ENTER.
tech with a heartbeat

LOW-END EMBEDDED SYSTEMS FOR HIGH-END PRODUCTS

INSIGHTS FROM A REAL PRODUCTS DEVELOPMENT

CAIO OLIVEIRA

TODAY'S STORY

LOW-END EMBEDDED SYSTEMS AND CODE SIZE:

GETTING BLOOD OUT OF STONE

PART I

INTRODUCTION

BACKGROUND
OVER ME

Caio Souza Oliveira (30)
Brazilian

- **Profile**
  - Working for **Enter** since 2017;
  - Embedded Software Engineer;
  - Involved in several projects within **Philips** ever since;
- **Education**
  - Master in Electrical Engineering (UFMG-Brazil);
    Major: **Embedded System Design**
    (Heterogeneous Computing);
  - Bachelor in Computer Engineering (UNIFEI-Brazil);
- **General**
  - Sweet spot for **C/C++** and **Assembly**;
  - Working on homebrew for retro-video games (SNES/GB);
  - Deep interest
    - Quantum Computing
    - Compiler Theory;
    - Languages;
    - Astronomy;
    - Exercicing;

BACKGROUND
PROJECT'S OVERVIEW

- **Embedded Sofware Engineer in Philips Drachten**
  - Wi-Fi connected device, with rich user interface, mobile app and back-end connectivity;
  - Original firmware was developed by an external partner;
    - Not the best development practices;
    - Not maintainable in the long run;

- **Rewrite the Firmware!**
  - The firmware is meant to run on legacy hardware;
  - It must be written in C++ and fully tested (integration + unit);
  - Must be compatible with product's ecosystem (FW+CLOUD+APP);
  - Must be continuously updated over the span of several years;

BACKGROUND
HARDWARE OVERVIEW

- The hardware was designed in 2016 based on an external partner's specification. The system is quite complex, and it can be summarized as:
    - End-of-life **Cypress' 32-bit ARM Cortex-M0+** based microcontroller;
    - 40.5MHz MCU, **128KB internal Flash and 16KB RAM**;
    - **8MB External (*off-board*) Flash chip** for data storage;
    - Multiple connectivity and multi-media components not relevant for this presentation;

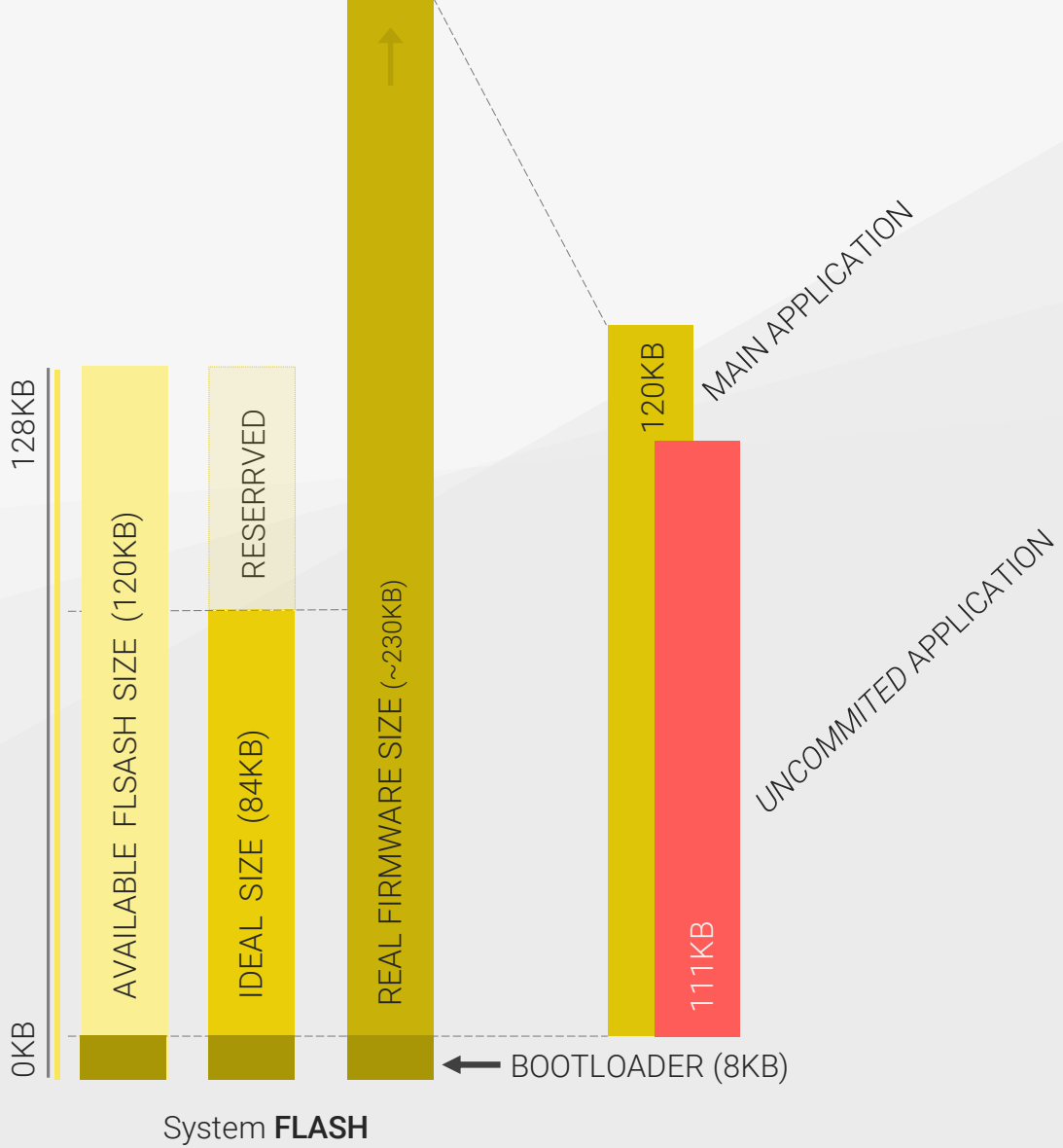
BACKGROUND
SOFTWARE OVERVIEW

- Bare Metal;
- Fully **layered architecture** following OOP paradigm;
- *Plug-and-Play* components architecture (for services and feature abstractions);
- Rich *template-based* UI rendering;
  - Almost **one hundred different** screens;
  - Also provides the concept of UI Controls/Views for *tighter* software development;
  - Event-driven user-input handling;
- REST-API host;
  - Provides **hundreds of properties and methods** to allow remote control;
  - Including *transactional* memory manager;
- More **than a dozen user-level features**;
- **Command Line Interface** for advanced automated testing;
- Services, Infrastructure, HAL layers;
- And lots more…

BACKGROUND
THE PROBLEM

- *It will **not fit** in 128 KB;*

BACKGROUND
THE PROBLEM



BACKGROUND
THE PROBLEM

BACKGROUND
THE PROBLEM

- Changing the hardware is not an option;
- We could not find a commercial/open source solution that would fit our needs;
  - Even IAR has been officially contacted but they had no appropriate solution;

BACKGROUND
THE SOLUTION

CODE BANKS
BANK SWITCHING

Formally:

*"Bank Switching (or code banking) is a technique where one can **increase the amount of usable memory** without directly changing addressable space reachable by the microprocessor" (Wikipedia, modified)*

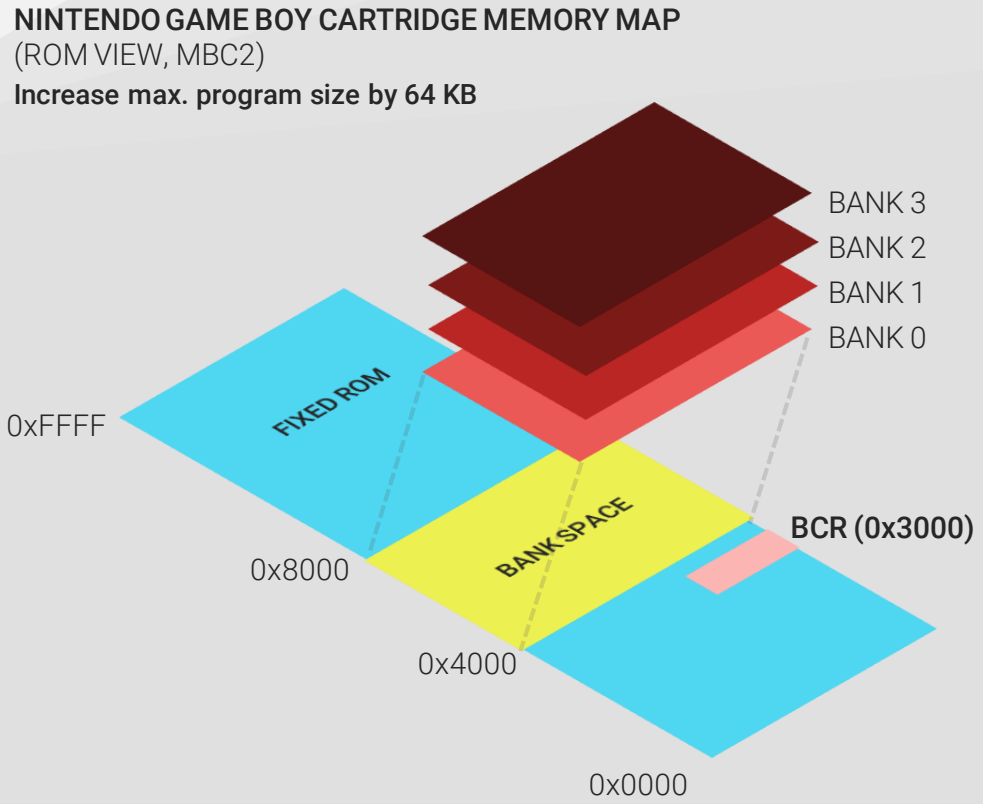
CODE BANKS

BANK SWITCHING

- **Idea**: use a single addressing space, and **dynamically switch code/data segments in-and-out** as needed.

