FOSDEM 2024 – Emulation Track

Panda3DS

Climbing the tree of 3DS emulation

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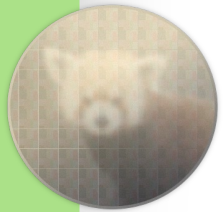


What is Panda3DS?

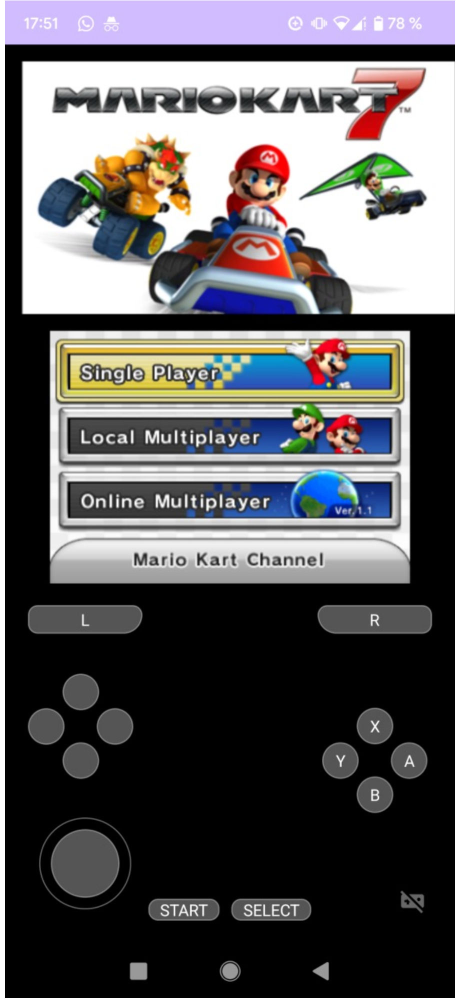
Panda3DS is a Nintendo 3DS emulator for Windows, MacOS, Linux and Android. Some goals and aspirations include:

- Providing end-users with a pleasant experience playing their 3DS games on all their devices
- Creating a portable, modern, easy-to-maintain codebase
- Exploring new possibilities in 3DS emulation:
  - Virtualization, ubershaders, and more
- Researching the 3DS software and hardware architecture
- Expanding the red panda cult
- Aiding homebrew devs in writing their own 3DS software
- Fun (...mostly)!

A peek at **Panda3DS**

The SDL frontend
`panda-sdl`

The Qt frontend
`panda-qt`

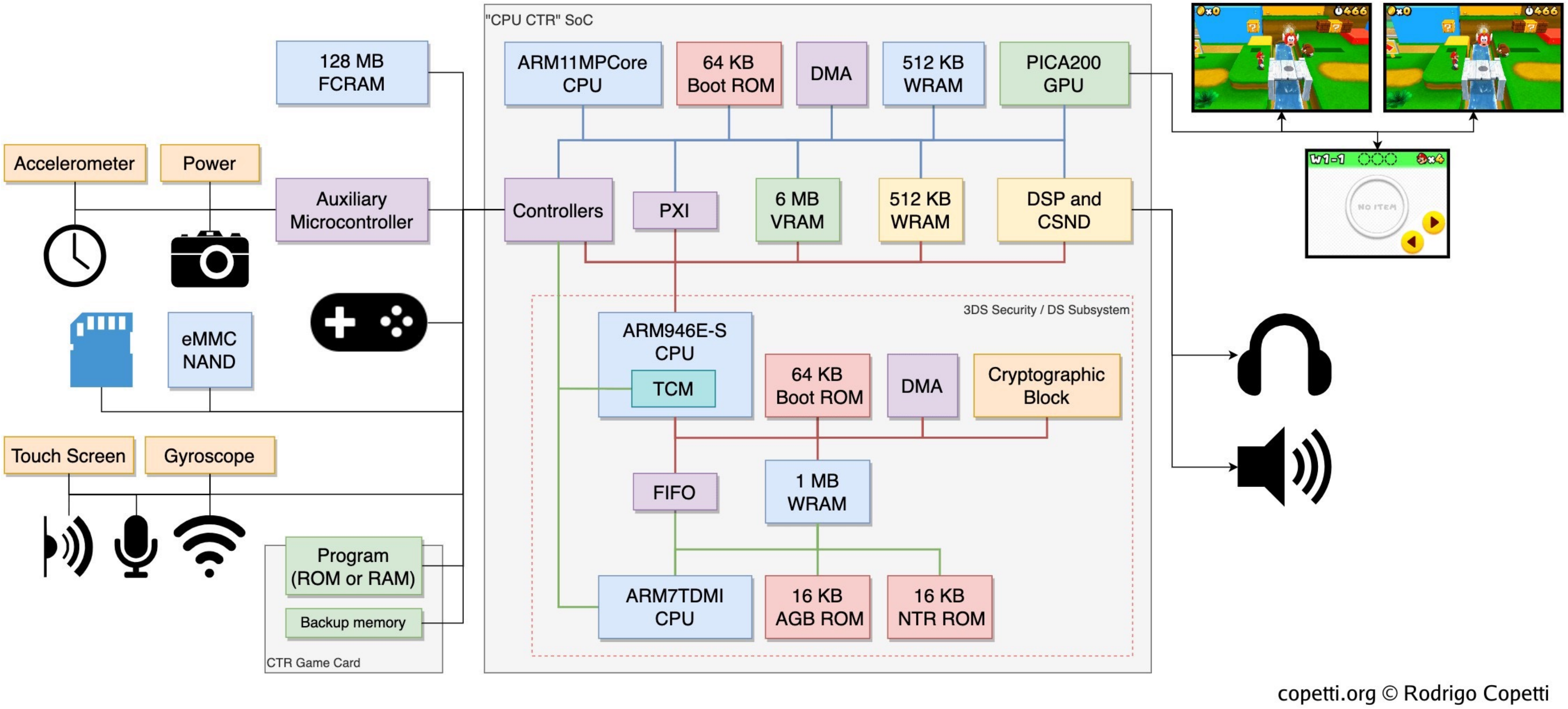


The Android version
`pandroid`

Agenda

- **Hardware Architecture**
  - **CPUs** (There's too many)
  - **GPU** The PICA200
  - **Audio DSP** XpertTeak
  - The Rest of the System
- **3DS Software Stack**
  - Nintendo’s Horizon OS
  - The 3DS Userland
- **Emulating the 3DS**
  - The “Levels” of Emulation
  - Difficulties & Points of Interest
  - New & Unexplored Territory

