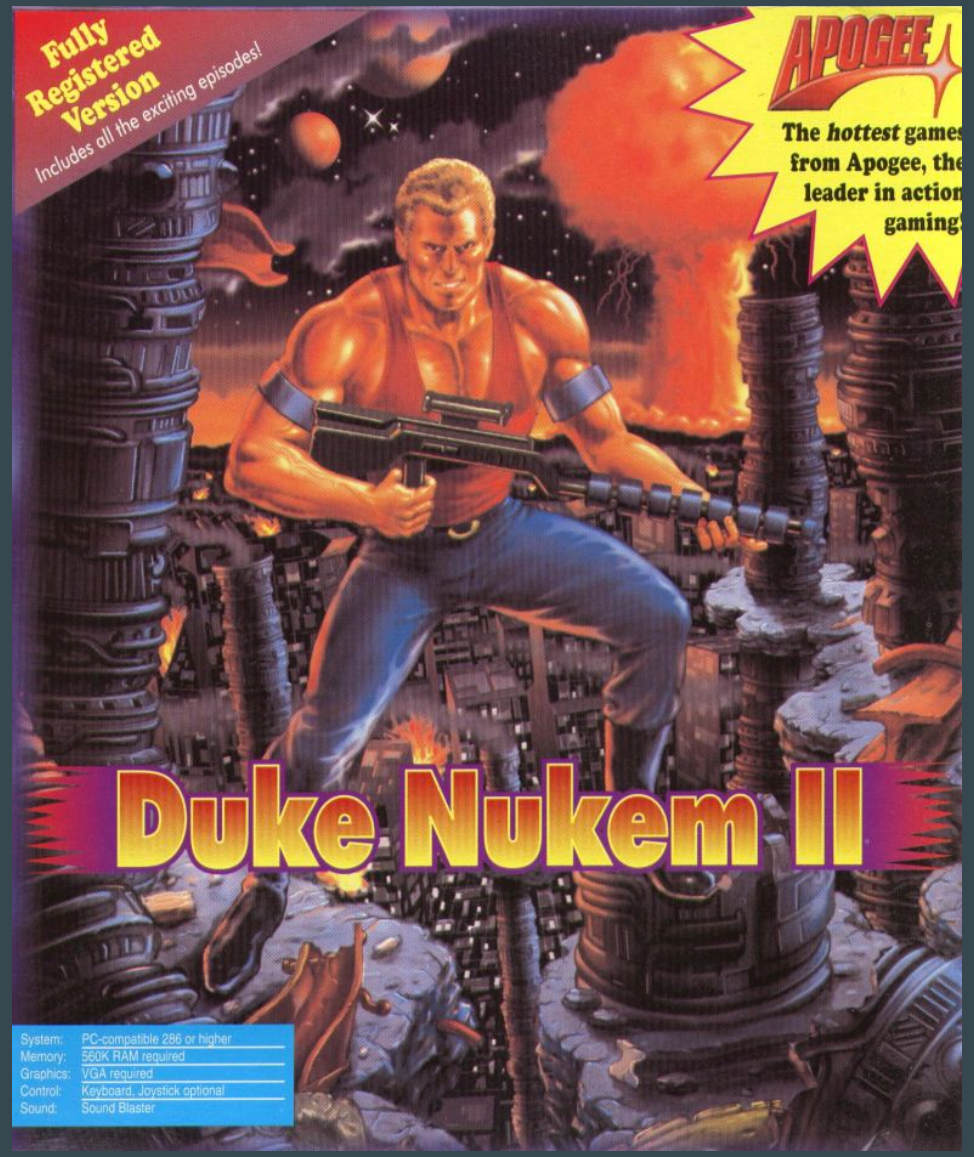
Rigel Engine

Reimplementing an old DOS game in modern C++

The game: Duke Nukem II



Duke Nukem II

Released: Dec. 1993

Free shareware version (¼ of full content)
Paid full version ($ 35)

System requirements:

- 286 CPU (386 recommended)
- 560 KB RAM
- MS-DOS 3.3
- VGA-compatible video card

Optionally supported:

- Soundblaster + AdLib sound cards
- Joysticks

http://www.mobygames.com/images/covers/l/21879-duke-nukem-ii-dos-front-cover.jpg

Duke Nukem II

Size on disk (executable + data):

- 3.4 MB (shareware)
- 5.7 MB (full version)

Audio/video output:

- 320x200 screen resolution (stretched to 4:3 by CRT)
- 16 color palette (256 for intro movies)
- 17.5 FPS (70 Hz ÷ 4)
- Monoaural sound output
- No mixing (only 1 sound effect at a time)

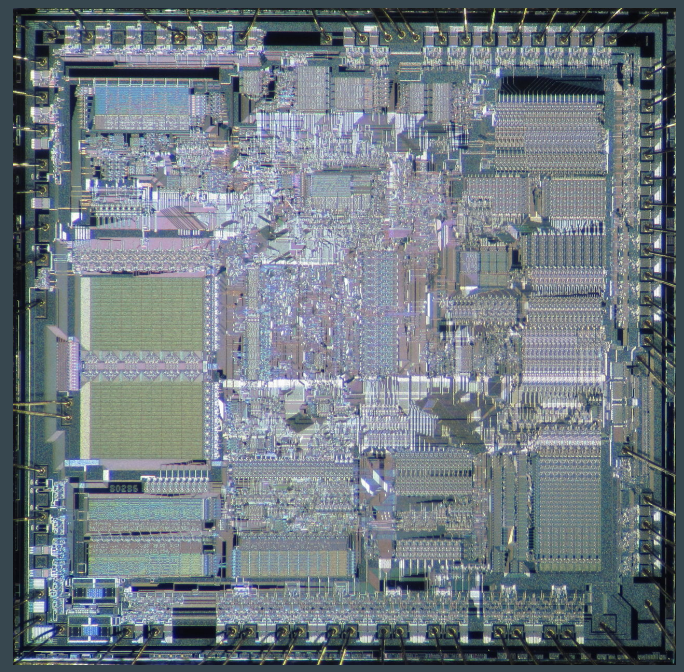
Hardware of the time

CPUs

80286 (1982)

- Clock speed: 4 to 12.5 MHz, later 20 to 25 MHz
- At 12 MHz: ~2.66 MIPS

- No L1/L2 cache
- Only 16-bit registers
- No floating point (unless co-processor installed)



https://en.wikipedia.org/wiki/Intel_80286#/media/File:Intel_80286_die.JPG

CPUs

80386 (1985)

- Clock speed: 12 to 40 MHz
- At 33 MHz: ~9.9 MIPS
- Optional cache (out-of-chip)

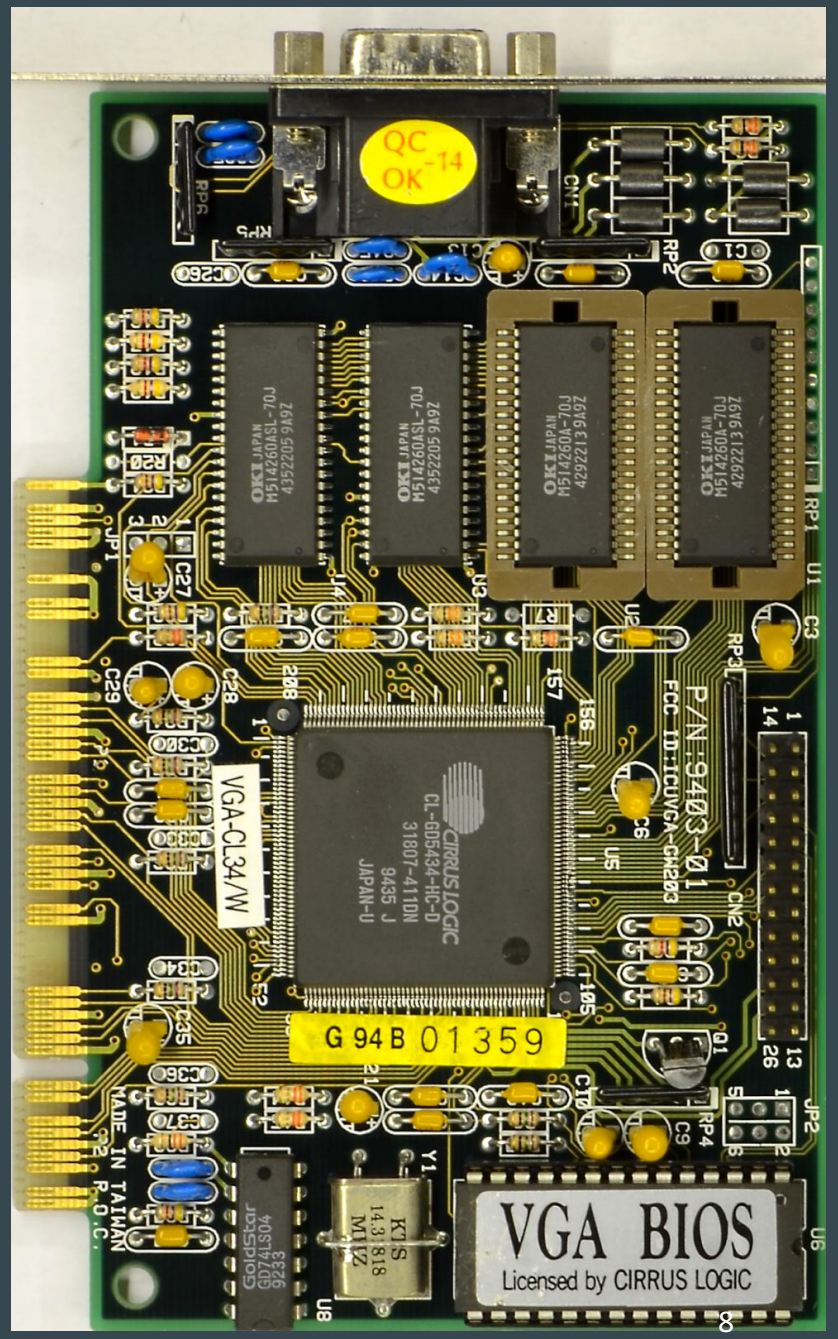
80486 (1989)