- Very common technique in older computer, where addressing space would be from 10, 12 or 16-bits while the programs were much larger than what would fit in those address-ranges.

    - Used in old computer and video games (8080, Z80, 6502, 6809, etc.) using special hardware registers/instructions;
    - Switching *floppies* or changing CDs can also be considered a type of bank switching.



CODE BANKS
IMPLEMENTATION CHALLENGES

- **Cortex-M0+** has no hardware for bank switching. **Software is the only option!**
    - Expand CPU's addressing space…?
        - No, **increase the amount of usable code memory** seen by the CPU instead;
    - How dynamically swap code segments?
    - How to **properly build** code segments so that:
        - *Data sharing* among the multiple slices is allowed;
        - *Code sharing* is possible;
    - How to split the program into code banks?
    - Which programming model should be used to allow code banks to be used along with any C++ program?
    - How good would this solution perform?

CODE BANKS

IMPLEMENTING THE CONCEPT **IN SOFTWARE**

- What did I need:
  1. **Readily available** bank's storage location;
  2. ***Non-degradable*, exactable** memory resource;
  3. **A software architecture** to abstract (and somehow *hide*) the banking concept;
     - In other words: banks must be *invisible* from the programmer's and CPU perspective
  4. **Very low latency** switching and execution

CODE BANKS

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CODE BANKS

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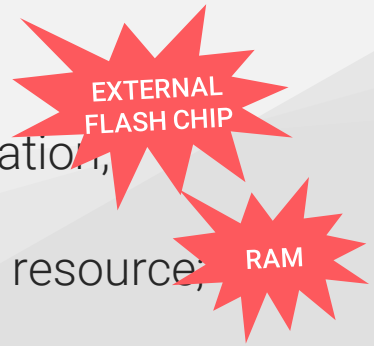

CODE BANKS

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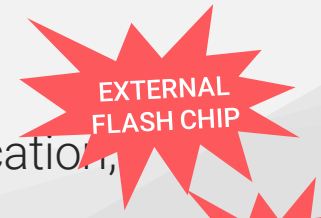

CODE BANKS

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EXTERNAL FLASH CHIP

RAM

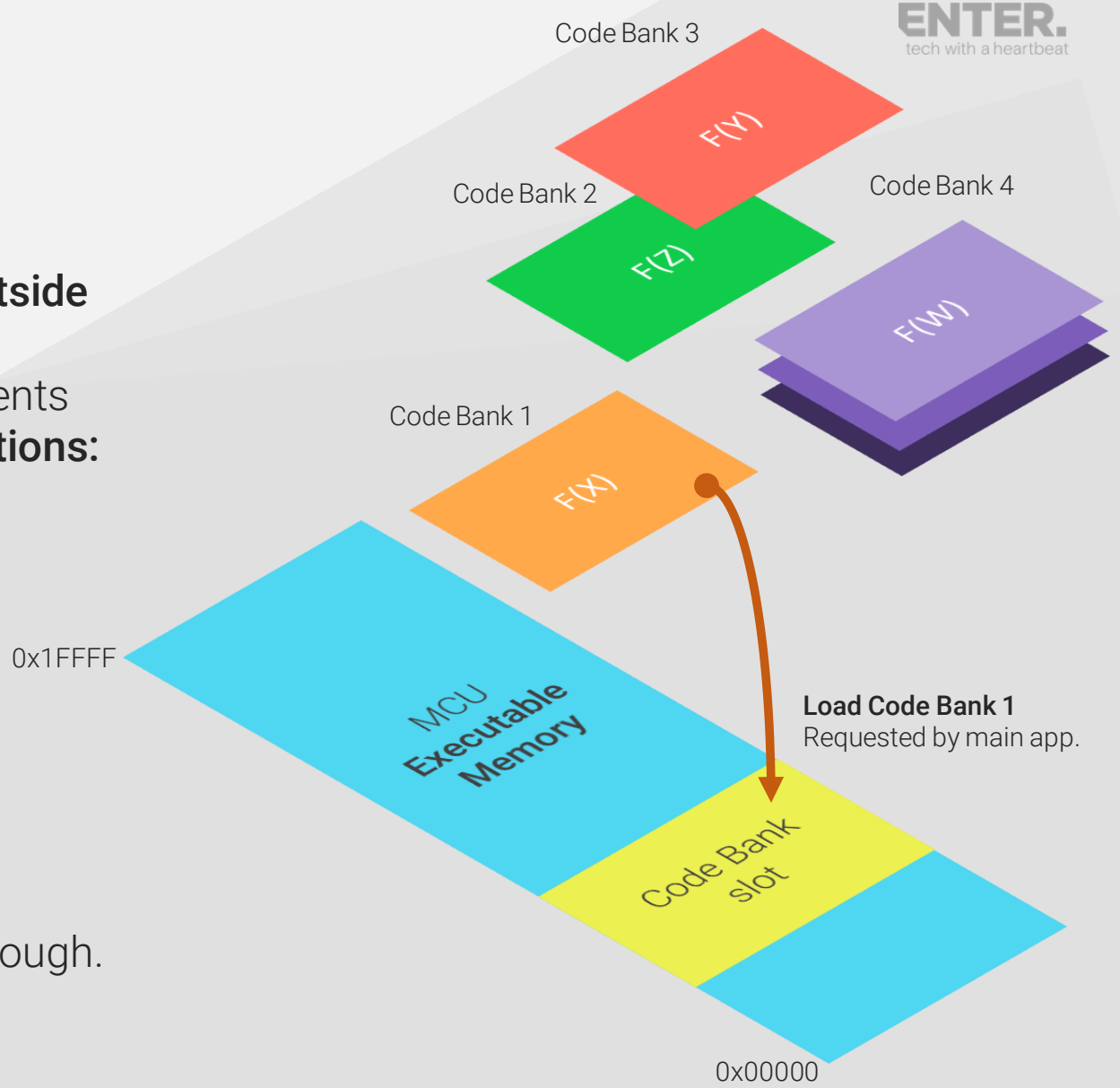
CUSTOM LIBRARY AND BUILD TOOLS

SIMPLE ARCH. & VIRTUAL BANKS

CODE BANKS

SIMULATING THE BEHAVIOR OF CODE BANKS

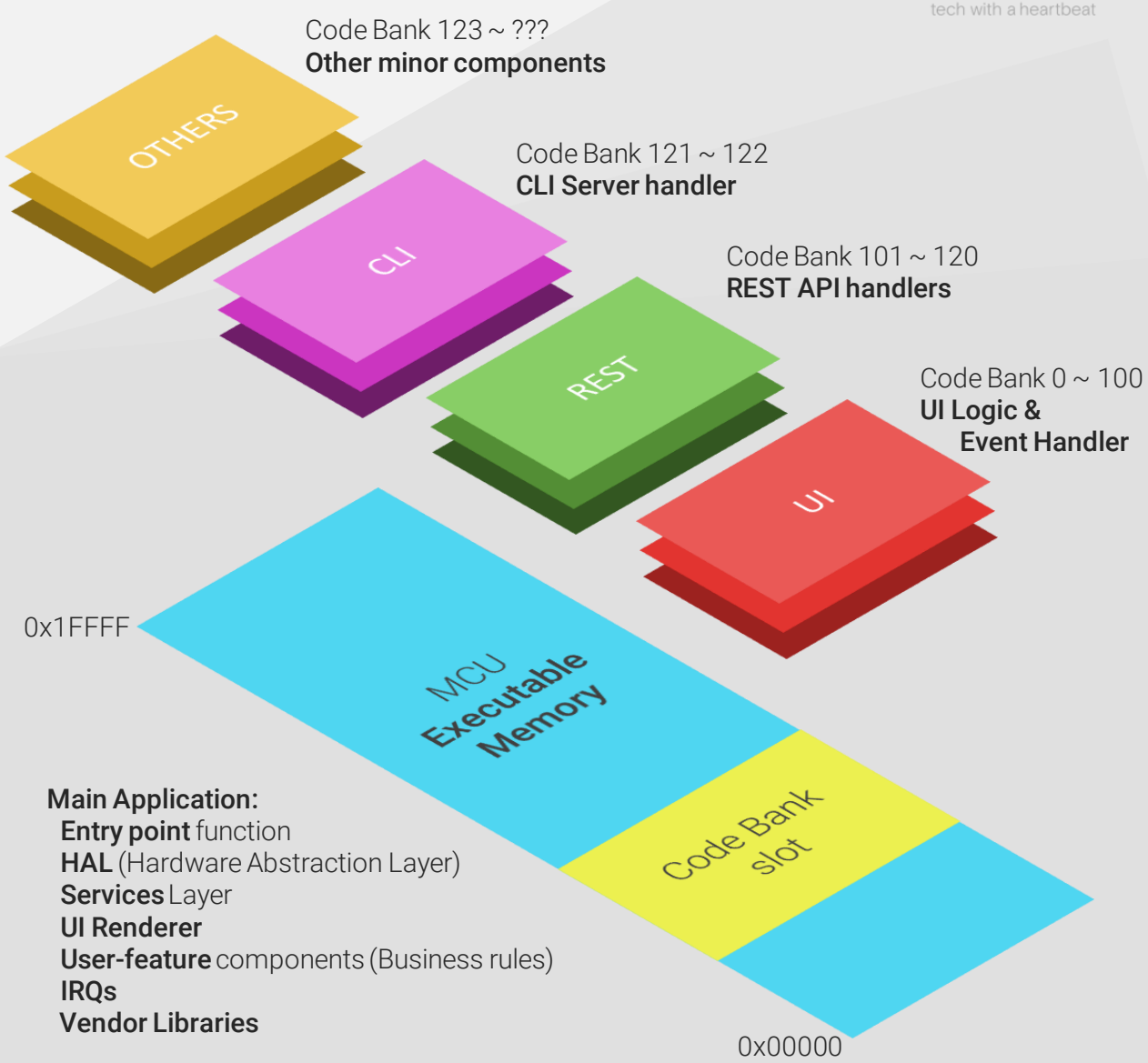
- How would it work?
  1. Code Segments (*AKA code banks*) are **stored outside of the microcontroller's** Flash;
  2. Upon **request from the application**, those segments would be **loaded and executed as ordinary functions:**
     a) It should be possible to **pass arguments** to it;
     b) It should be possible get **return values** from it;
  3. When the code is no longer needed, other code segments **could take its place**;
- This would effectively allow the application to be considerably bigger!
  - The application should be designed differently, though.