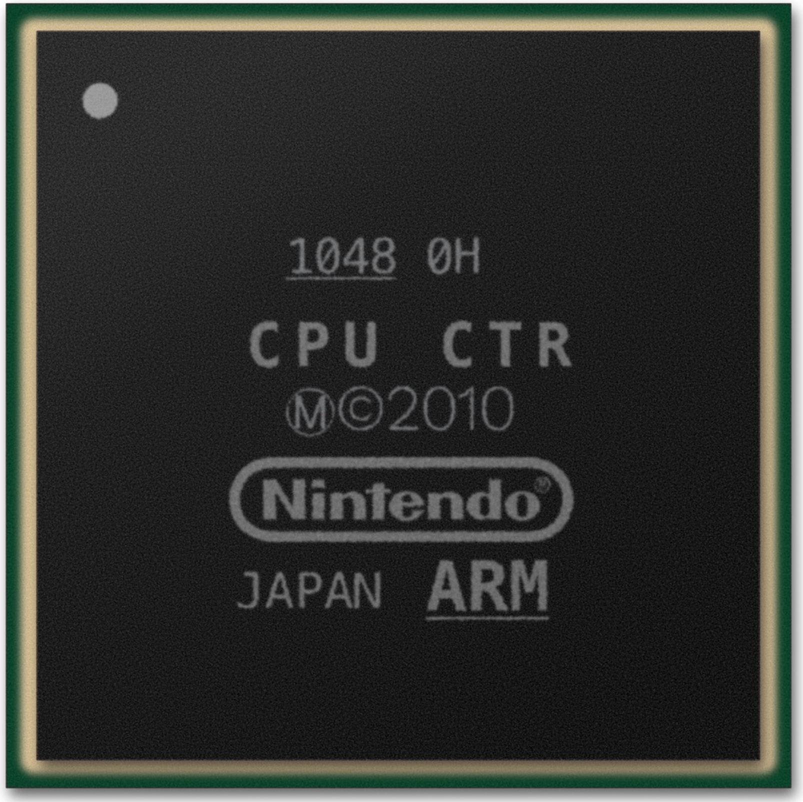
First glance 3DS hardware



Source copetti.org

The System-on-a-Chip **SoC**

The Nintendo 3DS is capable of natively running Game Boy Advance, Nintendo DS, and 3DS software. Most of the hardware used to achieve this resides in a small System-on-a-Chip, named “CPU CTR”



Fun facts:

- Many people don’t know the 3DS can run GBA games natively, since only those who were part of Nintendo’s “Ambassador program” could use this feature officially.

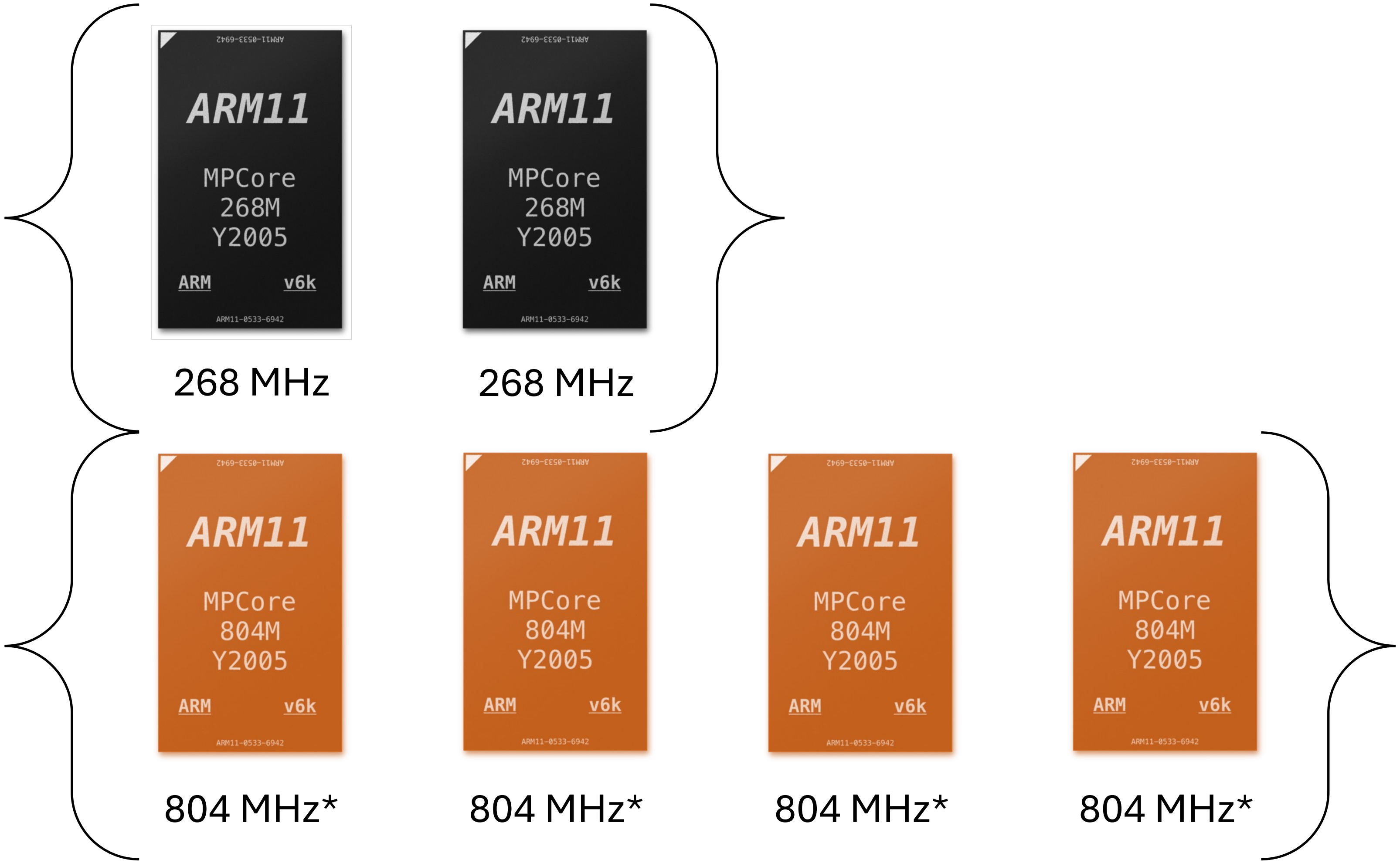
  Nowadays, there’s an open-source interface for running GBA games natively, called open_agb_firm.
- Diffused by Panasonic in Japan on their 45nm process

Inside the SoC: The **ARM11**

Running most of the code in 3DS mode

Original 3DS

New 3DS



268 MHz

268 MHz

804 MHz*

804 MHz*

804 MHz*

804 MHz*

Inside **ARM11** MPCore

3 Instruction Sets

ARMv6K Architecture
32-bit

- ARM
- Thumb
- Jazelle

VFPv2
Vector Floating Point

Faster processing of single/double precision floats

Media Instructions
for Video/Audio

MMU
for running multitasking OSes

16KB I-Cache

16KB D-Cache

Branch Predictor

Out-of-Order Completion
for some instructions

+ Multicore Coherency & More

Making use of the multiple ARM11 cores

Aiming to make good use of the multicore ARM11, the 3DS OS allocates different tasks to each core

Core 0 Appcore

Runs userland apps including games & system apps

Core 1 Syscore

Dedicated to OS. Runs many processes often known as "services" used to interface with world.
Apps can borrow some syscore compute time.

Core 2 New 3DS Only

Reserved for "QTM", the camera-based head tracking service.

Core 3 New 3DS Only

Available as another Appcore.

