer page, and mark the corresponding tiles only in the tile buffer array with a ’2’.

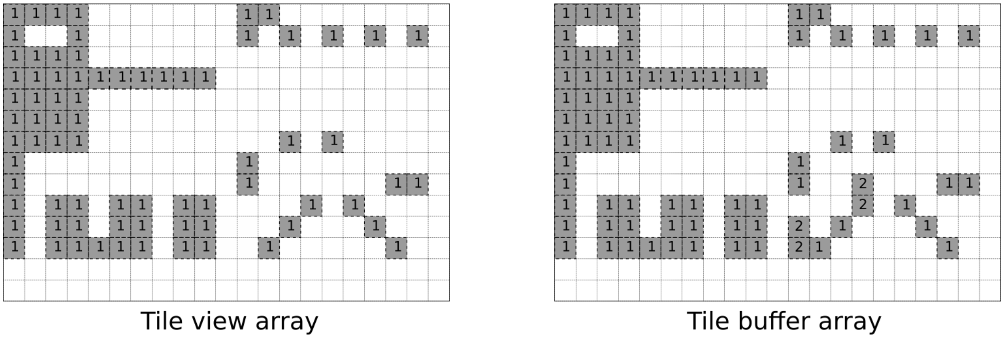



***Figure 33:*** Mark removed sprites with ’2’ in tile buffer array only.

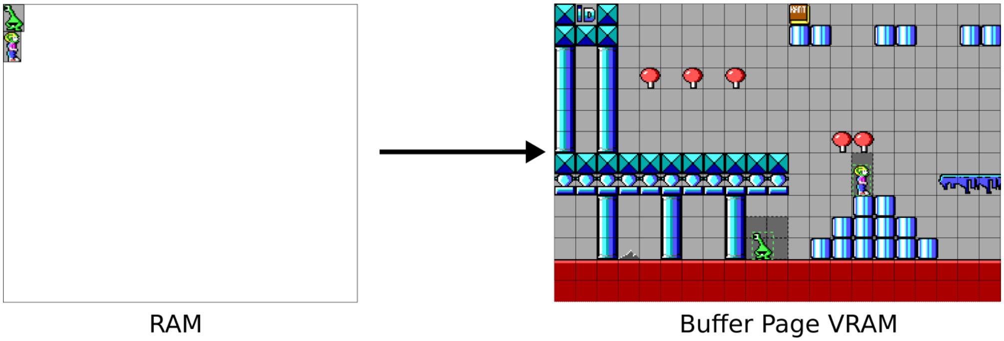



***Figure 34:*** Step 5: Scan sprite list and copy sprite onto buffer page

Next, the engine scans the sprite list. Validate if the sprite is in the visible part of the view port and copy the sprite image to the buffer page. Mark the corresponding tiles in the tile buffer array with a '3'.

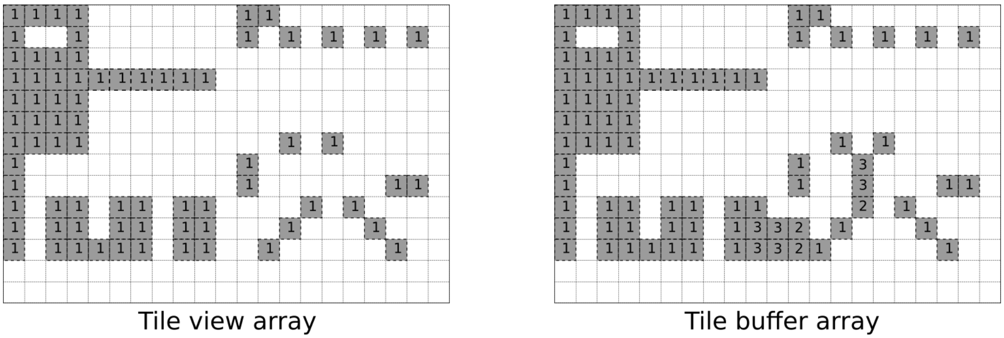



***Figure 35:*** Mark new sprites locations with '3' in tile buffer array only.

In the last step, point the visible screen to the buffer page by updating the CRTC start address and horizontal Pel Panning register. Finally, the tile buffer array is cleared to '0' and both arrays are swapped (so tile buffer becomes the tile view). Then step 1 is repeated.