CODE BANKS

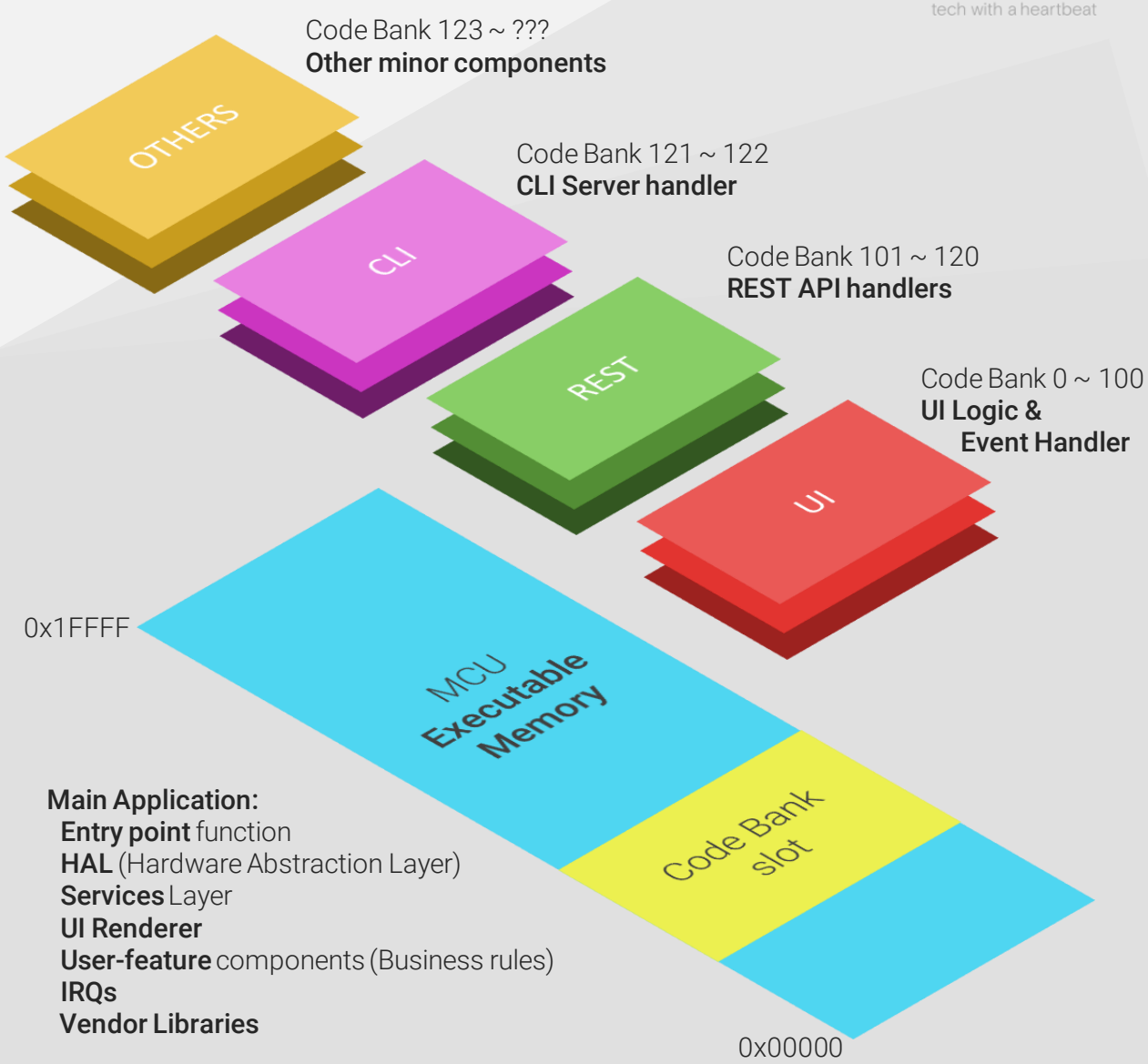
SOFTWARE PARTITION

- To simplify development (and debugging) the software should be split into *two* groups: ***bankable*/*non-bankable***;
- General functionality (HAL, Services, User Features) was considered ***non-bankable*** would remain in the CPU's internal Flash;
- Those functionalities are **constantly used throughout the entire code**, and if set in a code bank, it would require continuous bank switching (possibly degrading performance);



CODE BANKS
SOFTWARE PARTITION

- To simplify development (and debugging) the software should be split into *two* groups: ***bankable*/*non-bankable***;
- Most of the *stateless* logic has been considered ***bankable***;
  - Little to no data sharing;
- UI Logic, REST API and CLI are **predictable and context-sensitive components** that only need to be executed based on user/system generated events – good candidate to be ***banked***;



CODE BANKS

IMPLEMENTING THE CONCEPT IN SOFTWARE

- **SPOILERS**: It works!

- On the bright side:
  - It provides maximum program size of **2,5MB (up to 256 different banks)**;
  - It is *mostly* compatible with the existing code base, requiring minor adjustments;
  - It is performant enough to be indistinguishable from code running directly from the microcontroller's Flash;

- However,
  - It took about 1.5 months of intensive work to be fully implemented and integrated;
  - It requires understanding of low-level programming and Arm assembly (Thumb-2 to be more specific);
  - It reduces the amount of usable RAM in the system;

CODE BANKS

SYSTEM COMPONENTS OVERVIEW

Development time
(programming and building)

Annotated source code

Pre-build

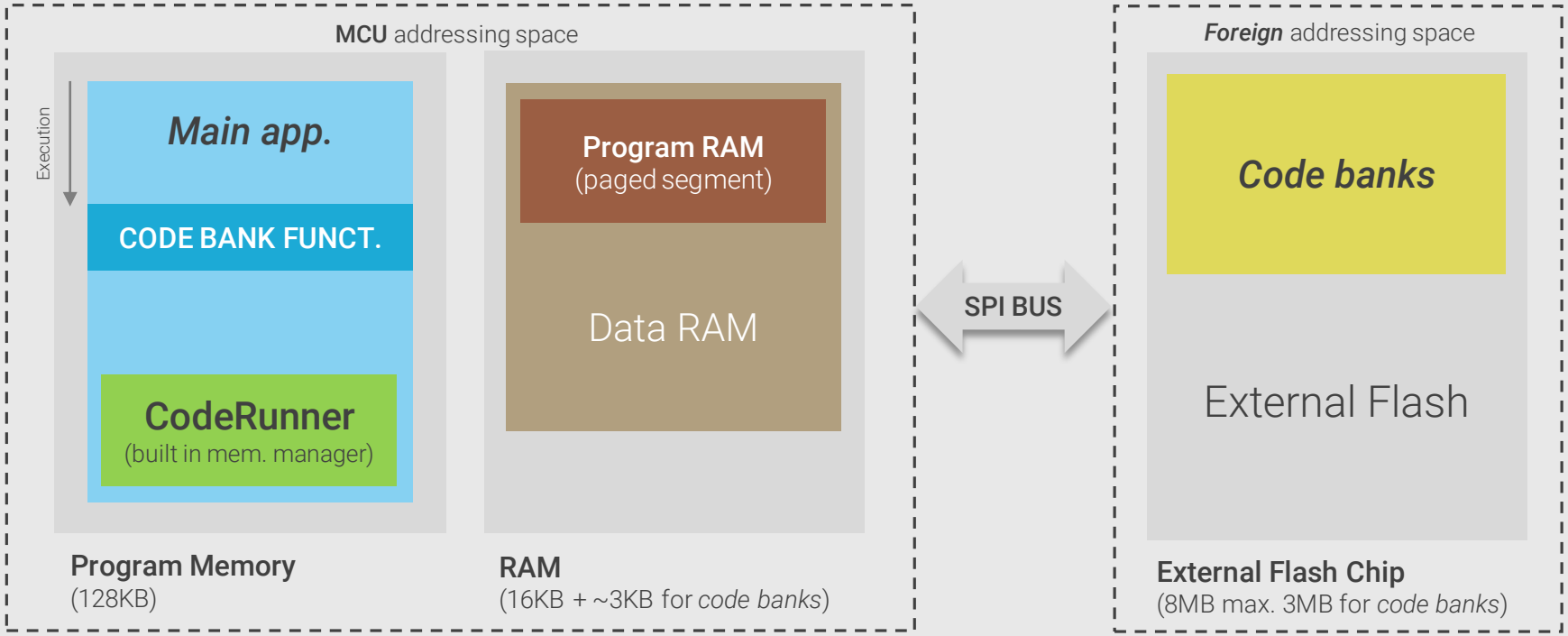
Build

Post-build

Code banks Image

Main app. Image

Runtime
(code banks execution flow)