- On-chip cache, improved pipelining, integrated floating point unit
- Clock speed: 20 to 66 MHz, 100 MHz
- At 50 MHz: ~40 MIPS

https://en.wikipedia.org/wiki/Intel_80386#/media/File:KL_Intel_i386DX.jpg

VGA Graphics

- First release: 1987
- (min.) 256 KB VRAM
- 16 or 256 color palettes
- Common resolutions:
  - 640x480
  - 640x350
  - 640x200
  - 320x200



http://www.vgamuseum.info/images/palcal/cirrus/669_vga-cl34_w_cirrus_logic_cl-5434-hc-d_top_hq.jpg

AdLib and Sound Blaster sound

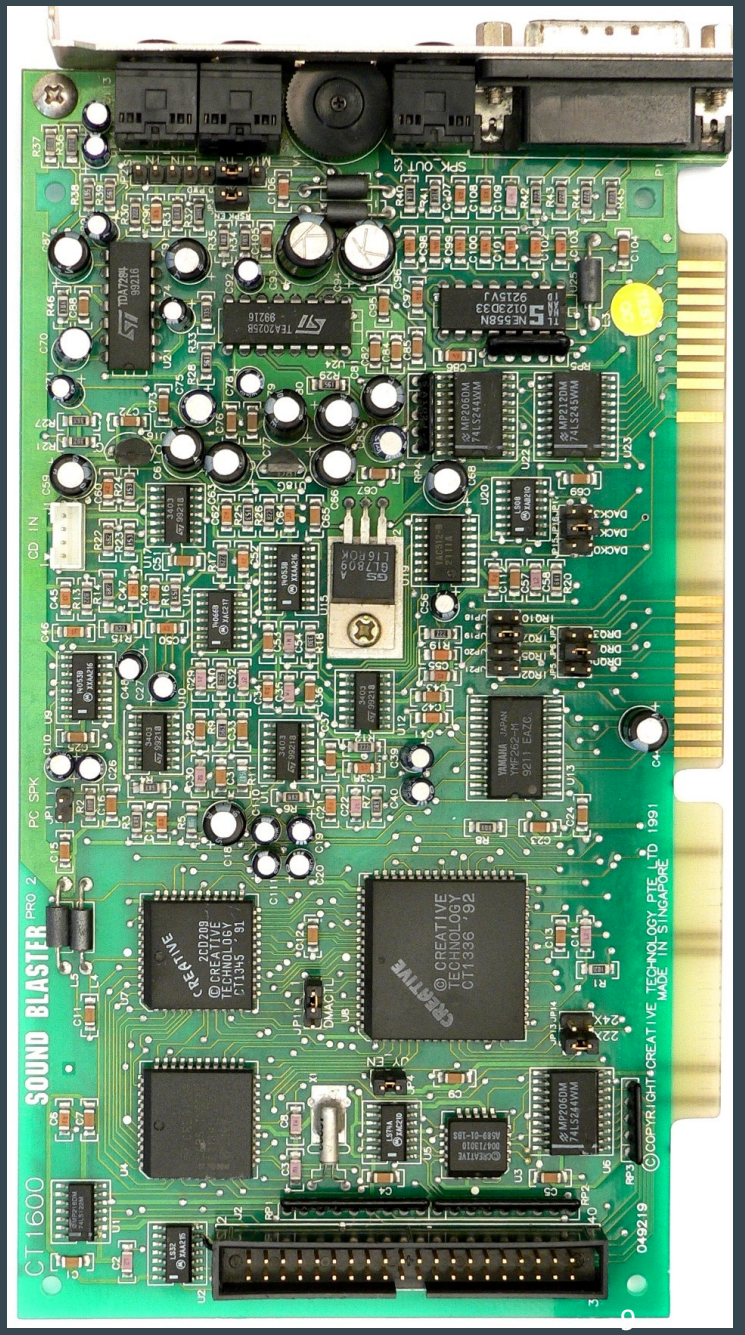
AdLib (1987)

- Add-on card with FM synthesizer chip
- Intended for music, but can do some sounds

Sound Blaster (1989), Sound Blaster Pro (1991)

- Full compatibility to AdLib
  - Includes the same synthesizer chip
- Additional support for digitized sound playback
  - 8-bit, 22.05 kHz (44.1 kHz on SB Pro)

http://www.mediafire.com/convkey/44ba/4qwdgeqjuummj35zg.jpg?size_id=a



The project: Rigel Engine

What is Rigel Engine?

- 2D game engine based on OpenGL and Entity-Component-Systems
- Code to read assets (data) from original game's files
  - Graphics, sounds, music
  - Maps/level data
- Implementation of original game logic/enemy behaviors etc.
  - Based on reverse-engineering

All written in modern C++

What is it not?

- An emulator*
  - Logic is completely re-implemented in native code
- Recreating the original source code/architecture
  - Aiming for equal behavior, but very different architecture under the hood
- Able to run on the original hardware
  - Being free of the (very tight) constraints is part of the fun
- An editor/file extraction tool
  - There are many projects for that already

* Emulation is used to play back music

Advantages of a modern re-implementation

- No emulator necessary – fully native
  - More responsive controls
  - Shorter loading times
  - Proper gamepad/controller support
- Possibility for enhanced graphics and sound
- Software preservation – source code allows:
  - Porting to future platforms
  - Bug fixes
  - Enhanced modding support

Similar projects

https://davidgow.net/keen/omnispeak.html

Omnispeak is an open-source reimplementation of Commander Keen episodes 4, 5, and 6. It aims to be a pixel-perfect, bug-for-bug clone of the original games, and is compatible with savegames from the DOS version.

http://clonekeenplus.sourceforge.net/

Commander Genius is a software piece that interprets the Commander Keen Invasion of the Vorticons and Galaxy series. As fans and developers, we are, we try to implement new features, improve the gameplay, and give players an experience that feels like playing the original game but a bit more refreshing.

Quick project overview

- C++ 14 (migration to 17 planned)
- ~ 16,700 LOC (1.2k LOC tests)
- GPL v2
- CMake
- CI via Travis CI/AppVeyor

Quick project overview

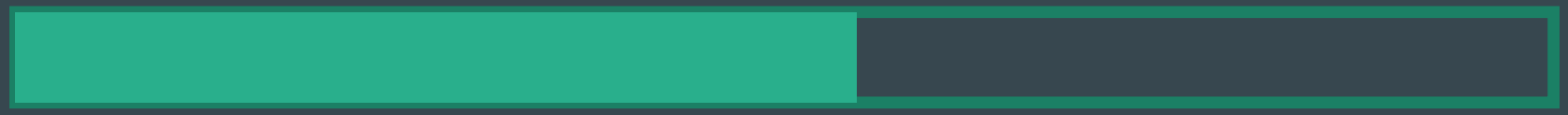
- OpenGL 3.0 (or ES 2.0)
- SDL (http://www.libsdl.org/)
- Boost (optional, variant, program options, signals2)
- EntityX (https://github.com/alecthomas/entityx)
- DBOPL AdLib emulator (from DosBox, *https://www.dosbox.com/*)

Project evolution

- First commit: 21 Aug 2016 (On GitHub: 22 Oct)
- 831 commits (584 on GitHub)
- Pause: April/May till end of August (4-5 mo)
- Total time worked on: 9-10 months

Implementation progress (Shareware only)

13/24 enemies



14/29 game mechanics

6/15 non-ingame features

Implemented enhancements

- Concurrent sound effects
- No loading screens
- More responsive controls (still WIP)
- Removed limitations
  - Max number of particles
  - Max number of explosions, debris and other effects

Supported platforms

- Windows (MSVC 2015)
- Linux (Clang 3.9, GCC 5.4)
- Mac OS X (AppleClang 8.0.0)
- Raspberry Pi (GCC 5.4 for ARM)

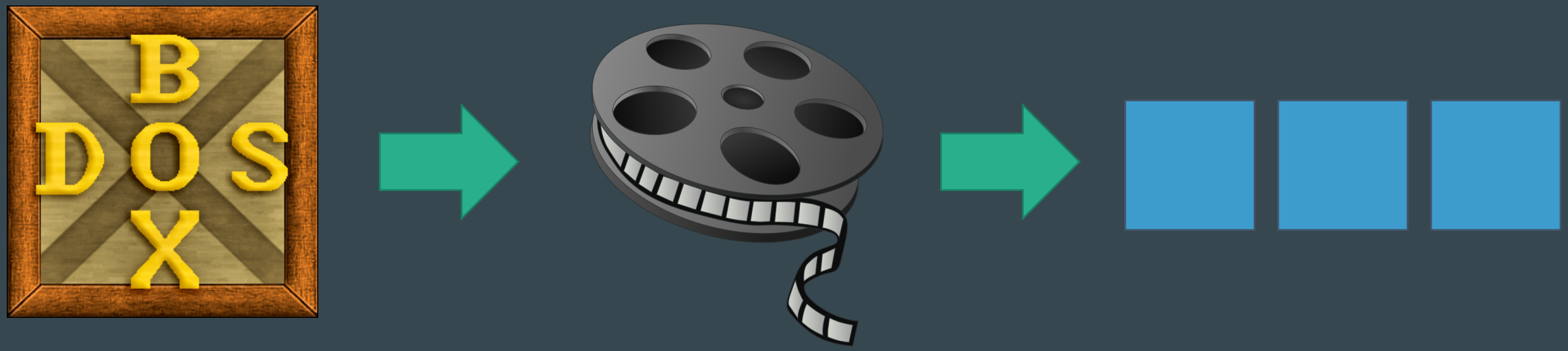
Live Demo!