Inside the SoC: The **ARM9** & **ARM7**

ARM946E-S

ARMv5TE Architecture
32-bit

Same model as DS/DSi ARM9

66 MHz in DS compatibility mode

133 MHz in DSi mode and 3DS mode

3DS Mode

manages storage and cryptography hardwa re

Cartridge/NAND/SD

DS/DSi
Compatibility Mode

ARM7TDMI-S

ARMv4T Architecture
32-bit

Same model as GBA/DS/DSi ARM7

33 MHz in DS compatibility mode

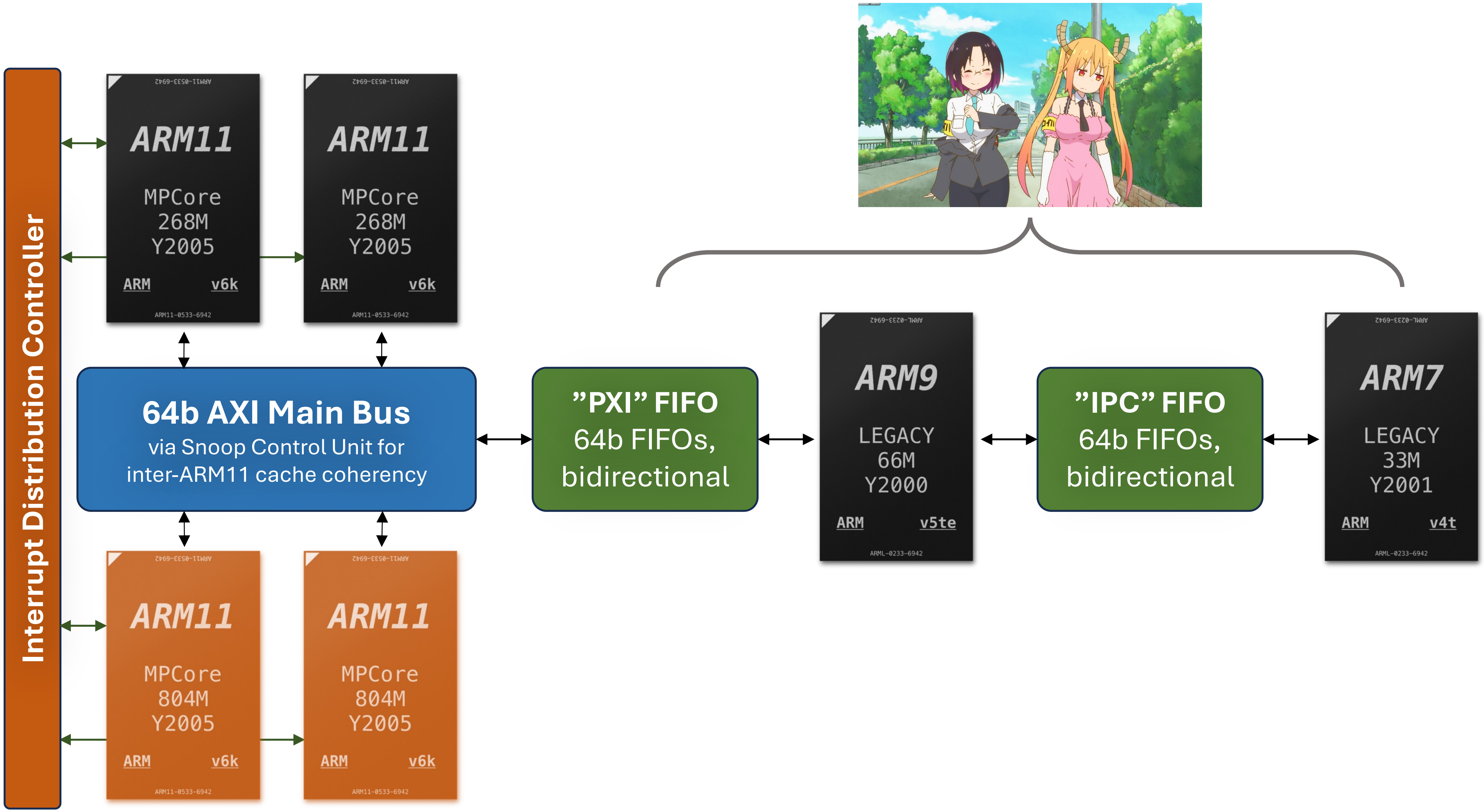
16 MHz in GBA compatibility mode

DS/DSi
Compatibility Mode

GBA
Compatibility Mode

Disabled in 3DS Mode

CPU Intercommunication



DMP PICA200 Everyone's favourite GPU

DMP MAESTRO

Custom Programmable Shaders

- **Vertex Shaders**
- **Geometry Shaders**

Fragment Lighting
Per-pixel
fixed-function effects

Hardware Shadow Mapping & Texture Projection

+ More Procedural Graphics Effects (DMP MAESTRO technology)

OpenGL ES 1.1

Compatible Features *

Nintendo's first off-the-shelf GPU in a handheld.

*But most 3DS games don't actually use GLES

PICA200 A Vertex Shader

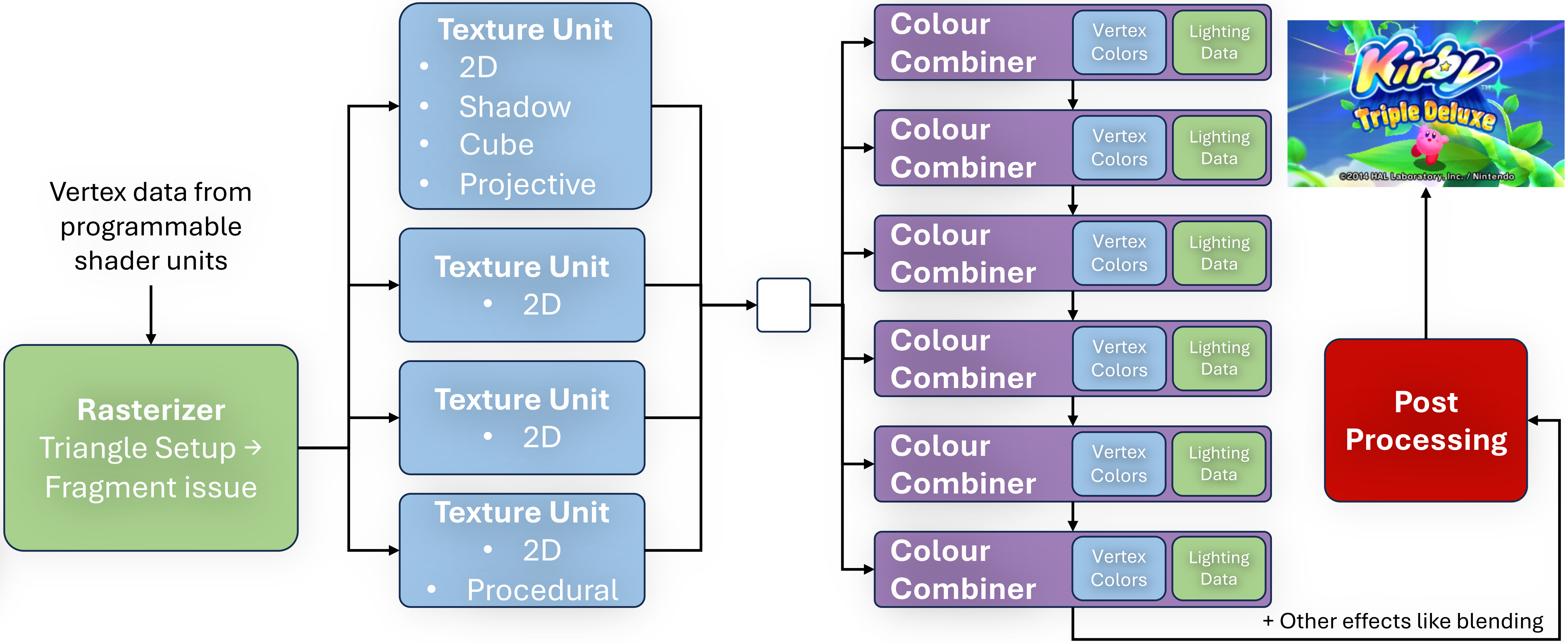
```
// Uniforms
.fvec projection[4]

// Constants
.constf myconst(0.0, 1.0, -1.0, 0.1)
.constf myconst2(0.3, 0.0, 0.0, 0.0)
.alias  zeros myconst.xxxx // Vector full of zeros
.alias  ones  myconst.yyyy // Vector full of ones

// Outputs
.out outpos position
.out outclr color

// Input attributes
.alias inpos v0
.alias inclr v1
```

```
.proc main
    // Force the w component of inpos to be 1.0
    mov r0.xyz, inpos
    mov r0.w,   ones

    // Output coords = projection matrix * input coords
    // 4 dot-products perform this matrix multiply.
    dp4 outpos.x, projection[0], r0
    dp4 outpos.y, projection[1], r0
    dp4 outpos.z, projection[2], r0
    dp4 outpos.w, projection[3], r0

    // Vertex out color = in color
    mov outclr, inclr

    end
.end
```

The pixel pipeline

Modern GPUs use programmable shaders to fill in pixels (fragments).