CODE BANKS

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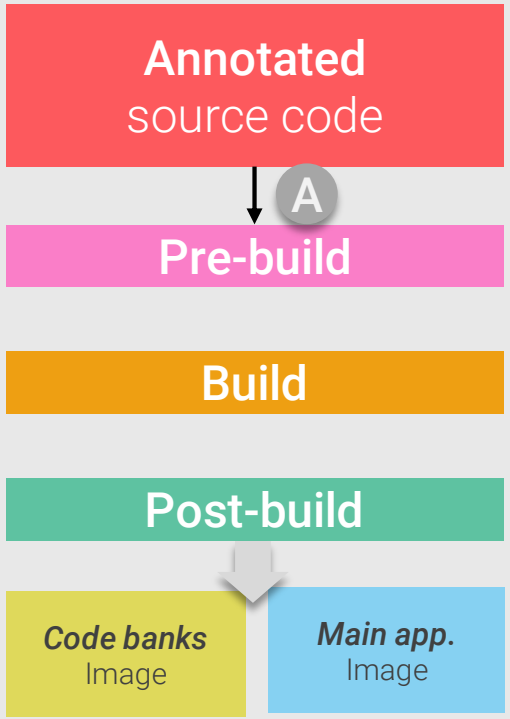

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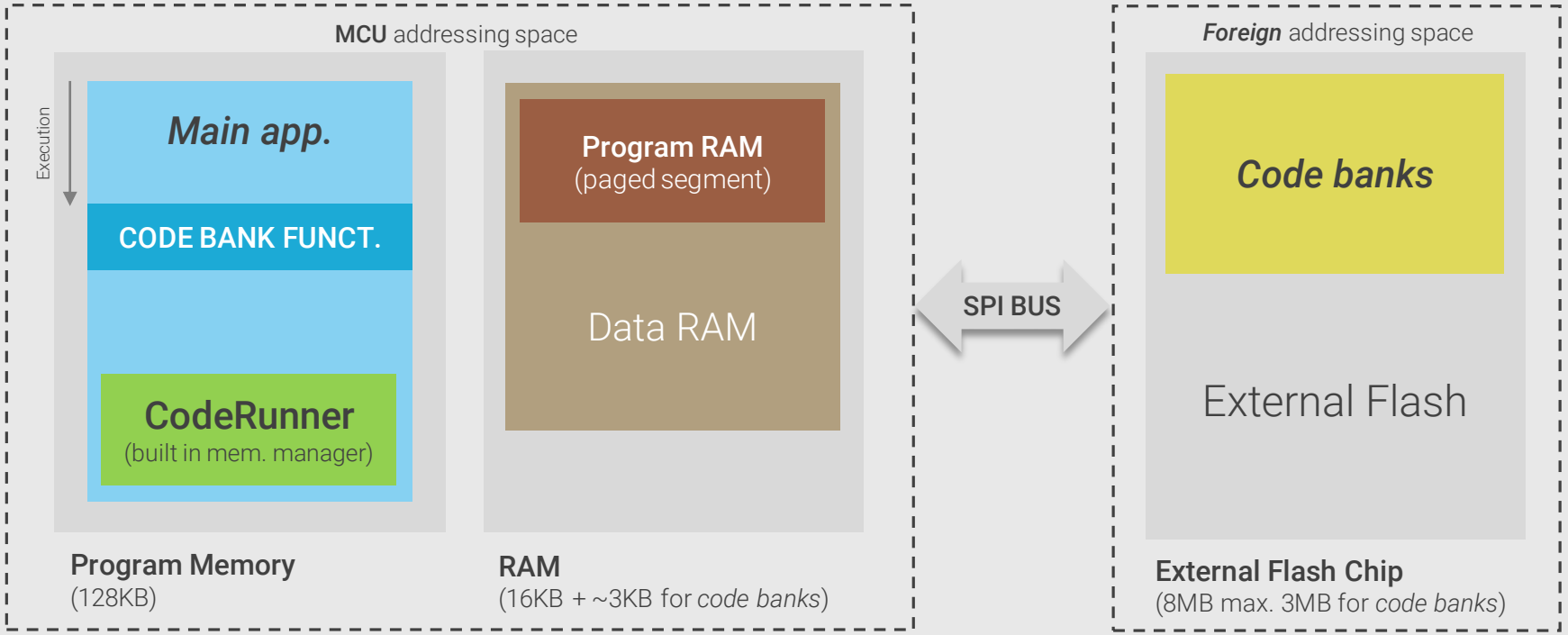

CODE BANKS

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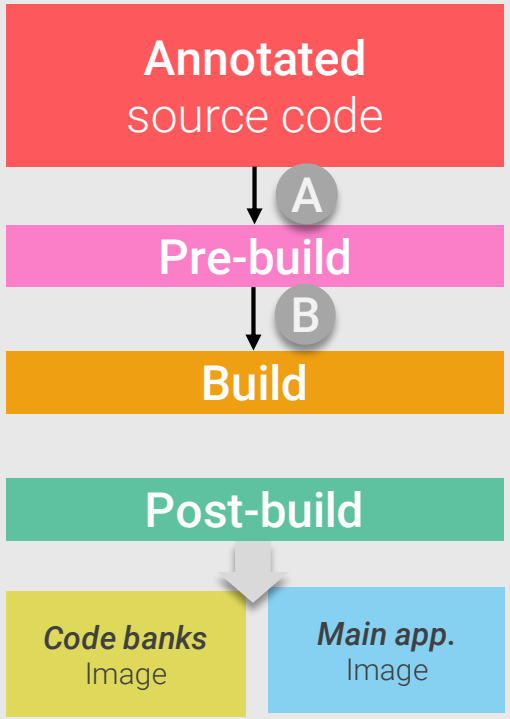

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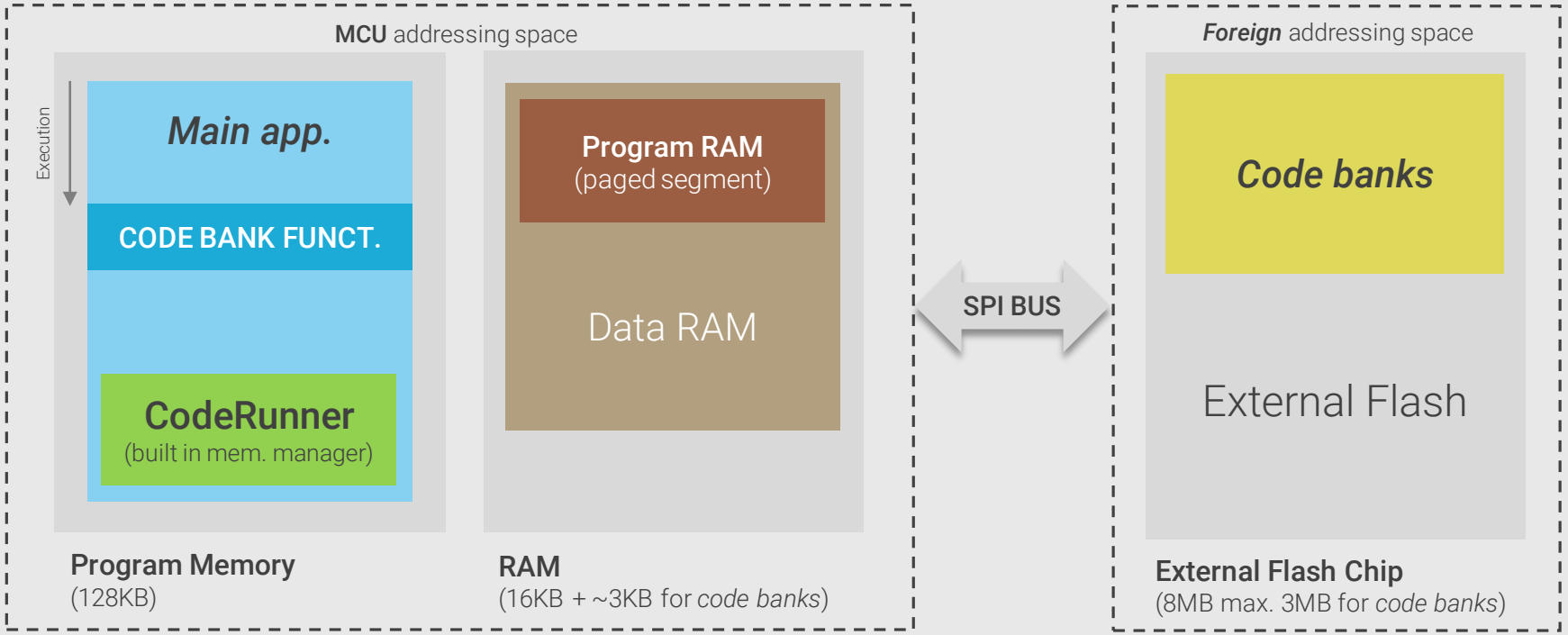

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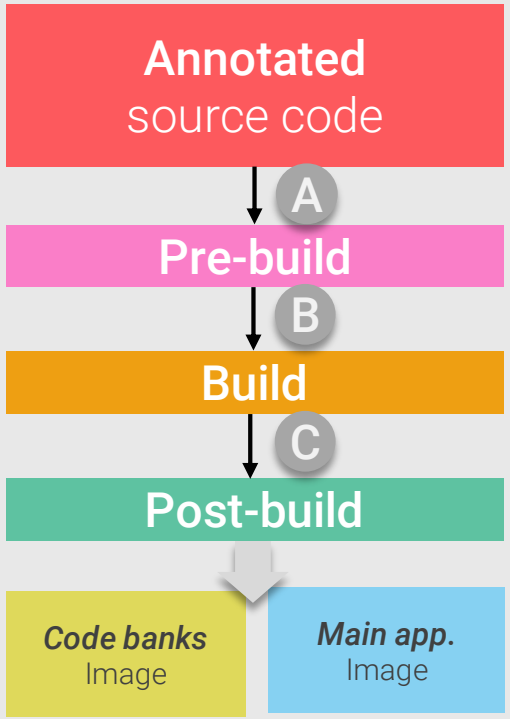