Reverse Engineering the original

Reverse engineering techniques

- Observing the original
  - Stepping through video captures
  - Building custom levels for testing
- Reading the assembly

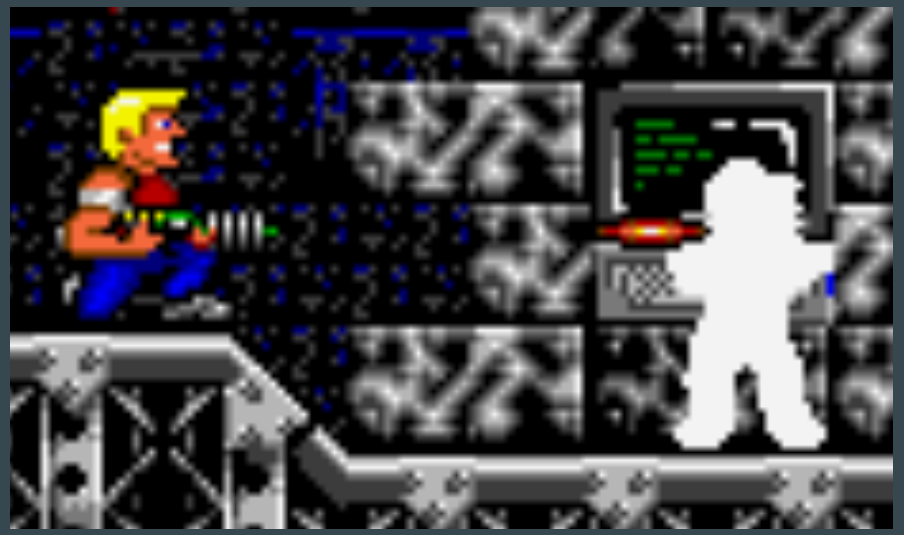
Stepping through video captures



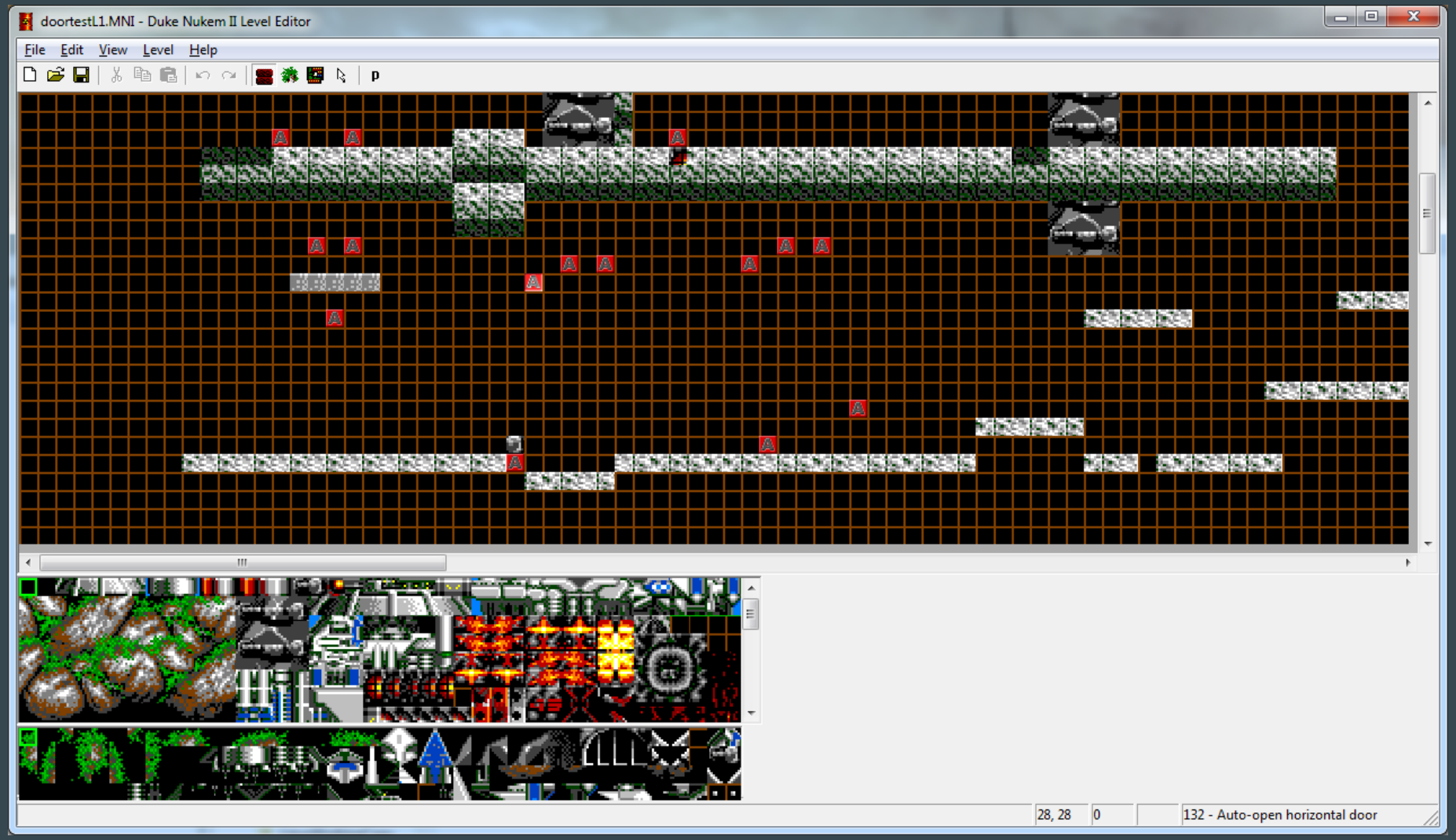

```
ffmpeg -i nukem2_051.avi -r 17.5 f%000d.png
```

https://upload.wikimedia.org/wikipedia/commons/d/dd/DOSBox_icon.png
https://openclipart.org/detail/29273/movie-reel