PICA200 uses a configurable pipeline.



Using the **Color Combiners**

The beanstalk texture is mixed with the lighting from a light source using the colour combiner – creating a sheen.

On the leaf Kirby is standing on, there's a darkening gradient from left to right.

Showing off the **PICA**

Captain Toad: Treasure Tracker, a game known for being clever with all sorts of lighting and shadow effects

Showing off the **PICA**

The Legend of Zelda: Ocarina of Time 3D
using the PICA's fog rendering hardware
Also texture compression with ETC1 and ETC1A4!

Showing off the **PICA**

Mario and Luigi: Paper Jam generates the seawater via procedurally-generated textures

Showing off the **PICA**

Super Mario 3D Land uses all sorts of features, such as stencil testing, logic ops, good usage of lighting, GPU command lists that invoke other command lists, and more

The **XpertTeak** DSP

More Processors! The 3DS also has a **D**igital **S**ignal **P**rocessor for audio.
It's the same model as the DSi DSP but it's used far more.

Most games shipped a common DSP firmware which includes:

Support for up to
24 audio channels

AAC Audio Decoder
Used in games like Pokémon X/Y

Multiple Audio Encodings

- PCM8
- PCM16
- ADPCM

Effects

- Reverb
- Delay
- Filters
  One-pole & Biquad

Mono Input

Stereo Input

Stereo Output

Teak architecture

Signal Processing Instructions
Plenty for multiply, multiply-add, division, etc.

Loop Instructions
Supporting tight loops

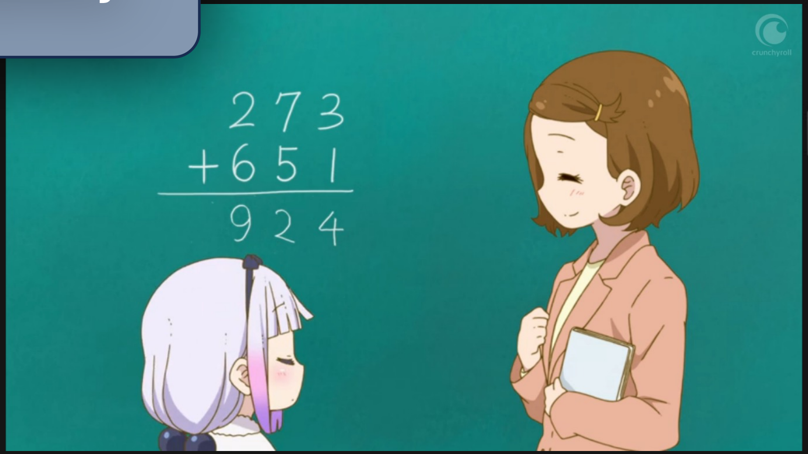
16-bit Bytes
Instead of the typical 8b

ARM11 Synchronization
With data exchange and a semaphore register

256KB Instruction Memory

256KB Data Memory

With ~~awful~~ complicated instruction encodings



Misc hardware

128 / 256* MB FCRAM
64-bit "Fast Cycle RAM"
Built by Fujitsu

6 / 10 MB of VRAM
Inside the chip

One-Time-Programmable Memory
Stores console-unique keys

Microcontroller
For extra IO & Power Management

Arm CoreLink DMA
programmable DMA engine

Hardware Cryptography Engine
AES / SHA / RSA / RNG

SD Card Slot
Expandable Game Storage

IR Transceiver
for Amiibo & CirclePadPro

WiFi Controller

Xtensa CPU

GBA & DSi Hardware
for game compatibility

eMMC NAND
Stores system data

IR Front LED
for New 3DS Face Tracking

2 LCDs

PDC PICA Display Controller

Bottom Display Resistive Touch

Motion Sensors
Gyroscope & Accelerometer

Cameras
2 Back Cameras
Front Camera

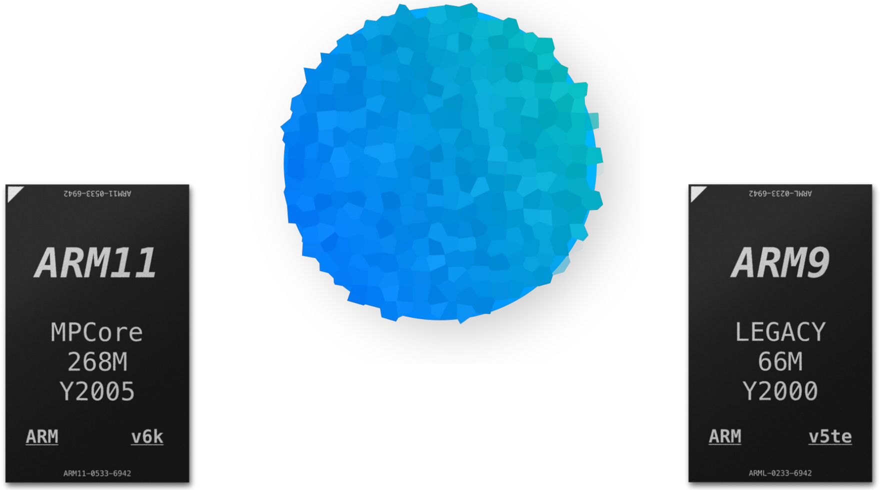
NFC Reader
for New 3DS Amiibo Support

Software stack!

The 3DS OS: **Horizon**®

To tame this hardware,

We have Nintendo’s beautifully architected operating system



We’ll look at **Horizon** on **ARM11** Syscore

& **Horizon** on **ARM9** for Security & I/O

Getting a firm grasp of **FIRMs**

The 3DS comes with multiple different "firmware" programs running on the ARM cores with low-level control of the underlying hardware:

`NATIVE_FIRM`

Runs **3DS** Games Natively: "3DS Mode"

ARM11
- Runs Userland
- Majority of OS code

ARM9
- Cryptography
- Cartridge & SD I/O

`AGB_FIRM`

Runs **GBA** Games Natively

ARM7
- Downclocked to GBA speeds
- Runs game code

Internal GBA Hardware

`TWL_FIRM`

Runs **DS** or **DSi** Games Natively

ARM9
- Downclocked to DS or DSi speeds
- Runs game code

ARM7
- Downclocked to DS(i) speeds
- Runs game code

Internal DSi Hardware

`SAFE_FIRM`

Older, bare-bones version of `NATIVE_FIRM` for recovery

Use a button combo to enter **Safe Mode** with **System Updater**

A microkernel architecture

The kernel is the core of an OS. The 3DS ARM11 kernel is called `kernel11`.

`kernel11`

Memory Management

Map Memory to processes & configure their access permissions

Process & Thread Management

Creation, multithreading primitives, Lifecycling

Service & Process Inter-communication

Via the sync request API and shared memory

Kernel calls are performed with the Arm SVC (Supervisor Call) instruction.

```
EXPORT svcExitThread
svcExitThread
SVC        9
BX         LR
```

An ARM assembly function for calling the `exitThread` SVC.