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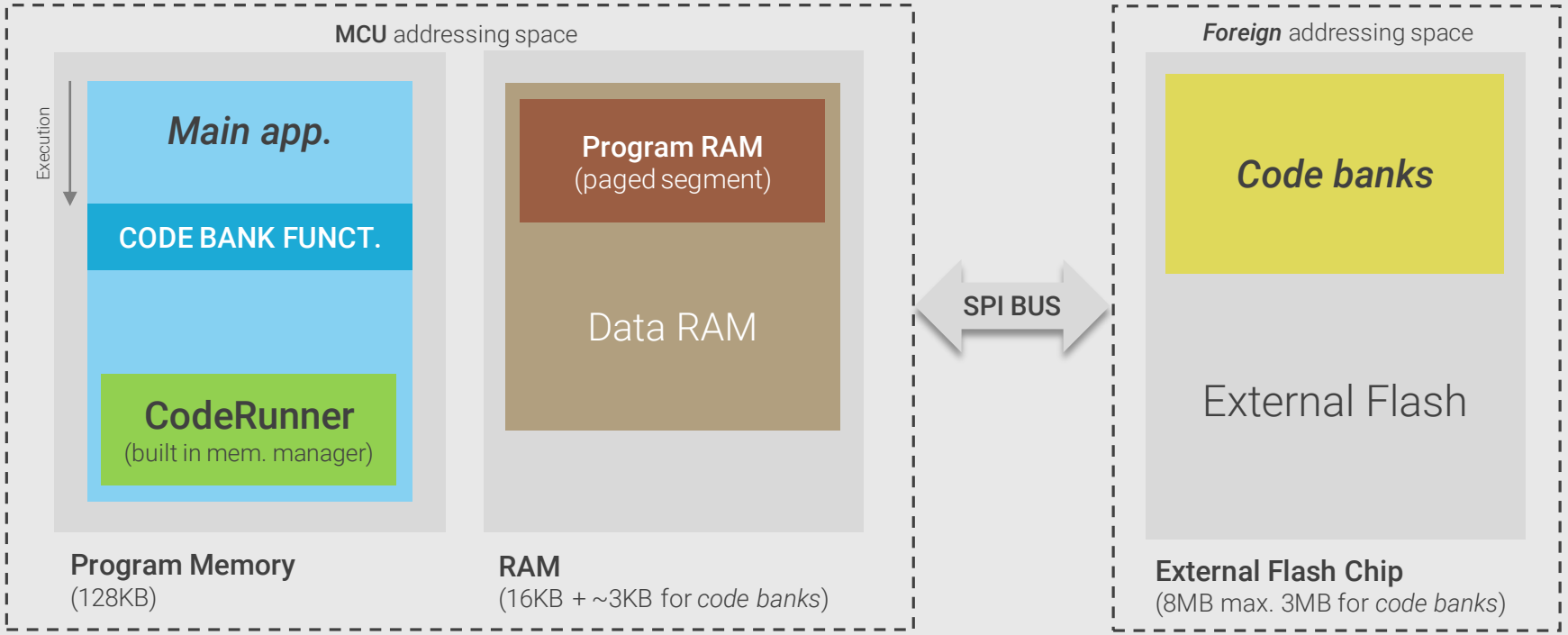

CODE BANKS

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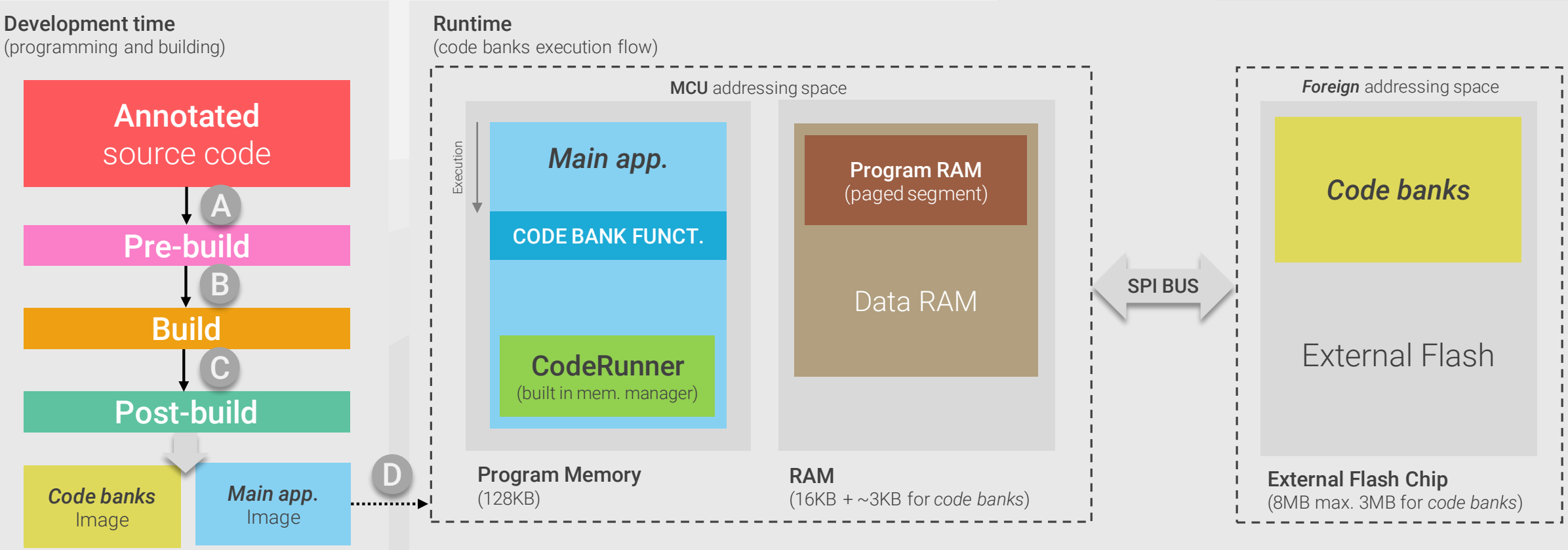

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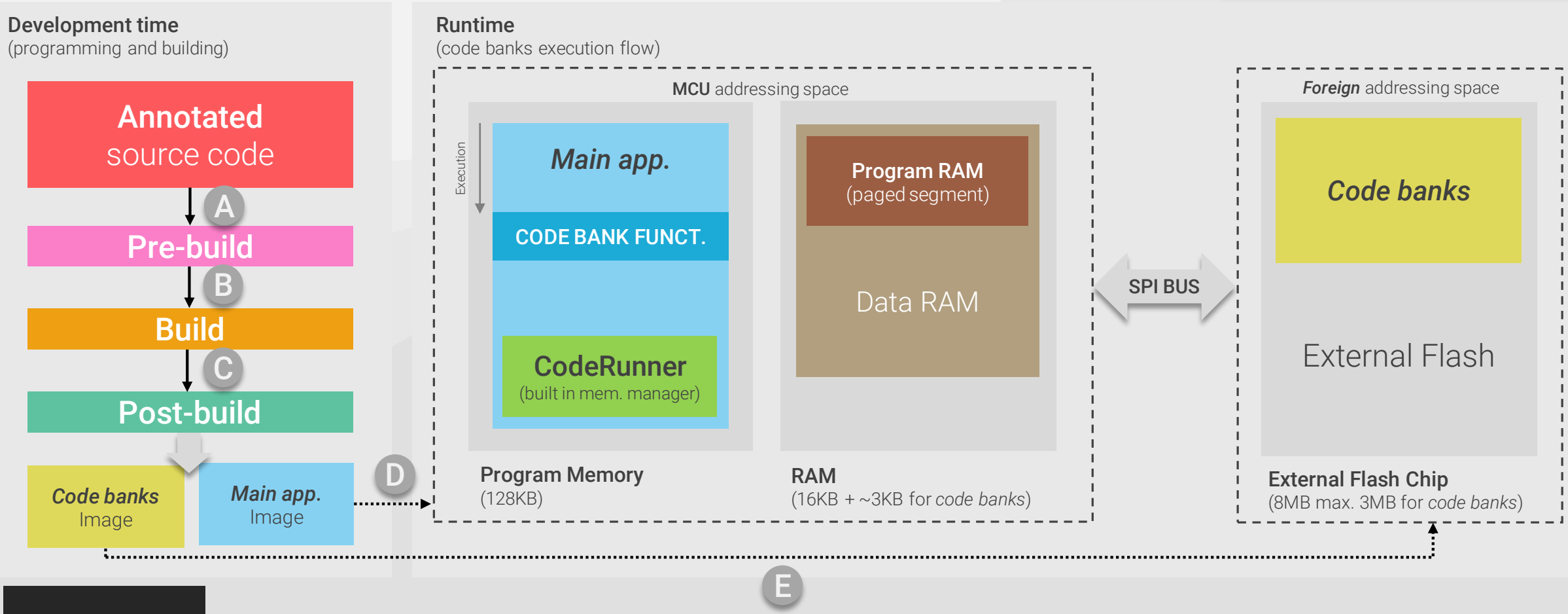