Stepping through video captures



Building custom levels for testing



Disassembling with Ida Pro

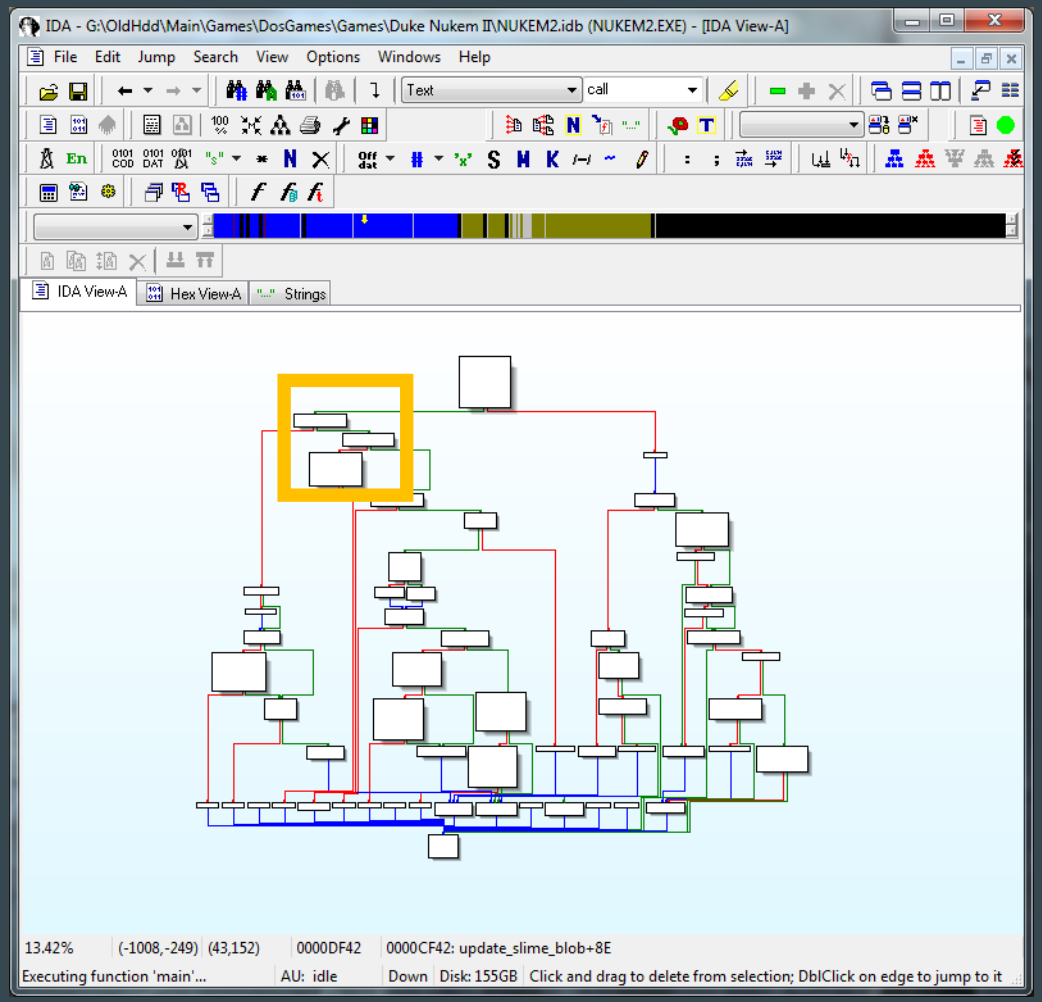
Ida Pro – The interactive disassembler

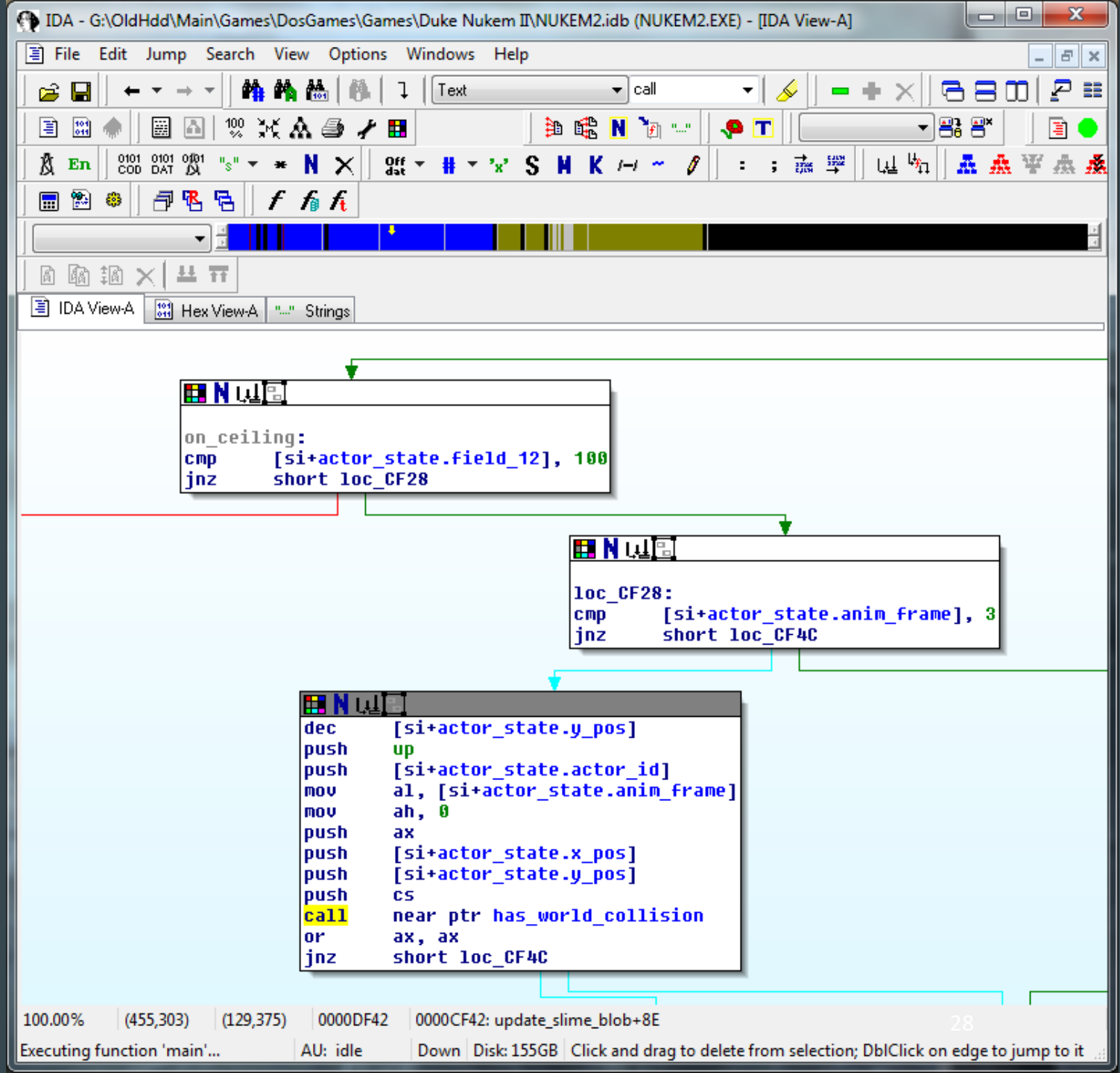
Features:

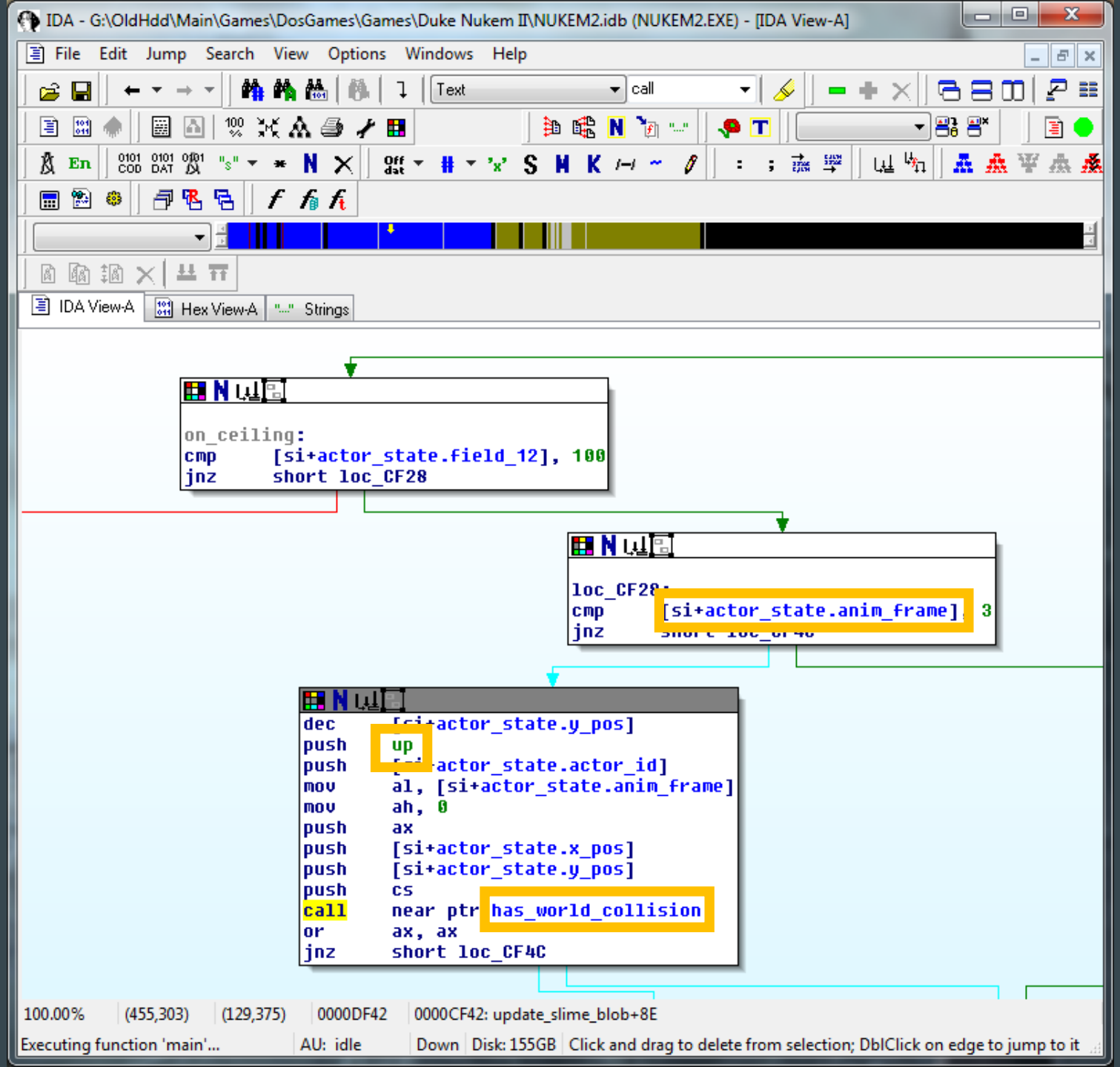
- Visualize control flow as graph
- Assign names to function parameters, variables, functions etc.
- Define struct layouts
- Jump to cross-references

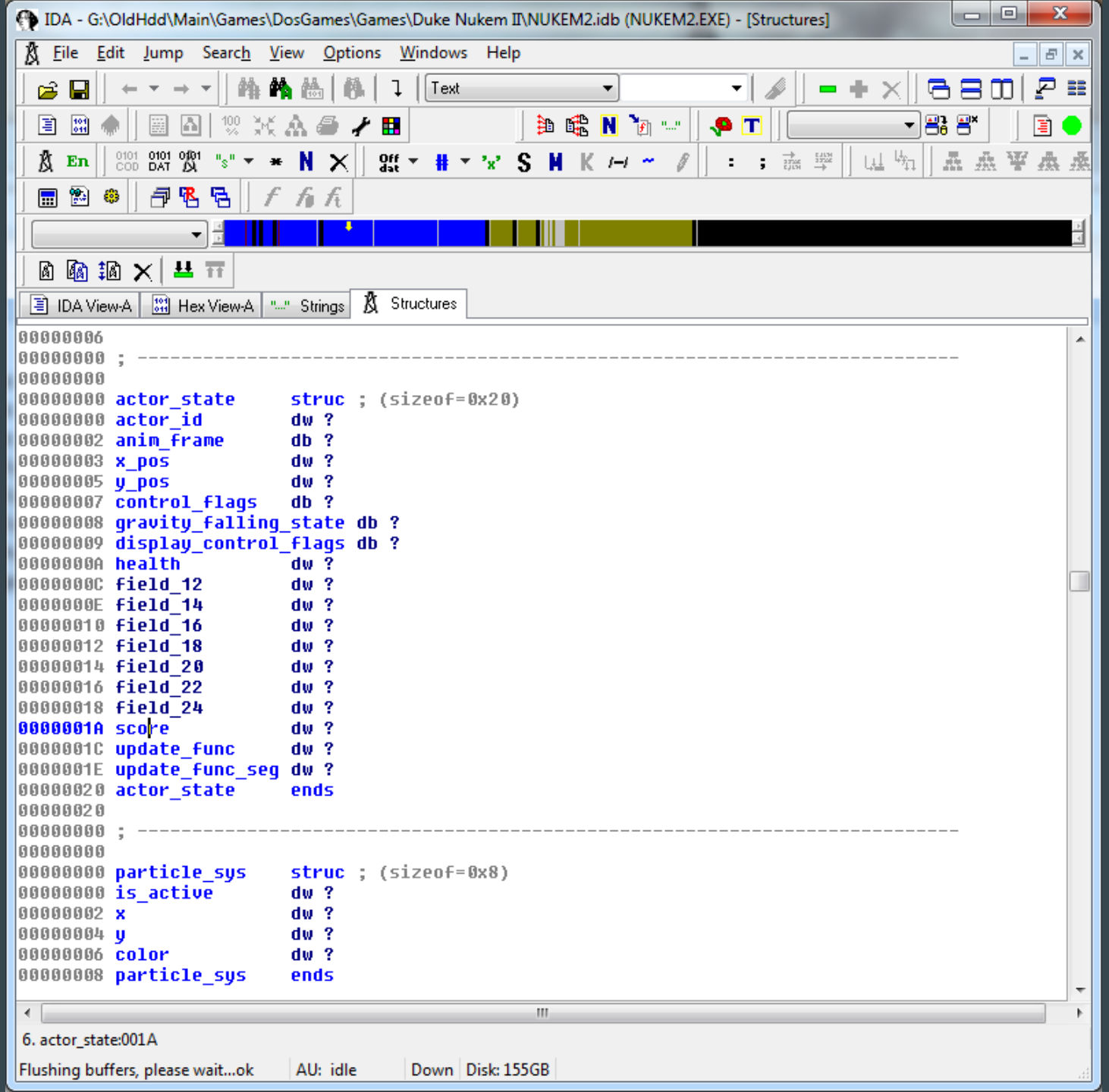
Version 5 free for non-commercial use:

https://www.hexrays.com/products/ida/support/download_freeware.shtml


IDA - G:\OldHdd\Main\Games\DosGames\Games\Duke Nukem II\NUKEM2.idb (NUKEM2.EXE) - [IDA View-A]
File Edit Jump Search View Options Windows Help
IDA View-A
Hex View-A
Strings
13.42%
(-1008,-249)
(43,152)
0000DF42
0000CF42: update_slime_blob+8E
Executing function 'main'...
AU: idle
Down
Disk: 155GB
Click and drag to delete from selection; DblClick on edge to jump to it

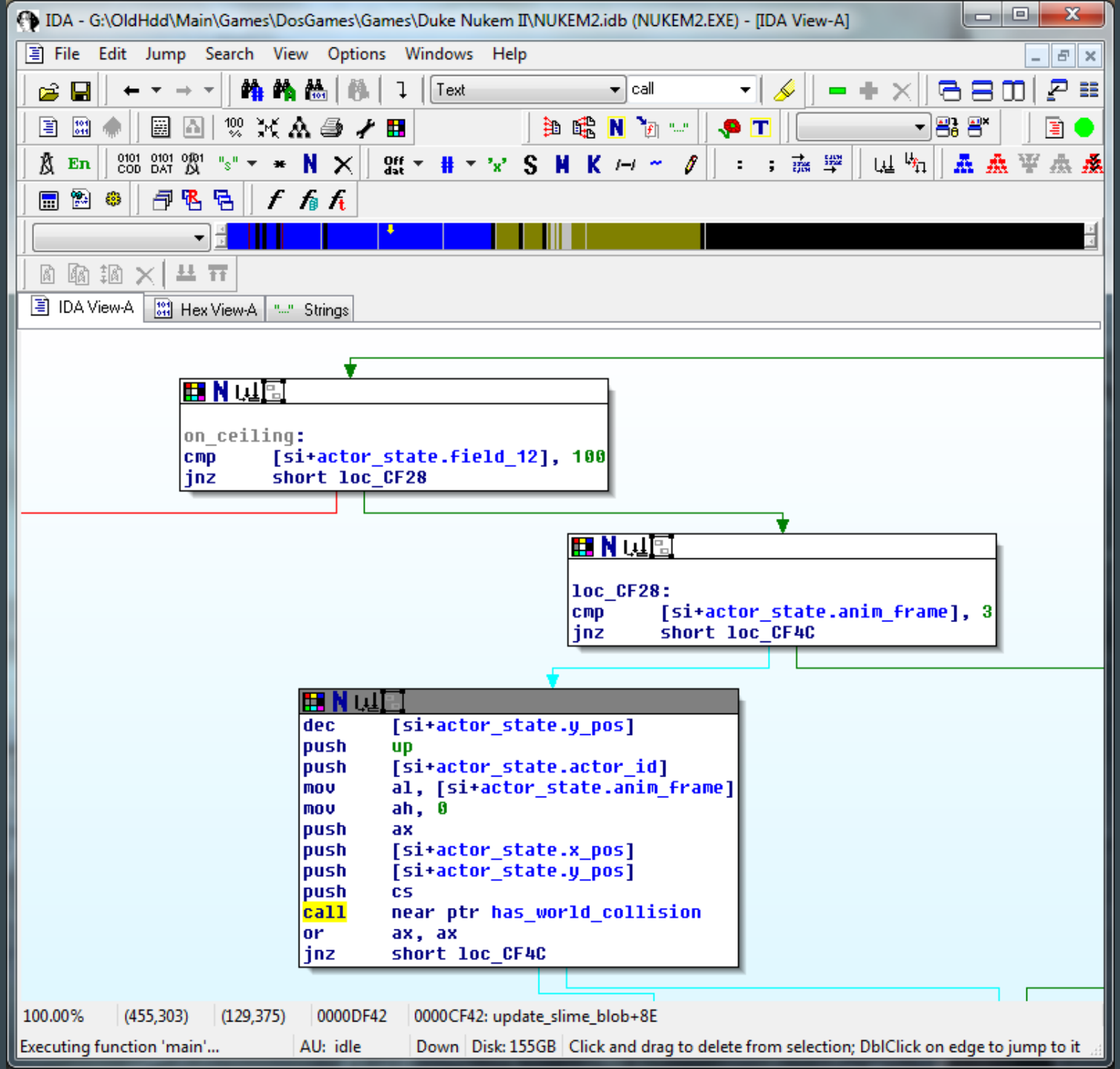

IDA - G:\OldHdd\Main\Games\DosGames\Games\Duke Nukem II\NUKEM2.idb (NUKEM2.EXE) - [IDA View-A]
File Edit Jump Search View Options Windows Help
IDA View-A
Hex View-A
Strings
on_ceiling:
cmp [si+actor_state.field_12], 100
jnz short loc_CF28
loc_CF28:
cmp [si+actor_state.anim_frame], 3
jnz short loc_CF4C
dec [si+actor_state.y_pos]
push up
push [si+actor_state.actor_id]
mov al, [si+actor_state.anim_frame]
mov ah, 0
push ax
push [si+actor_state.x_pos]
push [si+actor_state.y_pos]
push cs
call near ptr has_world_collision
or ax, ax
jnz short loc_CF4C
100.00%
(455,303)
(129,375)
0000DF42
0000CF42: update_slime_blob+8E
Executing function 'main'...
AU: idle
Down
Disk: 155GB
Click and drag to delete from selection; DblClick on edge to jump to it


IDA - G:\OldHdd\Main\Games\DosGames\Games\Duke Nukem II\NUKEM2.idb (NUKEM2.EXE) - [IDA View-A]
File Edit Jump Search View Options Windows Help
IDA View-A
Hex View-A
Strings
on_ceiling:
cmp [si+actor_state.field_12], 100
jnz short loc_CF28
loc_CF28:
cmp [si+actor_state.anim_frame], 3
jnz
dec [si+actor_state.y_pos]
push up
push [si+actor_state.actor_id]
mov al, [si+actor_state.anim_frame]
mov ah, 0
push ax
push [si+actor_state.x_pos]
push [si+actor_state.y_pos]
push cs
call near ptr has_world_collision
or ax, ax
jnz short loc_CF4C
100.00% (455,303) (129,375) 0000DF42 0000CF42: update_slime_blob+8E
Executing function 'main'... AU: idle Down Disk: 155GB Click and drag to delete from selection; DblClick on edge to jump to it


IDA - G:\OldHdd\Main\Games\DosGames\Games\Duke Nukem II\NUKEM2.idb (NUKEM2.EXE) - [Structures]
File Edit Jump Search View Options Windows Help
Text
IDA View-A
Hex View-A
Strings
Structures
00000006
00000000 ; ---
00000000
00000000 actor_state struc ; (sizeof=0x20)
00000000 actor_id dw ?
00000002 anim_frame db ?
00000003 x_pos dw ?
00000005 y_pos dw ?
00000007 control_flags db ?
00000008 gravity_falling_state db ?
00000009 display_control_flags db ?
0000000A health dw ?
0000000C field_12 dw ?
0000000E field_14 dw ?
00000010 field_16 dw ?
00000012 field_18 dw ?
00000014 field_20 dw ?
00000016 field_22 dw ?
00000018 field_24 dw ?
0000001A score dw ?
0000001C update_func dw ?
0000001E update_func_seg dw ?
00000020 actor_state ends
00000020
00000000 ; ---
00000000
00000000 particle_sys struc ; (sizeof=0x8)
00000000 is_active dw ?
00000002 x dw ?
00000004 y dw ?
00000006 color dw ?
00000008 particle_sys ends
6. actor_state:001A
Flushing buffers, please wait...ok
AU: idle
Down
Disk: 155GB

Disassembling: Workflow

- Open graph for function
- Make sure known names/definitions etc. are applied
- Transcribe assembly into C-like pseudo-code
- Simplify pseudo-code, identify underlying logic
- C++ implementation




```
const int UP = ...;

if (state->field_12 != 100) {
  if (state->anim_frame == 3) {
    --state->y_pos;
    if (has_world_collision(
      UP,
      state->actor_id,
      state->anim_frame,
      state->x_pos,
      state->y_pos)
    ) {
      // ...
    }
  }
```

Disassembling: It’s not that bad!