HorizonOS services

Service Handle

Request a service handle from “Service Manager”

↓

Set Up The Parameter Buffer

with the function to call | and necessary parameters

↓

Send Request To Service

Call SendSyncRequest SVC with service handle & buffer

↓

Receive Output Buffer

Function-Specific Output Data | Potential Error Codes

Some important services

FS
Filesystem IO for Cartridge, SD, Save Data & more

DSP
Communication with Audio DSP

GSP
GPU & Display Communication

APT
Inferface with system applets & manage some app controls

HID
Interface with many input devices like gamepad, motion, …

CFG
Read system configuration data like console model & region

AC / HTTP / SSL / SOC
Networking Tasks

CAM / MIC / NFC
Camera, Mic, & NFC Input

```
Result HIDUSER_DisableAccelerometer(void)
{
    // Get IPC command buffer for service data exchange
    u32* cmdbuf = getThreadCommandBuffer();
    // Setup the command header (0x13 = EnableGyproscope)
    cmdbuf[0] = IPC_MakeHeader(0x13,0,0);

    // Send buffer to service and wait for completion
    Result ret = svcSendSyncRequest(hidHandle);
    if(R_FAILED(ret)) // If SendSyncRequest failed,
returnreturn ret;

    // Otherwise, return result code from HID service
    return cmdbuf[1];
}
```

Function that asks the HID service to enable the gyroscope

adapted from `libctru`

Process9

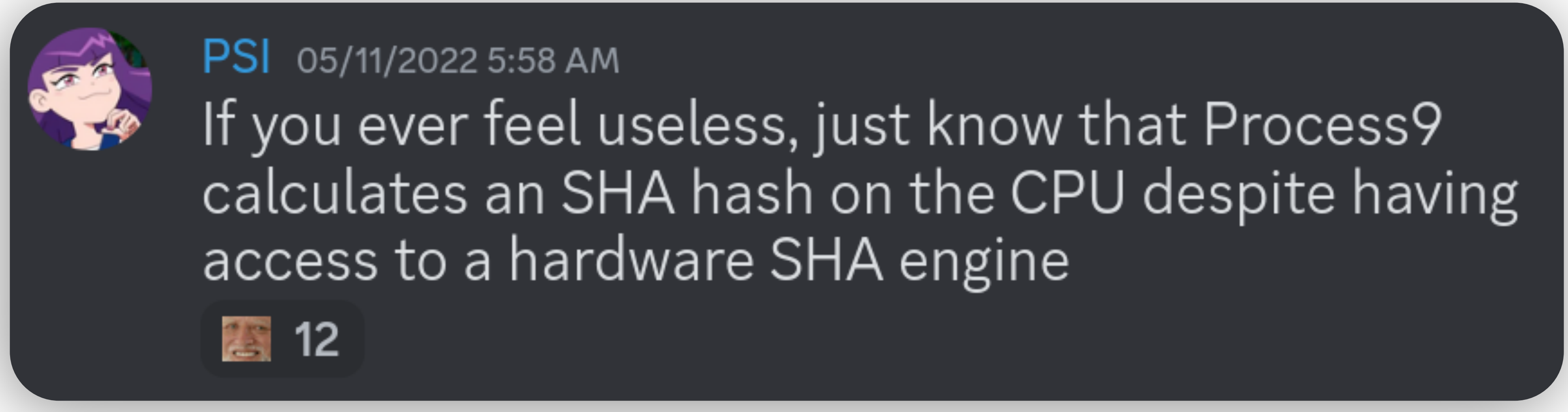
Unlike ARM11, the ARM9 in 3DS mode handles all its tasks in one big process called Process9.

Cryptography
Data encryption & decryption with crypto hardware

Device I/O
Talks to various devices like Cartridge / SD Card / …

Overcomplicated C++
That reverse engineers hate :(

Really big

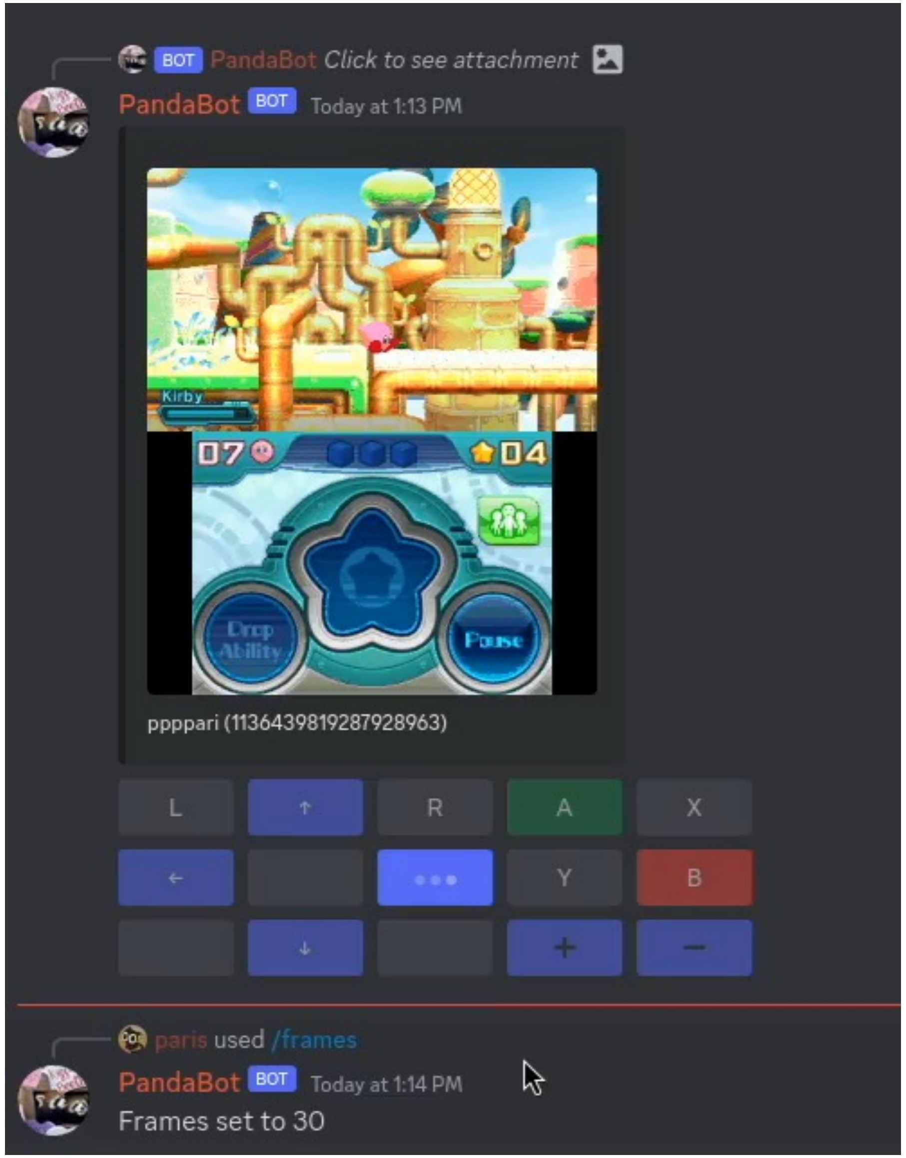


A lil' breather

Some live demos!