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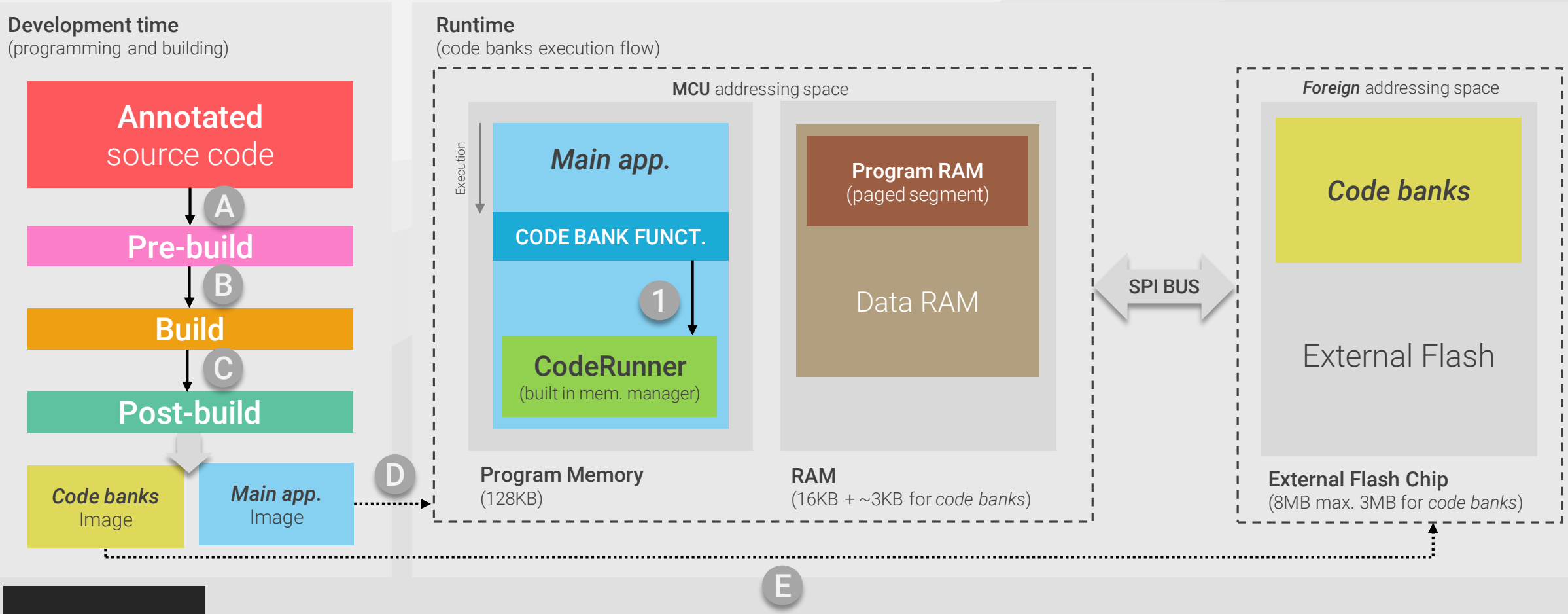

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CODE BANKS

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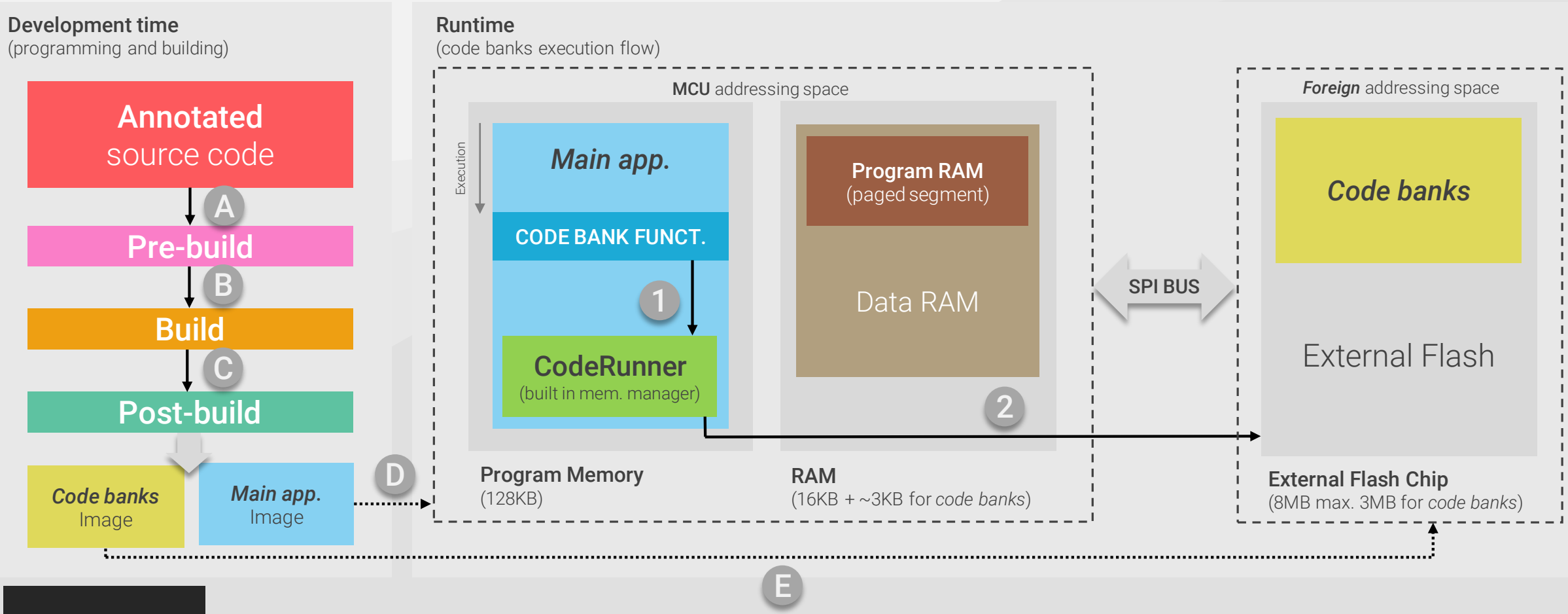

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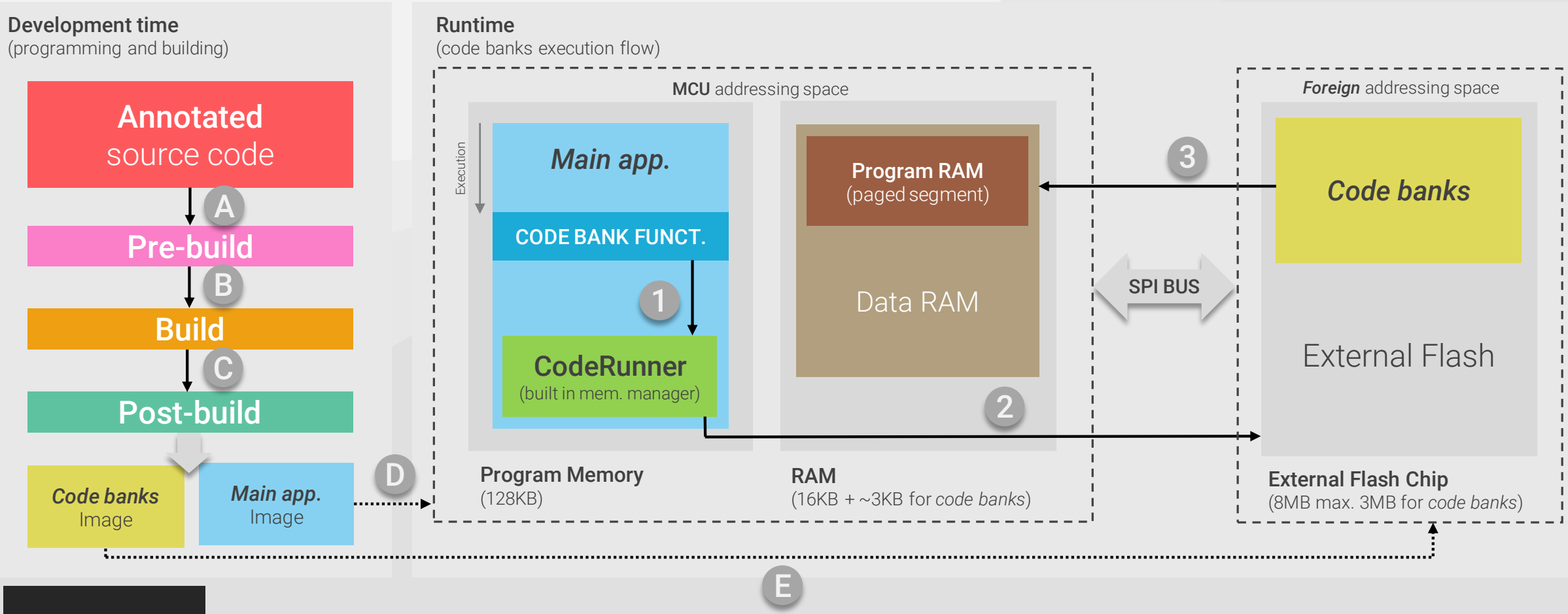