- Limited instruction set (16-bit real-mode)
- Original source code was in C
- Old compilers didn’t optimize as aggressively
- Mostly simple logic
  - Call well-known functions (collision checking, projectile spawning etc.)
  - Increment counters/animation frame index
  - Branch based on counter state

C++ goodies

C libraries and std::unique_ptr

```
SDL_Window* SDL_CreateWindow(…);
void SDL_DestroyWindow(SDL_Window* window);

SDL_Texture* SDL_CreateTexture(…);
void SDL_DestroyTexture(SDL_Texture* texture);

// etc...
```

C libraries and std::unique_ptr

Using unique_ptr's "deleter" argument

```
auto pWindow = std::unique_ptr<SDL_Window, void(*)(SDL_Window*)>{
  SDL_CreateWindow(...), SDL_DestroyWindow};
```

Determining the right deleter

```
template<typename SDLType>
struct DeleterFor {};

template<>
struct DeleterFor<SDL_Window> {
  static auto deleter() { return &SDL_DestroyWindow; }
};

template<>
struct DeleterFor<SDL_Texture> {
  static auto deleter() { return &SDL_DestroyTexture; }
};

template<typename SDLType>
auto deleterFor() { return DeleterFor<SDLType>::deleter(); }
```

Defining a Ptr template

```
template<typename SDLType>
using PtrBase = std::unique_ptr<SDLType, void(*)(SDLType*)>;

template<typename SDLType>
class Ptr : public detail::PtrBase<SDLType> {
public:
  template<typename P>
  Ptr(P&& p)
    : detail::PtrBase<SDLType>(std::forward<P>(p), deleterFor<SDLType>())
  {}

  Ptr() : Ptr(nullptr) {};
};
```

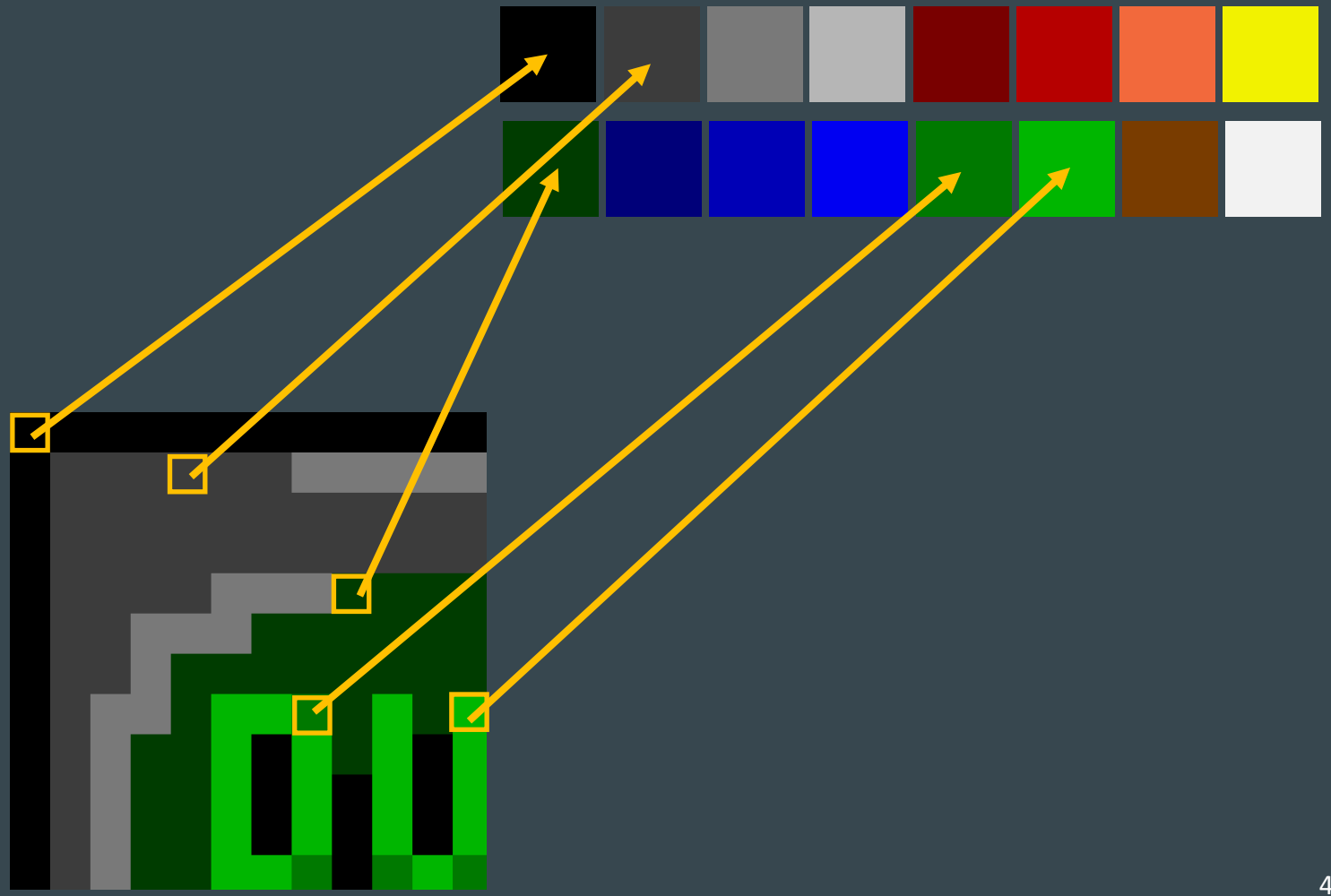
Client code with helper class

```
auto pWindow = std::unique_ptr<SDL_Window,
  void(*)(SDL_Window*)>{
    SDL_CreateWindow(...), SDL_DestroyWindow};
```

Client code with helper class

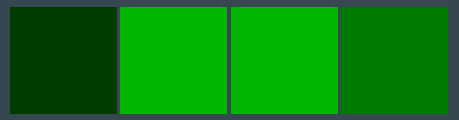
```
auto pWindow = Ptr<SDL_Window>{SDL_CreateWindow(...)};
```

Palette-based graphics



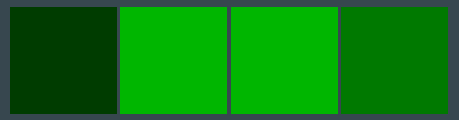
16 color palette
→need 4 bit per pixel
→2 pixels per byte

Planar memory layout



8, 13, 13, 12

Planar memory layout

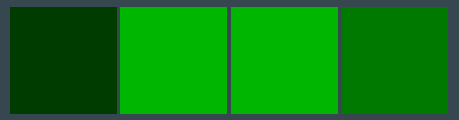


8, 13, 13, 12

$8 \rightarrow 1000_2$

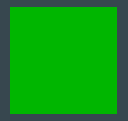
Bank A	Bank B	Bank C	Bank D
1	0	0	0

Planar memory layout



8, 13, 13, 12

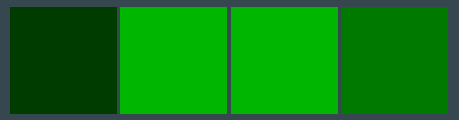
8 → 1000_2



13 → 1101_2

Bank A	Bank B	Bank C	Bank D
1, 1	0, 1	0, 0	0, 1

Planar memory layout



8, 13, 13, 12

Bank A	Bank B	Bank C	Bank D
1, 1, 1, 1	0, 1, 1, 1	0, 0, 0, 0	0, 1, 1, 0

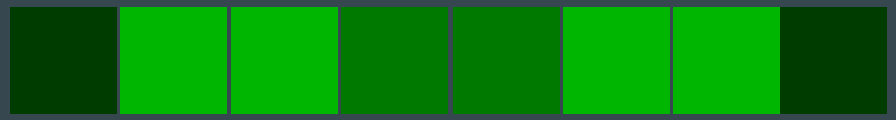
8 → 1000_2

13 → 1101_2

13 → 1101_2

12 → 1100_2

Original graphics format



Linear:
10001101_2, 11011100_2, 11001101_2, 11011000_2

Planar:
11111111_2, 01111110_2, 00000000_2, 01100110_2

Decoding the game’s graphics files

Required: Reading single bits

```
for (int bit = 7; bit >= 0; --bit) {
  const auto bitMask = 1 << bit;
  const auto valueOfBit = value & bitMask;
  // work with valueOfBit
}
```

Decoding the game's graphics files

Wanted: Abstract away the bit-wrangling, write algorithm in terms of "sequence of values"

Solution: Create adapter iterator

Adapter iterator: bit-wise reading

```
template<typename OriginalIterType>
class BitWiseIterator {
public:
  // some boilerplate omitted

  explicit BitWiseIterator(OriginalIterType originalIter) :
    mOriginalIter(originalIter), mBitIndex(0) {}

  // comparison operators, post-fix increment operator omitted

  BitWiseIterator& operator++();

  bool operator*() const;

private:
  OriginalIterType mOriginalIter;
  std::uint8_t mBitIndex;
};
```

Adapter iterator: bit-wise reading

```
BitWiseIterator& operator++() {
  ++mBitIndex;
  if (mBitIndex == 8) {
    ++mOriginalIter;
    mBitIndex = 0;
  }
  return *this;
}

bool operator*() {
  const auto actualBitIndex = 7 - mBitIndex;
  const auto bitMask = 1 << actualBitIndex;
  const auto bitPack = *mOriginalIter;
  return (bitPack & bitMask) != 0;
}
```

Adapter iterator: Client code

```
vector<uint8_t> decodedIndices(numPixels, 0);

BitWiseIterator<ByteBufferCIter> bitsIter(dataBegin);

for (auto plane = 0; plane < 4; ++plane) {
   auto destination = begin(decodedIndices);

   for (auto pixel = 0; pixel < pixelCount; ++pixel) {
     const auto planeBit = *bitsIter++;
     *destination++ |= planeBit << plane;
   }
}
```

State machines for enemy AI: Example

Flying

Hovering

Plunging down

Rising up

Red bird state machine

”Old-school” approach

```
enum class BirdState {
  Flying, Hovering, Plunging, Rising
};

struct RedBird {
  BirdState mState;
  int mOriginalHeight;
  int mElapsedTime;
};
```

```
switch (bird.mState) {
case BirdState::Flying:
  // Check if over player
  break;

case BirdState::Hovering:
  // etc.
```