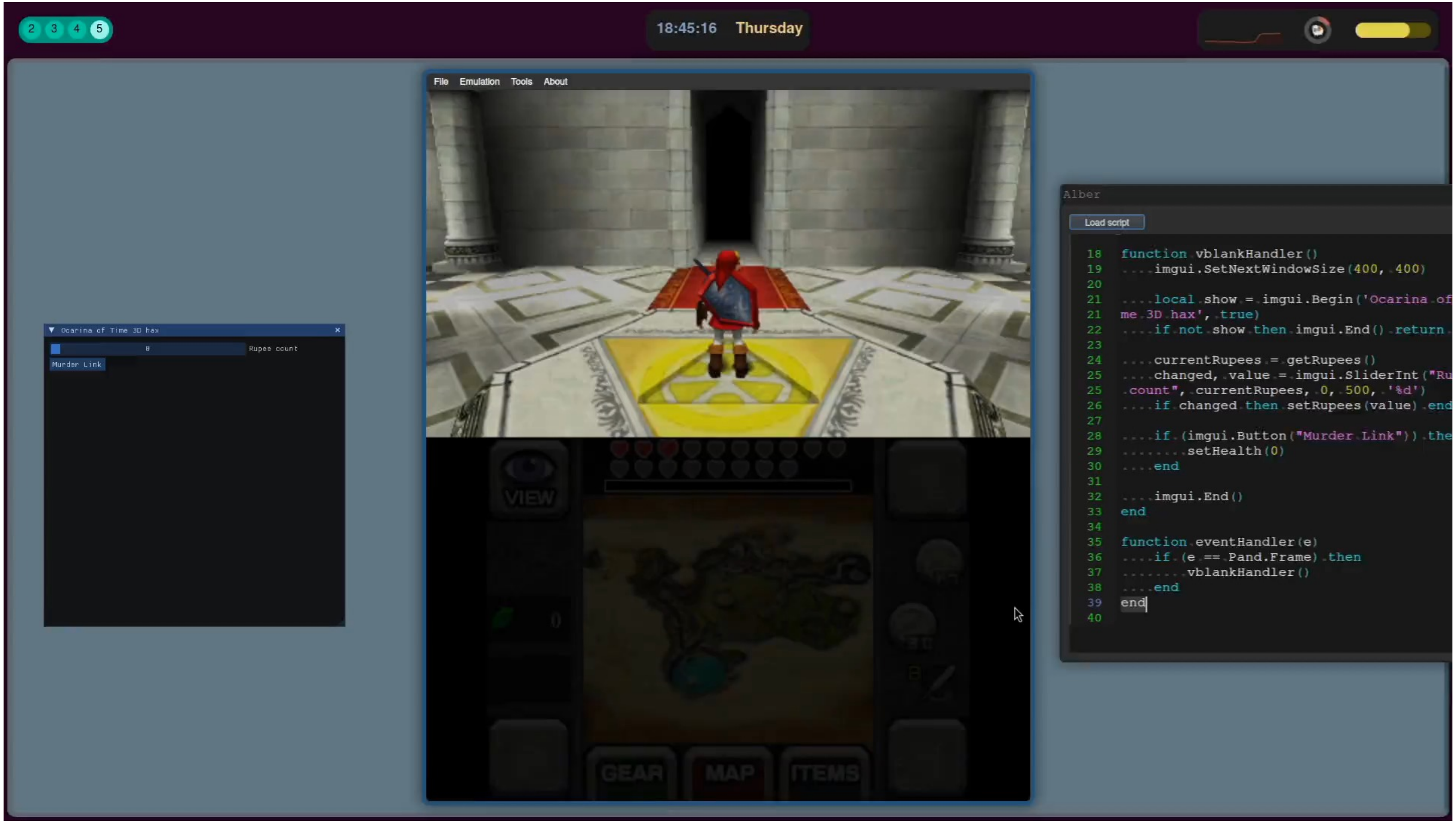
I knew this would fail

Here's a video instead



This failed too? 

Here's a video instead

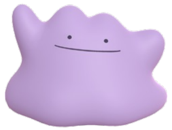


Emulation!

finally...

High & Low-Level Emulation

- **HLE** Reimplementing parts of the emulated system's software in our own code, to avoid emulating the hardware needed to run said software.



Eg. An LLE Audio DSP is expensive to emulate performance-wise

LLE & Actual Device

Audio DSP Hardware

DSP Firmware

HLE

C++ model reimplementing DSP firmware features

DSP Firmware Compatible Interface

For the 3DS, we can HLE the OS: **Kernel** **Services** **Process9** & …

```
void FSService::isSdmcDetected(u32 messagePointer) {
    log("FS::IsSdmcDetected\n");

    mem.write32(messagePointer, IPC::responseHeader(0x817, 2, 0));
    mem.write32(messagePointer + 4, Result::Success);
    mem.write8(messagePointer + 8, config.sdCardInserted ? 1 : 0);
}
```

HLE implementation of FS service function that returns if an SD card is inserted

We avoid emulating the complex SD hardware interface.

As an Emudev What parts to LLE, what to HLE?

LLE

Tedious to implement so much hardware

That much hardware reduces performance and is error-prone.

Beneficially, it can run any 3DS software incl. baremetal firms like 3DS Linux / GodMode9

HLE

Tedious to implement so many services

Performant but still error-prone.

Many elements left to reverse engineer.

Hybrid

We can HLE kernel11 & process9

We can LLE most OS services.

Balance

- Minimizing work
- Improving Performance
- Maintaining Accuracy

As an Emudev: The CPU

Interpreters
Loop and process CPU instructions in normal code. Slow, portable, good for a start but not for fullspeed emulation

Just-in-Time (JIT) Recompilation
Convert ARM code to host CPU code. This is the most common solution.
Citra & Panda3DS both use the *Dynarmic* library to perform `Arm32` to `x86` / `Arm64`

Virtualization (Potentially)
On Arm32/Arm64 devices, virtualization could be used to execute 3DS code natively. An ongoing Panda3DS PR is aiming to add this.

Ahead-of-Time (AOT) Recompilation (Potentially)
Recompile ARM code from the code section of 3DS executables to host CPU assembly ahead of time.

As an Emudev: The GPU

Software Rendering

Draws emulated triangle on the CPU in software.

Very slow but portable and simpler™

How can we speed it up?

- **Multithreading** drawing with several concurrent threads
- **Recompilers** Much like the CPU JIT, we can parse the PICA200 confiuguration for a draw call and generate optimized rasterization code at runtime.

Hardware Rendering

Draws on the GPU via a graphics API like OpenGL / Vulkan / DirectX / Metal.
Much faster - suitable for gameplay.