Note that after swapping, the tile buffer array has marked all tiles that have changed from scrolling the screen. This makes sense, as the current buffer page is not yet refreshed (it was displayed in the previous refresh cycle, and we never update the view page).

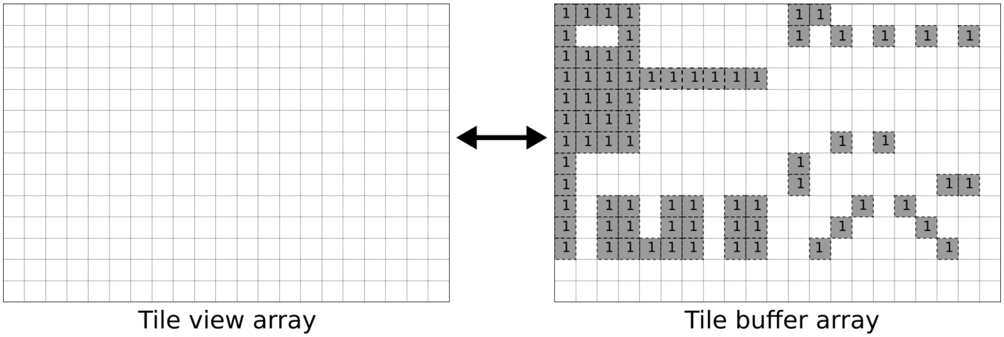



***Figure 36:*** Clear tile buffer array and swap tile arrays.

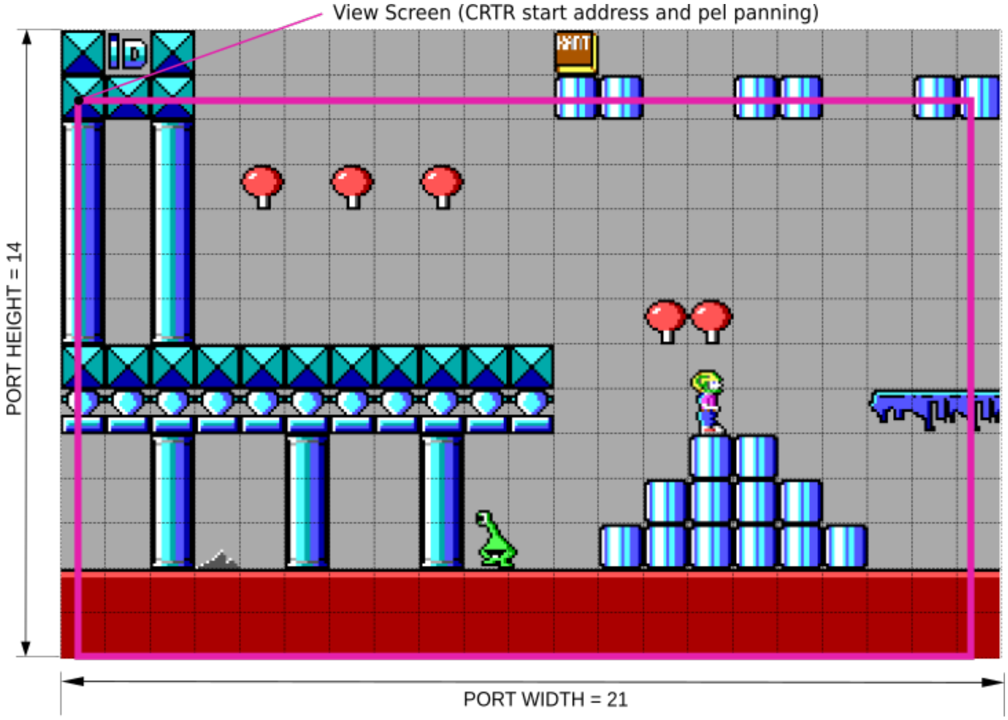



***Figure 37:*** Step 6: Swap buffer and screen page

Step 2 and 3 (except for the animated tiles) only needs to happen if Commander Keen is moving more than 16 pixels, where step 4 and 5 normally needs to happen for each refresh. So the number of drawing operations required during each refresh is controllable by the level designer. If they choose to place large regions of identical tiles (the large swathes of constant background), less redrawing (meaning: less redrawing in step 2 and 3) is required.