Encoding states in a variant<>

```
struct Flying {};
struct Hovering { int mFramesElapsed = 0; };
struct PlungingDown { int mInitialHeight; };
struct RisingUp { int mInitialHeight; };

using StateT = variant<
  Flying, Hovering, PlungingDown, RisingUp>;

struct RedBird {
  StateT mState;
};
```

Pattern matching on the state

```
atria::variant::match(birdState.mState,
  [&](const Flying&) {
    const auto wantsToAttack =
      position.y + 2 < playerPosition.y && position.x > playerPosition.x &&
      position.x < playerPosition.x + 2;

    if (wantsToAttack) {
      birdState.mState = Hovering{};
    }
  },

  [&](Hovering& state) {
    ++state.mFramesElapsed;
    if (state.mFramesElapsed >= 6) {
      birdState.mState = PlungingDown{position.y};
    }
  },

  // etc. for remaining states
```

Other uses for variant pattern matching

- Script interpreter
  - Parse text into command objects
  - Script → `std::vector<variant<Command1, Command2, ...>>;`
- Game mode management (ingame vs. bonus-screen)
- Effect specification DSL

```
const EffectSpec SPIDER_KILL_EFFECT_SPEC[] = {
  {EffectSprite{{-1, 1}, 1, EffectMovement::None}, 0},
  {RandomExplosionSound{}, 0}
};

const EffectSpec RED_BIRD_KILL_EFFECT_SPEC[] = {
  {Particles{{}, INGAME_PALETTE[5]}, 0},
  {EffectSprite{{}, 1, EffectMovement::None}, 0},
  {RandomExplosionSound{}, 0}
};
```

Pattern matching in C++

- Library-based (https://github.com/Ableton/atria, others)
- C++ Weekly Ep. 49: Inheriting lambdas to make a combined visitor
- Proposal to add native pattern matching to C++: P0095
- Rant about `std::visit`: https://bitbashing.io/std-visit.html

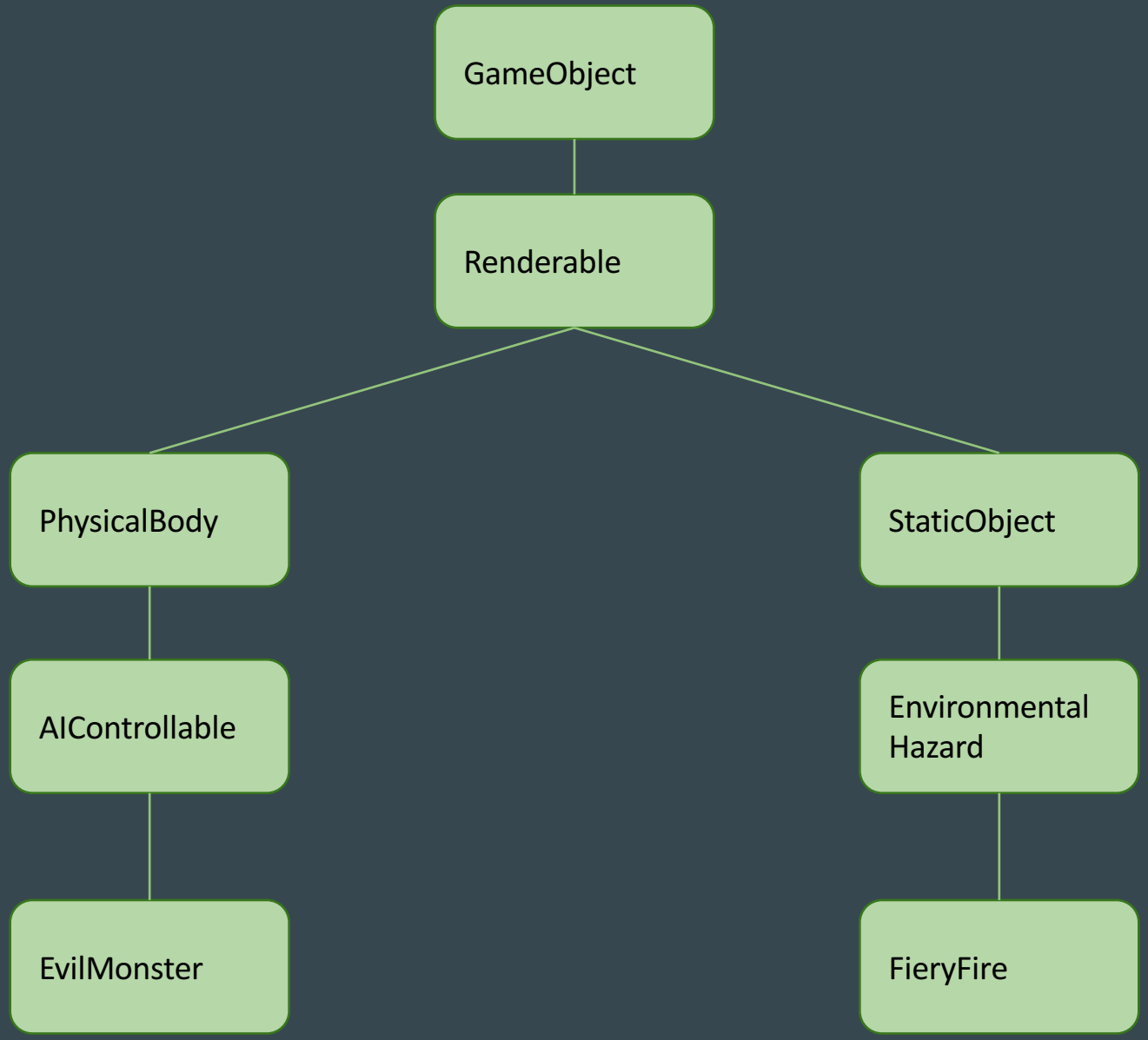
Entity-Component-Systems

Motivation: Provide more flexibility than OOP

```
class GameObject {
public:
  virtual void update(float timeDelta);
};


class Game {
private:
  vector<unique_ptr<GameObject>> mObjects;

public:
  void updateGame(const float timeDelta) {
    for (auto& pObject : mObjects) {
      pObject->update(timeDelta);
    }
  }
};
```


GameObject
Renderable
PhysicalBody
StaticObject
AIControllable
Environmental Hazard
EvilMonster
FieryFire

“Can we have a monster that’s also on fire?”

Entity, Component, System

Component
Holds state, POD-like

Entity
Handle/ID for a set of components

System
Implements logic for combination of components

Example components

Position

`x, y, z`

Renderable

`vertices, textures`

DamageInflictor

`damageAmount, affectedGroups`

BoundingBox

`minX, minY, minZ, maxX, maxY, maxZ`

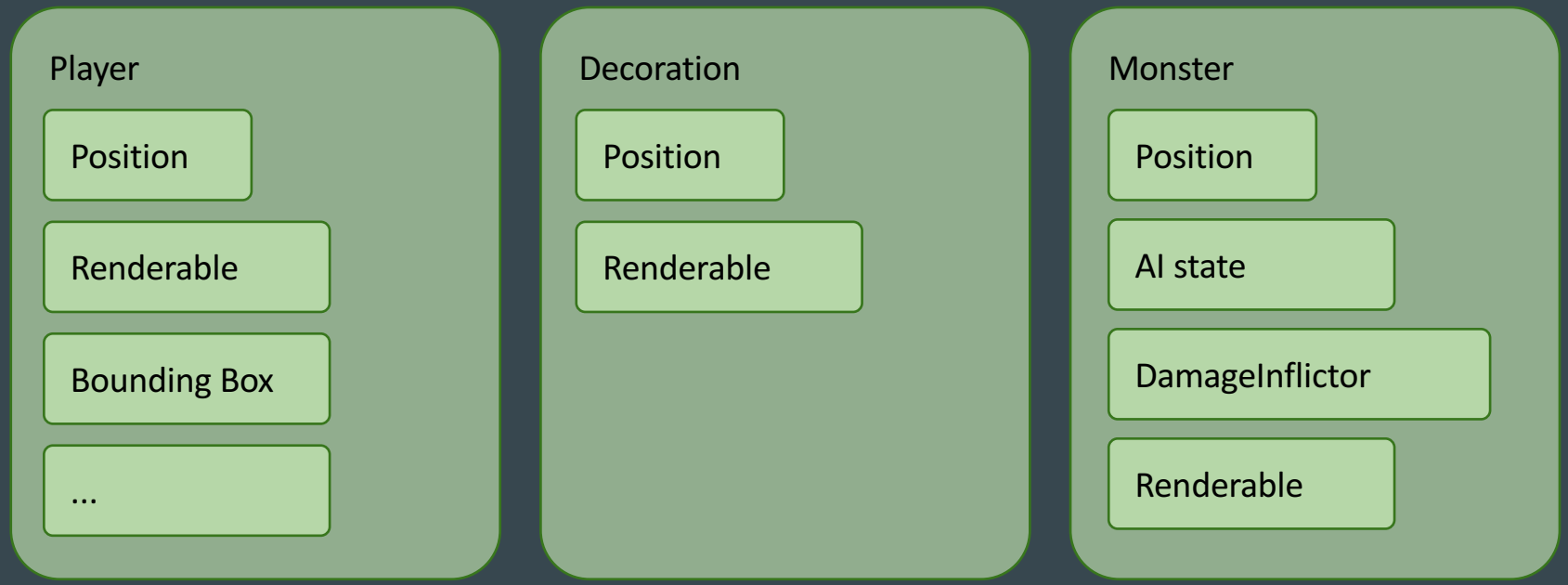
ItemPickup

`givenItemType`

PhysicalBody

`velocity, acceleration`

Example entities



Systems

Implement specific logic for certain combination of components

Can read and write components’ data

Only operate on entities with required components

Can send and receive events from/to other systems/outside world

Example systems

PhysicsSystem - needs Position, PhysicalBody

```
// update position component
position += physicalBody.velocity;

// update velocity
physicalBody.velocity += physicalBody.acceleration * dt;
```