Challenges

- Choosing the ideal API
- Efficient & Correct Surface Management

  textures, color buffers, depth buffer
- Many, many other problems to solve

Emulating PICA shaders

Interpreter

Simple
Too slow

JIT on CPU

Decent Performance
But could be better

Recompiling Shaders for GPU

Good Performance
Only for HW Rendering
Might not be possible for select PICA shaders

```
.proc main
    mov r0.xyz, inpos
    mov r0.w,   ones

    ; outpos = projectionMatrix * inpos
    dp4 outpos.x, projection[0], r0
    dp4 outpos.y, projection[1], r0
    dp4 outpos.z, projection[2], r0
    dp4 outpos.w, projection[3], r0

    ; outclr = inclr
    mov outclr, inclr

    ; We're finished
    end
.end
```

CPU JIT

```
proc near
movaps  xmm2, xmmword ptr [r8+740h]
movaps  xmm0, xmmword ptr [r8+0B50h]
blendps xmm0, xmm2, 7
movaps  xmmword ptr [r8+0B50h], xmm0
pshufd  xmm2, xmmword ptr [r8+630h], 5
vpsrldq xmm0, xmm2, 0Ch
movss   dword ptr [r8+0B5Ch], xmm0
movaps  xmm2, xmmword ptr [r8+40h]
movaps  xmm3, xmmword ptr [r8+0B50h]
dpps    xmm2, xmm3, 0FFh
movss   dword ptr [r8+840h], xmm2
movaps  xmm2, xmmword ptr [r8+50h]
movaps  xmm3, xmmword ptr [r8+0B50h]
dpps    xmm2, xmm3, 0FFh
vpsrldq xmm0, xmm2, 4
movss   dword ptr [r8+844h], xmm0
movaps  xmm2, xmmword ptr [r8+60h]
movaps  xmm3, xmmword ptr [r8+0B50h]
dpps    xmm2, xmm3, 0FFh
vpsrldq xmm0, xmm2, 8
movss   dword ptr [r8+848h], xmm0
movaps  xmm2, xmmword ptr [r8+70h]
movaps  xmm3, xmmword ptr [r8+0B50h]
dpps    xmm2, xmm3, 0FFh
vpsrldq xmm0, xmm2, 0Ch
movss   dword ptr [r8+84Ch], xmm0
movaps  xmm2, xmmword ptr [r8+750h]
movaps  xmmword ptr [r8+850h], xmm2
```

Emulating the PICA pixel pipeline

Specialized Shaders

Compile a specialized shader for each PICA pixel pipeline configuration.

Low GPU Usage

However lots of time is spent compiling shaders, Causing stutters.

Most common approach, currently WIP in Panda3DS

Ubershaders

Include an entire “emulator” for the pixel pipeline inside a GPU fragment shader.

Higher GPU usage but no compilation stutter.

Works well on modern PC GPUs but struggles on mobile GPUs.

Implemented in Panda3DS

Hybrid emulation

Compile specialized shaders in the background. The ubershader is used for each draw call until the relevant shader is ready.

Good performance with minimum stutter.

Works well on all GPUs. Higher code complexity.

What Panda3DS wishes to achieve.

As an Emudev Audio DSP

LLE

How do we optimize it?

- Recompiling firmware
- AOT Compilation

Teakra
An emulator / assembler / disassembler for the Teak DSP used in Citra & MelonDS

HLE

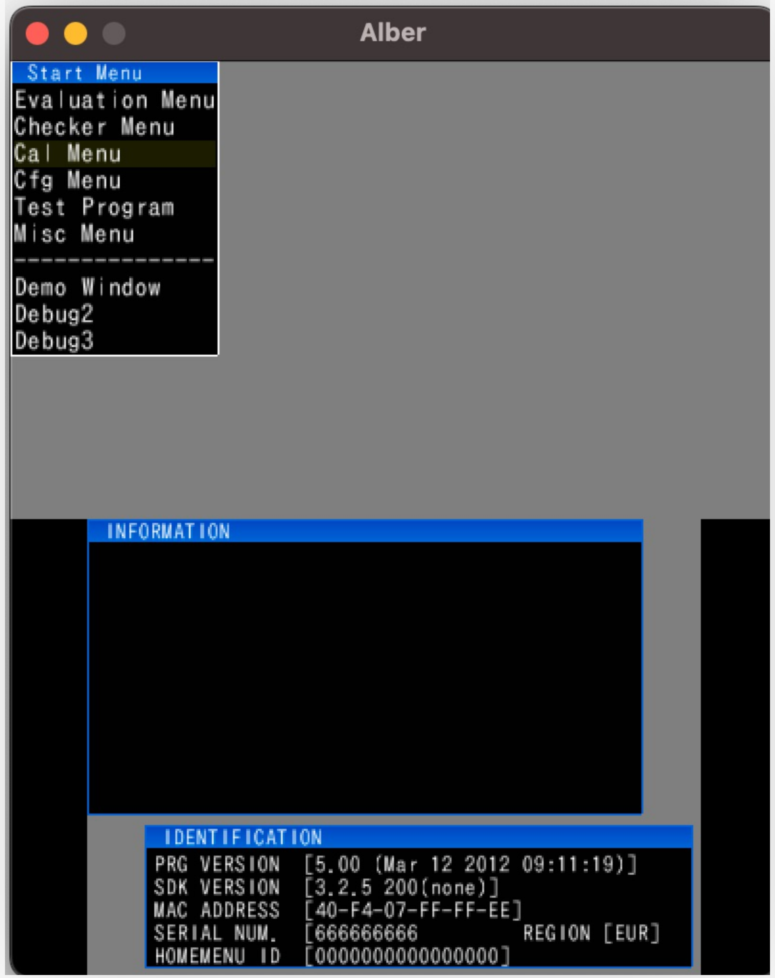
Improving current DSP reverse engineering efforts By making test ROMS & RE tooling.

Techniques for optimized audio mixing
SIMD / Multithreading / ...

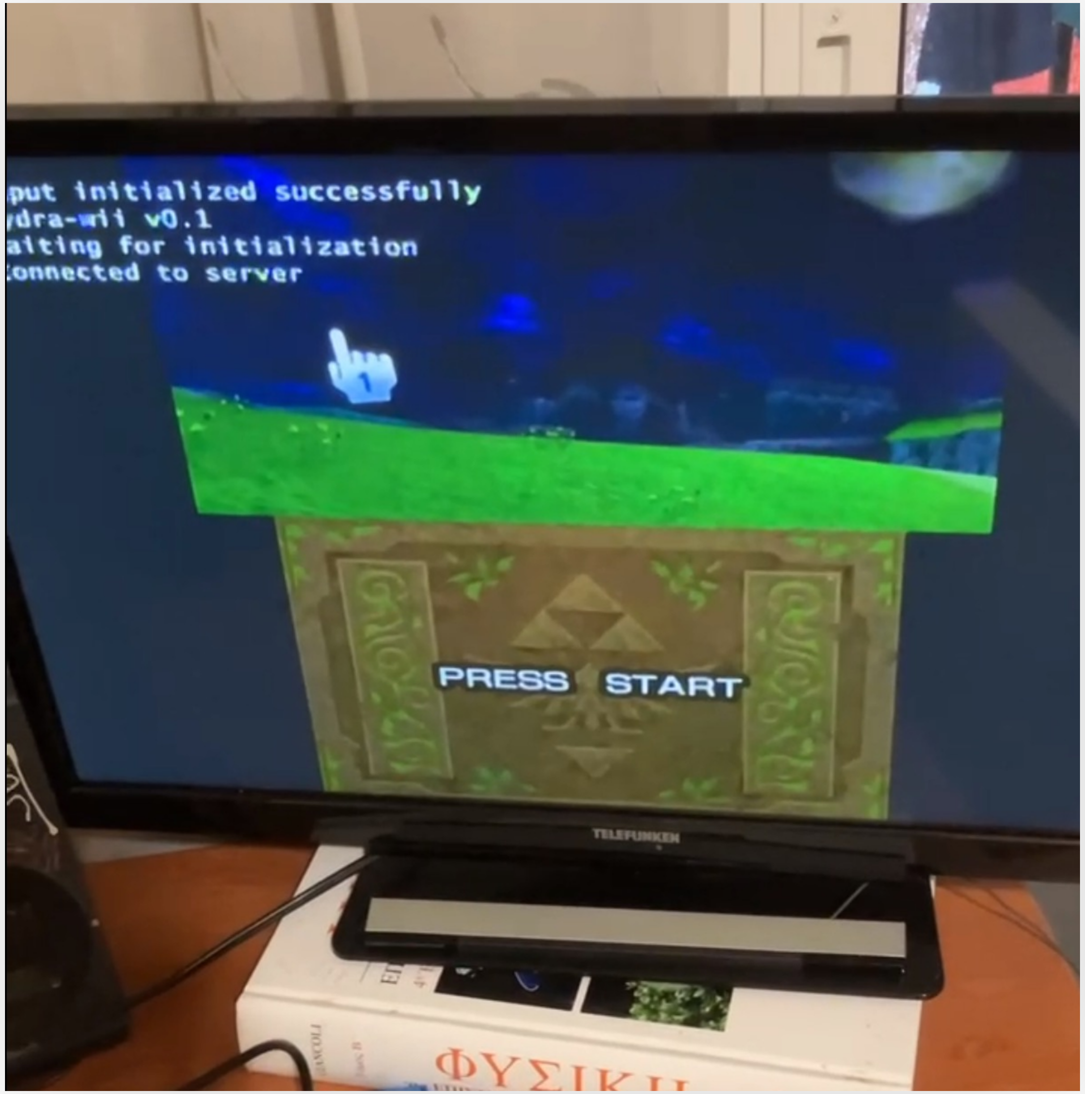
Exploring new territory in 3DS emulation