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CODE BANKS

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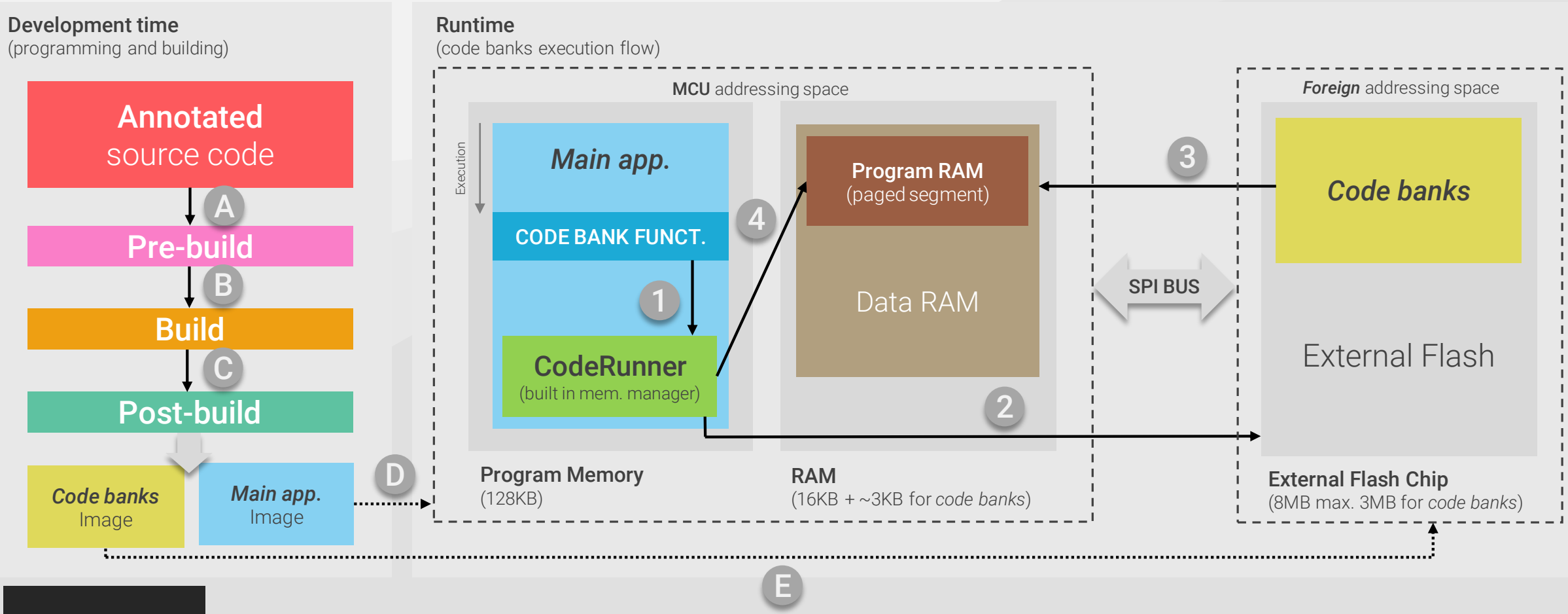

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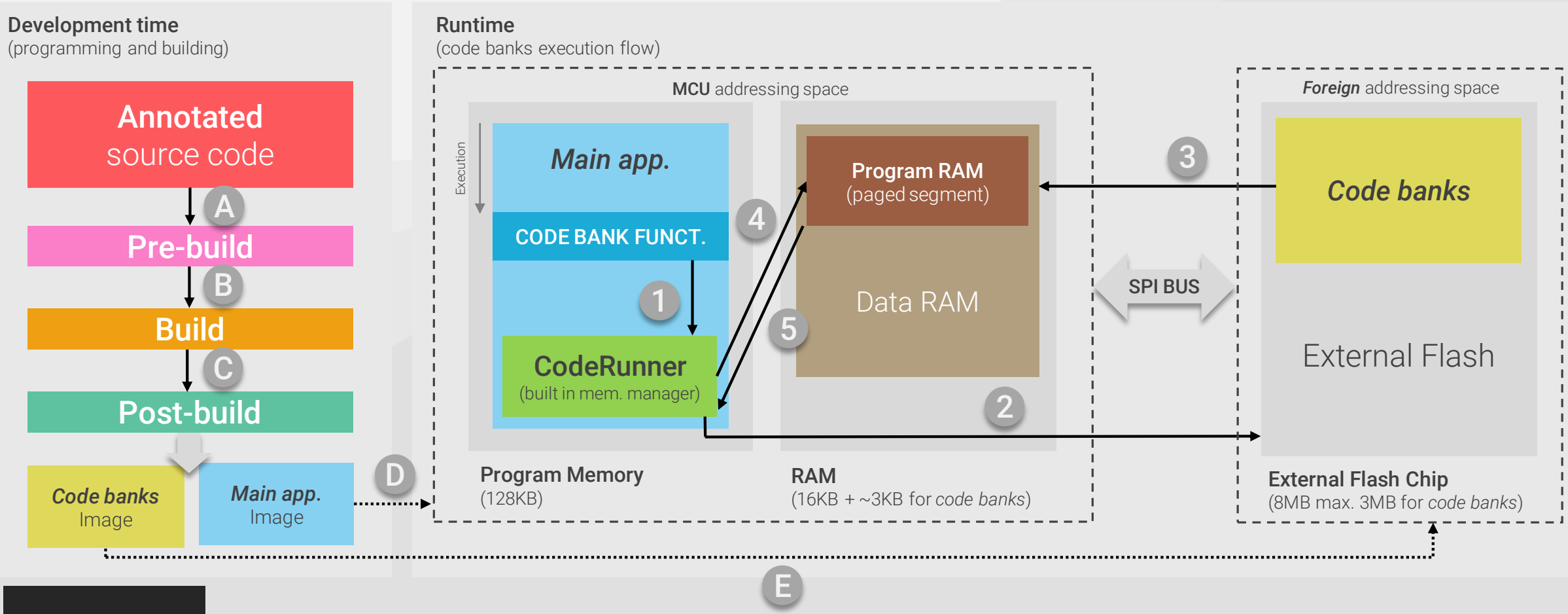

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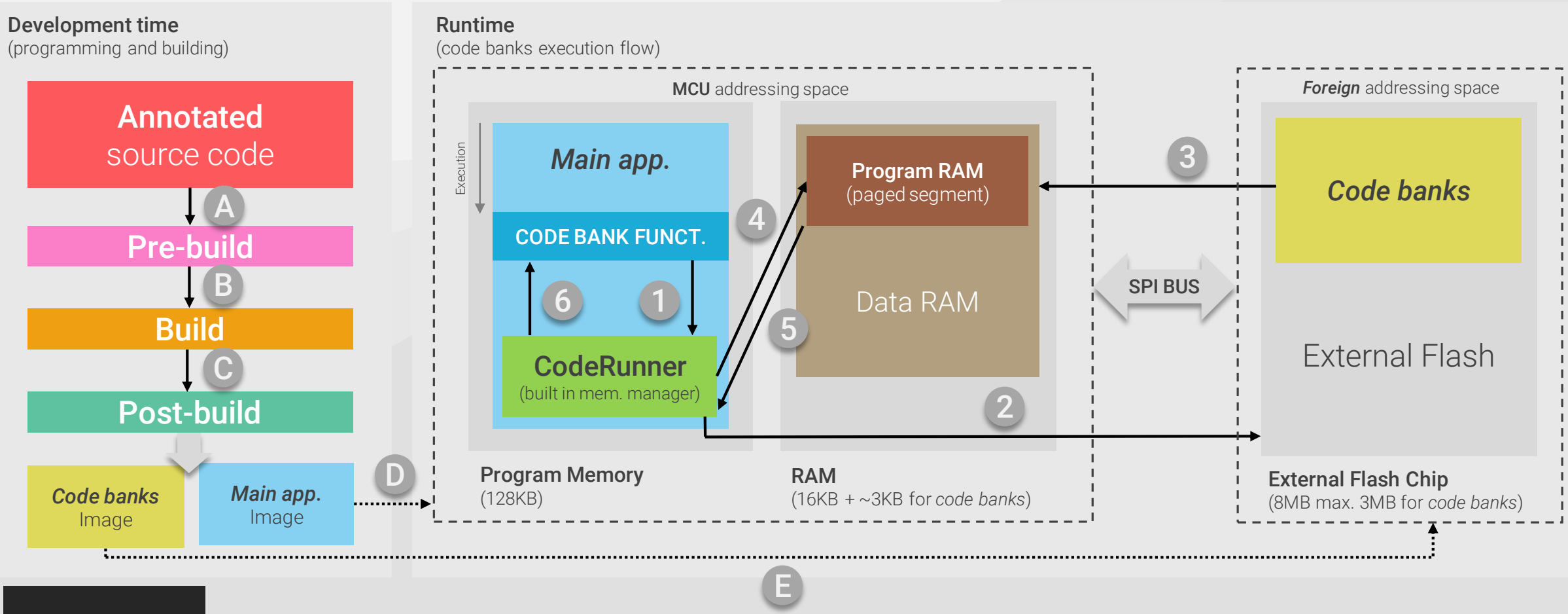

CODE BANKS
IN SUMMARY

Code banks **are**...

- A way to **allow bigger program sizes** in restricted embedded environment.
  It allow **cost reduction** by being compatible with lower-end embedded platforms.
- Meant to provide a flexible framework to **store code in any storage medium** available in the embedded system.
  Not in the CPU addressing space.
- Designed to be **easily integrated** in existing code base.
  There is **no significant difference in development times** when using *code banks*.

Code banks **are not**...

- NOT
  Platform agnostic
  currently compatible with ARM on IAR toolchain.
- NOT
  Meant for **low-power applications**.
  Code banks make **intensive use of external memory access** (typically through SPI) which might be prohibitive for certain applications;
- NOT
  Open source
  The code is currently not disclosed.

PART II

HANDS ON

This section covers:

WRITE

BUILD

RUN

PART II.A

WRITING CODE BANKS

```
#ifndef BANK_HPP_
#define BANK_HPP_

#include <cstdint>
#include <limits>
#include <ctime>
// *REQUIRED* custom macros are defined here
#include "BankedCodeUtils.hpp"


//Declare code bank and places it at a speci
namespace Banks
{
CODE_BANK Bank : public SchedulableBank
{
   // From: SchedulableBank class
   EXPOSED: virtual void OnLoaded()    overr
   EXPOSED: virtual void OnStarted()   overr
   EXPOSED: virtual void OnScheduled() overr
   EXPOSED: virtual void OnFinished()  overr

   // Bank methods
   EXPOSED: void SetInternalValue(uint8_t va
   EXPOSED: uint8_t GetInternalValue();

   // Internal method
   RESTRICTED: uint8_t InternalCalculation()

    private:
   // Member attribute (always private from
   uint8_t _internalValue;
};

#endif // BANK_HPP_
} // namespace Banks
```

WRITING CODE BANKS

WHAT DO YOU NEED?