Example systems

CollisionDetectionSystem - needs Position, BoundingBox

```
const auto candidates = possibleColliders();
const auto it = find_if(begin(candidates), end(candidates),
  [&](const auto& collider) {
    return intersecting(collider.bbox, bbox);
  });

if (it != end(candidates)) {
  emitEvent(Collision{*it, currentEntity});
}
```

Example systems

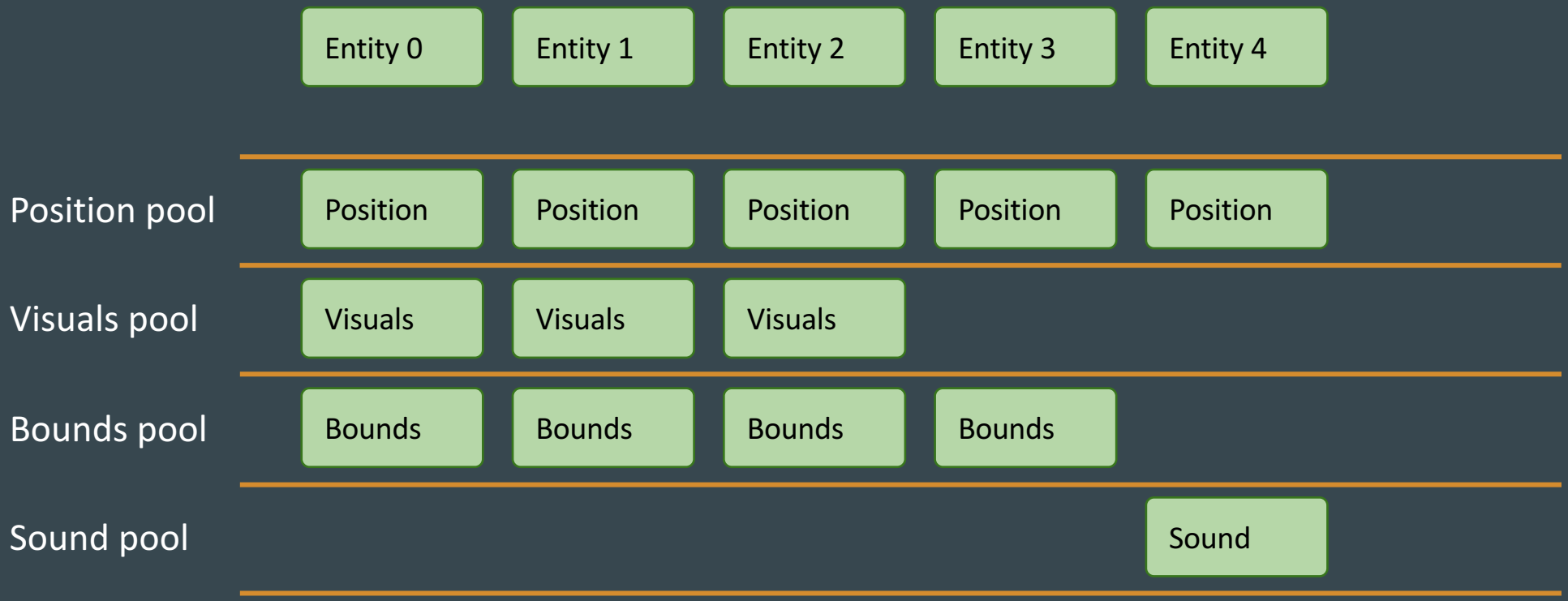
Rendering system – needs Renderable, Position, BoundingBox

AI controller system – needs AiState, Position

Sound emitter system – needs Sound, Position

etc.

Component storage



Composition at runtime

```
auto entity = entityManager.createEntity();

entity.addComponent<Position>(Position{3, 5});
entity.addComponent<AIState>(AIState{ai::Type::SmartMonster});


auto gameMap = loadMap();

for (const auto& description : gameMap.enemies()) {
  auto enemy = entityManager.createEntity();
  enemy.addComponent<Position>(description.position);
  enemy.addComponent<VisualRepresentation>(
    createVisualsForEnemyType(description.type));
}
```

Behavior as combination of systems

Example: Projectile

- Movement handled by PhysicsSystem
- Collision checked by CollisionDetectionSystem
- Inflicts damage on enemy via DamageInflictionSystem
- Visual representation handled by RenderingSystem

ECS libraries for C++

EntityX (https://github.com/alecthomas/entityx)

A fast, type-safe C++ Entity-Component system

ECST (https://github.com/SuperV1234/ecst)

Experimental & work-in-progress C++14 multithreaded compile-time Entity-Component-System header-only library.

EnTT (https://github.com/skypjack/entt)

EnTT is a header-only, tiny and easy to use Entity-Component System in modern C++

ECS in Rigel Engine

```
case 19: // Rocket launcher
{
  CollectableItem item;
  item.mGivenScore = 2000;
  item.mGivenWeapon = WeaponType::Rocket;
  configureItemBox(
    entity,
    ContainerColor::Green,
    100,
    item);
}
break;

case 50: // teleporter
case 51: // teleporter
  entity.assign<AnimationLoop>(1);
  entity.assign<Interactable>(InteractableType::Teleporter);
  entity.assign<BoundingBox>(BoundingBox{{2, 0}, {2, 5}});
  break;
```

```
void IngameSystems::update(const PlayerInputState& inputState, entityx::EntityManager& es) {
  mRenderingSystem.updateAnimatedMapTiles();
  engine::updateAnimatedSprites(es);
  engine::markActiveEntities(es, *mpScrollOffset);
  mpPlayerModel->updateTemporaryItemExpiry();
  mElevatorSystem.update(es, inputState);
  mPlayerMovementSystem.update(inputState);
  mPlayerInteractionSystem.update(es);

  mBlueGuardSystem.update(es);
  mHoverBotSystem.update(es);
  mLaserTurretSystem.update(es);
  mMessengerDroneSystem.update(es);
  mNapalmBombSystem.update(es);
  mPrisonerSystem.update(es);
  mRedBirdSystem.update(es);
  mRocketTurretSystem.update(es);
  mSecurityCameraSystem.update(es);
  mSimpleWalkerSystem.update(es);
  mSlidingDoorSystem.update(es);
  mSlimeBlobSystem.update(es);
  mSlimePipeSystem.update(es);
  mSpikeBallSystem.update(es);

  mPhysicsSystem.update(es);
  mPlayerAttackSystem.update();
  mPlayerDamageSystem.update(es);
  mDamageInflictionSystem.update(es);
  mEffectsSystem.update(es);
  mPlayerAnimationSystem.update(es);
  mPlayerProjectileSystem.update(es);
  mMapScrollSystem.update();
  mLifeTimeSystem.update(es);
  mParticles.update();
}
```

ECS: My experience

- Very easy to use (with a good library)
- Encourages code reuse/generic behaviors
- Encourages more “declarative” coding
- Explicit update order is very useful

- Solutions can be less obvious at first
- Needs some „getting used to”

Funny hacks and trivia

(Not so random) random numbers

```
int random_number() {
  static uint8_t index = 0;
  ++index;
  return RANDOM_NUMBER_TABLE[index];
}
```

(Not so random) random numbers

```
const std::array<int, 256> RANDOM_NUMBER_TABLE{
  0, 8, 109, 220, 222, 241, 149, 107, 75, 248, 254, 140, 16, 66, 74, 21, 211, 47,
  80, 242, 154, 27, 205, 128, 161, 89, 77, 36, 95, 110, 85, 48, 212, 140, 211,
  249, 22, 79, 200, 50, 28, 188, 52, 140, 202, 120, 68, 145, 62, 70, 184,  190,
  91, 197, 152, 224, 149, 104, 25, 178, 252, 182, 202, 182, 141, 197, 4,  81, 181,
  242, 145, 42, 39, 227, 156, 198, 225, 193, 219, 93, 122, 175, 249,  0, 175, 143,
  70, 239, 46, 246, 163, 53, 163, 109, 168, 135, 2, 235, 25, 92,  20, 145, 138,
  77, 69, 166, 78, 176, 173, 212, 166, 113, 94, 161, 41, 50, 239,  49, 111, 164,
  70, 60, 2, 37, 171, 75, 136, 156, 11, 56, 42, 146, 138, 229,  73, 146, 77, 61,
  98, 196, 135, 106, 63, 197, 195, 86, 96, 203, 113, 101, 170,  247, 181, 113, 80,
  250, 108, 7, 255, 237, 129, 226, 79, 107, 112, 166, 103,  241, 24, 223, 239,
  120, 198, 58, 60, 82, 128, 3, 184, 66, 143, 224, 145, 224,  81, 206, 163, 45,
  63, 90, 168, 114, 59, 33, 159, 95, 28, 139, 123, 98, 125,  196, 15, 70, 194,
  253, 54, 14, 109, 226, 71, 17, 161, 93, 186, 87, 244, 138,  20, 52, 123, 251,
  26, 36, 17, 46, 52, 231, 232, 76, 31, 221, 84, 37, 216,  165, 212, 106, 197,
  242, 98, 43, 39, 175, 254, 145, 190, 84, 118, 222, 187,  136, 120, 163, 236, 249
};
```

Clock deviation due to timer interrupt

Timer interrupt (INT 8): https://en.wikipedia.org/wiki/Intel_8253

Regular frequency: 18.2 Hz

Default handler: Advance time-of-day, time-out floppy disk drive, …

Game reprograms timer to approx. 280 Hz

invokes original handler every 15th time

280 / 18.2 ≈ 15,385

280 / 15 ≈ 18.6 → clock runs ≈ 2.5 % faster → 10 hrs game ≈ 15 min offset

Thanks for listening!

https://github.com/lethal-guitar/RigelEngine