Panda3DS comes with Lua scripting, including a text editor, so developers can make all sorts of scripts & mods, testing them fully within the app!

Exploring new territory in 3DS emulation

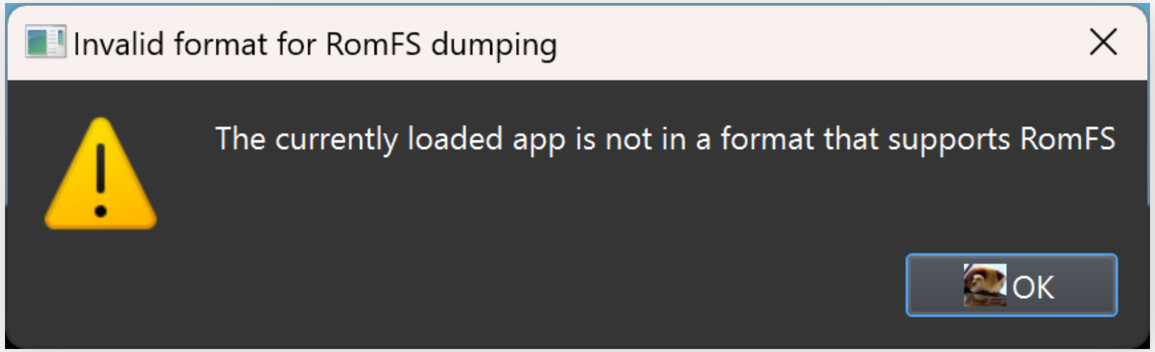


A Panda3DS dev branch running CTRAging, a factory test program some other emulators may struggle with

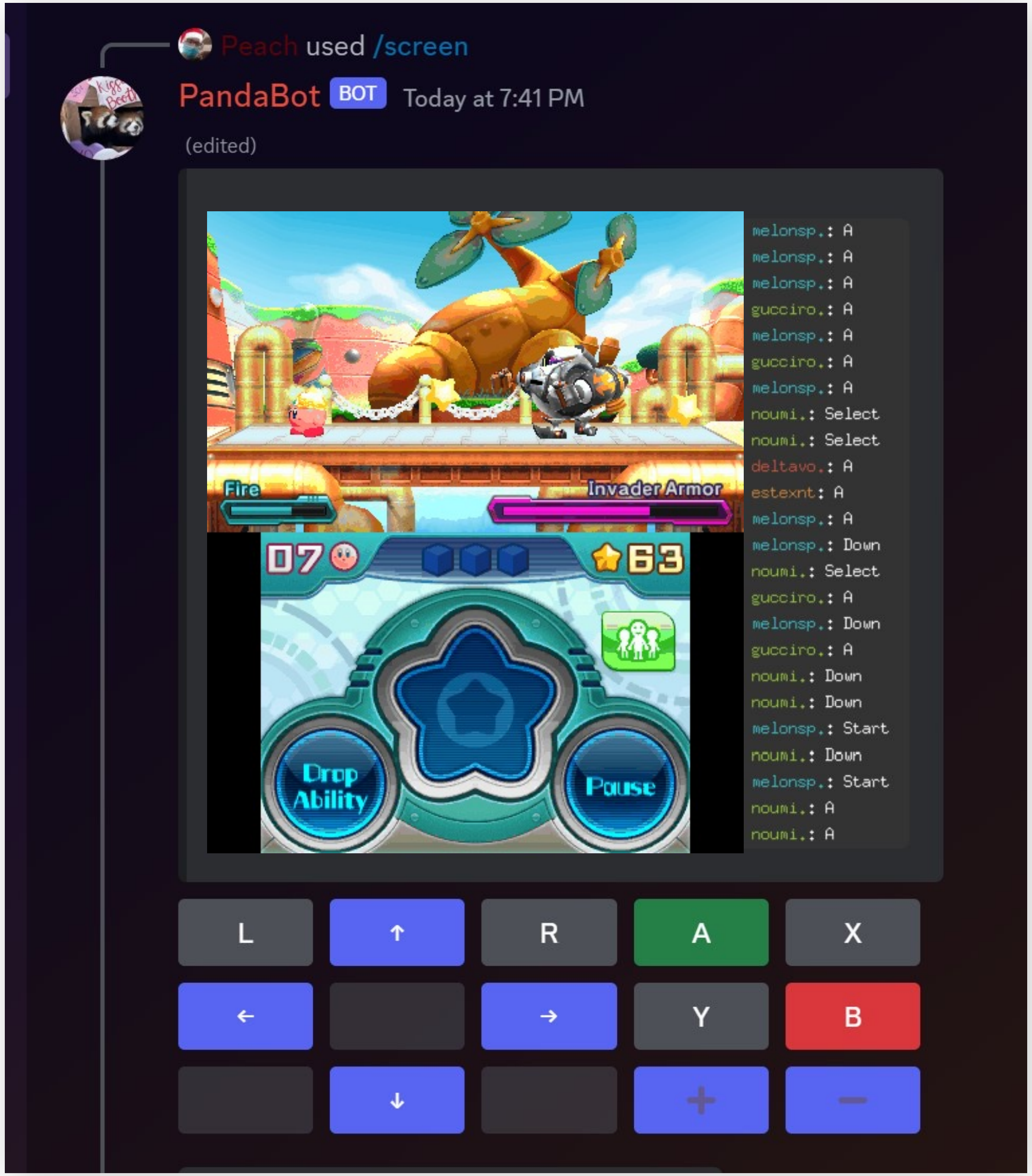


Panda3DS running on Wii, via HTTP streaming

Exploring new territory in 3DS emulation



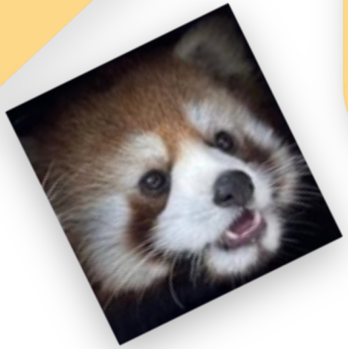
Revolutionary UI (Has panda icons)



Play on Discord with all of your friends!

Star us on GitHub

Thx



panda3ds.com

Panda Πάντα 熊猫 Панда Պանդա पांडा 팬더 الباندا パンダ