- Code banks are simple C++ Classes
  - A class that is marked to be banked is said to have a ***banked-type*** .
  - Two differences:
    - After building, a bank is surrounded by a **metadata block** (relevant for the `CodeRunner`);
    - There is no concept of an **instance of a code bank**;

- New keywords and operators were designed to extend the C++ Language:
  - These keywords and operators should have **no impact in the general compilation/linking steps** and are mostly used during **pre- and post-build.**

WRITING CODE BANKS

WHAT DO YOU NEED?

- Definition keywords and usage operators:

Type	Keyw./Oprt.	C++ Equivalence	Example
Definition	`CODE_BANK`	`class`	`CODE_BANK MyBank`
	`EXPOSED`	`public`	`EXPOSED: void MyMethod();`
	`RESTRICTED`	`private`	`RESTRICTED: void Secret();`
Usage	`of <BankedType>`	`[sizeof(MyBank)]`	`BankContext context of MyBank;`
	`@`	Expands to: `CodeRunner.RunXXXArgYYYRet`	`@MyBank.MyMethod(context);`

WRITING CODE BANKS

WHAT DO YOU NEED?

Bank.hpp

```
#ifndef BANK_HPP_
#define BANK_HPP_

#include <cstdint>
// *REQUIRED* custom macros are defined here.
#include "BankedCodeUtils.hpp"

//Declare code bank and places it at a specific address.
CODE_BANK Bank : public SchedulableBank
{
      // From: SchedulableBank class
      EXPOSED: virtual void OnLoaded()    override;
      EXPOSED: virtual void OnStarted()   override;
      EXPOSED: virtual void OnScheduled() override;
      EXPOSED: virtual void OnFinished()  override;

      // Bank methods
      EXPOSED: void SetInternalValue(uint8_t value);
      EXPOSED: uint8_t GetInternalValue();

      // Internal method
      RESTRICTED: uint8_t InternalCalculation();

    private:
      // Member attribute (always private from banks persp.).
      uint8_t _internalValue;
};

#endif // BANK_HPP_
```

Bank.cpp

```
#include "Bank.hpp“

// Implementation comes here.
void Bank::OnLoaded()
{...}
void Bank::OnStarted()
{...}
void Bank::OnScheduled()
{...}
void Bank::OnFinished()
{...}
void Bank::SetInternalValue(uint8_t value)
{...}
uint8_t Bank::GetInternalValue()
{...}
uint8_t Bank::InternalCalculation()
{...}
```

Somewhere.cpp

```
// *REQUIRED* to run any method from a code bank.
#include "BankDefinitions.hpp"

// Implementation comes here.
void DoSomethingWithBanks()
{
      BankContext context of Bank;
      @Bank.SetInternalValue(context, 0x10);
}
```

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WRITING CODE BANKS

WHAT DO YOU NEED TO KNOW?

- *Banked-type* members can be `public`, `private` or `protected`
  - Access modifiers only apply in the context of inheritance, though;
  - Member types (`struct` and `class`) are also allowed;

- `virtual` and `override` are fully allowed.
  - **Be very careful with them, though!**

- `static` attributes are **not recommended**
  - That's due to the volatile nature of the bank's context
    - Could be added in a future implementation.
  - Specifiers such as `const`, `mutable`, `extern`, `volatile`, etc. are allowed.

- Use of `this` is allowed, although with some caveats.

WRITING CODE BANKS

CODE BANKS CONTEXT

- A *banked-type* is in essence a class type:
  - For classes, the C++ compiler allocate and generate code to manage a valid (and `const`) reference to the object instance's context (seen as `this` pointer).
    - A reference to that context is automatically passed as the first function argument for each member method call.
  - For *banked-types*, `this` is a **mutable context reference** that must be explicitly provided during an `EXPOSED` method call.
    - *Banked-types* do **not manage its context**, and have **no responsibility over its life-cycle**: the **caller is responsible** to allocate, handle and destroy any context data used across call.

PART II.B

BUILDING CODE BANKS

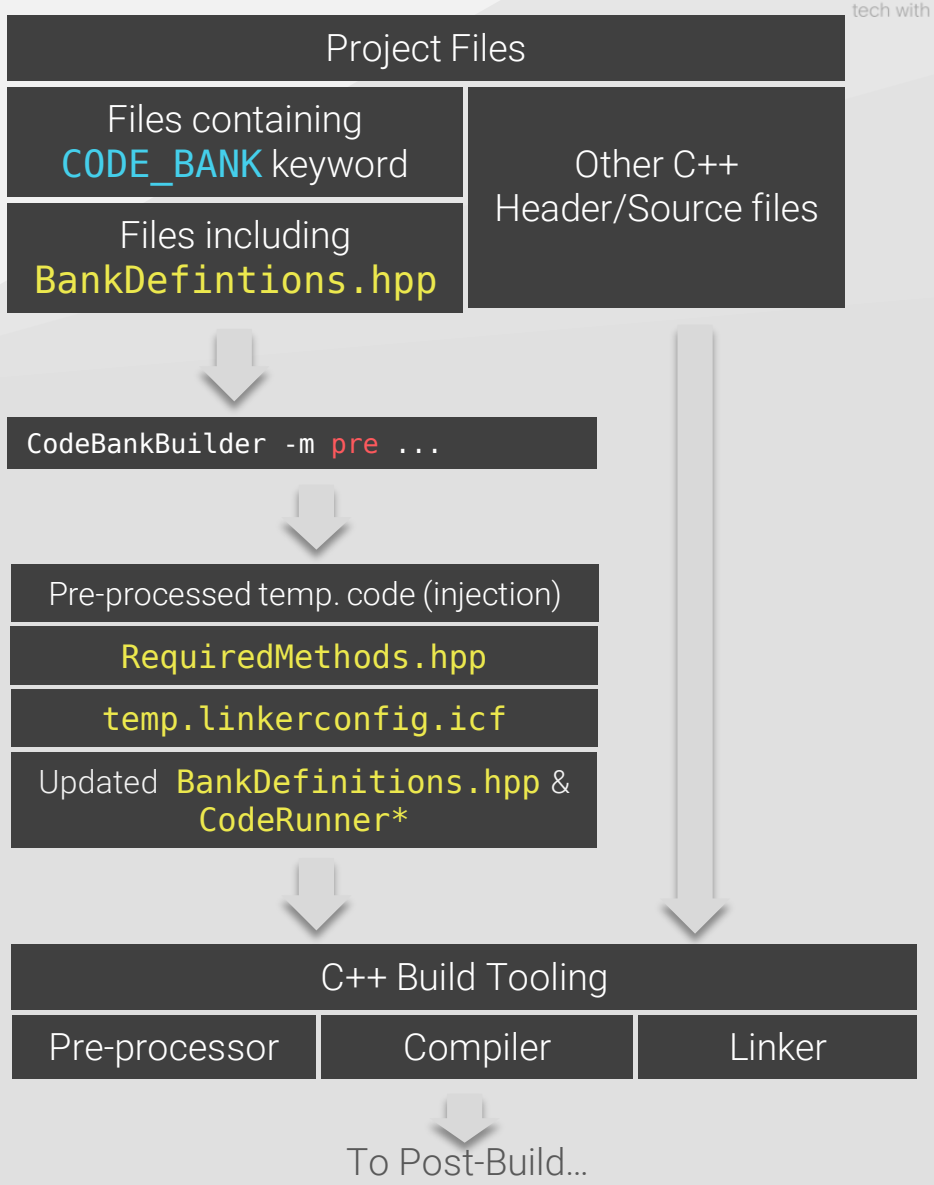
```
$ IarBuild.exe project.ewp -build Debug
$ Running pre-build script at $PROJECT_ROOT
$ CodeBankBuilder -m pre -c $BANKED_CONFIG -v
$ Code Bank Builder v1.0.0
$ > Opening Configuration File (banks.json)
$ > Configurations loaded
$         ObjDump located.
$         $IAR_ROOT updated.
$         658 files detected
$ > Fetching Code Banks
$   Bank 'MyBank' found. Extracting symbols...
$   Parsing 'MyBank.hpp'... Done!
$         Exposed Method Detected: EXP1 (0 arg
$         Exposed Method Detected: EXP2 (1 arg
$         Restricted Method Detected: RES1 (0
$   Region 'RegionMyBank' allocated at 0x10000
$   Symbol table updated with 4 new tokens
$   Bank 'ThatBank' found. Extracting symbols.
$   Parsing 'ThatBank.hpp'... Done!
$         Exposed Method Detected: Exposed (2
$   Region 'RegionThatBank' allocated at 0x110
$   Symbol table updated with 2 new tokens
$ > Writing RequiredMethods.hpp...
$         12288 bytes written
$ > Backing up linker file (s6e1c12_rom.icf)..
$         63602 bytes written
$ > Patching linker file... Done!
$ > Backing up bank files...
$         Two new files created at $PROJECT_RO
$         639124 bytes written
$ > Expanding header files...
$         Expanding 'MyBank.hpp'... Done!
$         Expanding 'ThatBank.hpp'... Done!
$ > Backing up 'BankDefinitions.hpp'... Done!
```

BUILDING CODE BANKS

UNDER THE HOOD

- To allow proper bank's code generation, the project's build must be expanded with extra pre- and post- build steps.

- Both build steps are processed by the **BankedCodeBuilder** tool, developed for the project using C#;
  - The tool requires a JSON input file, describing the project's structure and some output files.
  - Multiple temporary (source, object etc.) files are generated during the build process.



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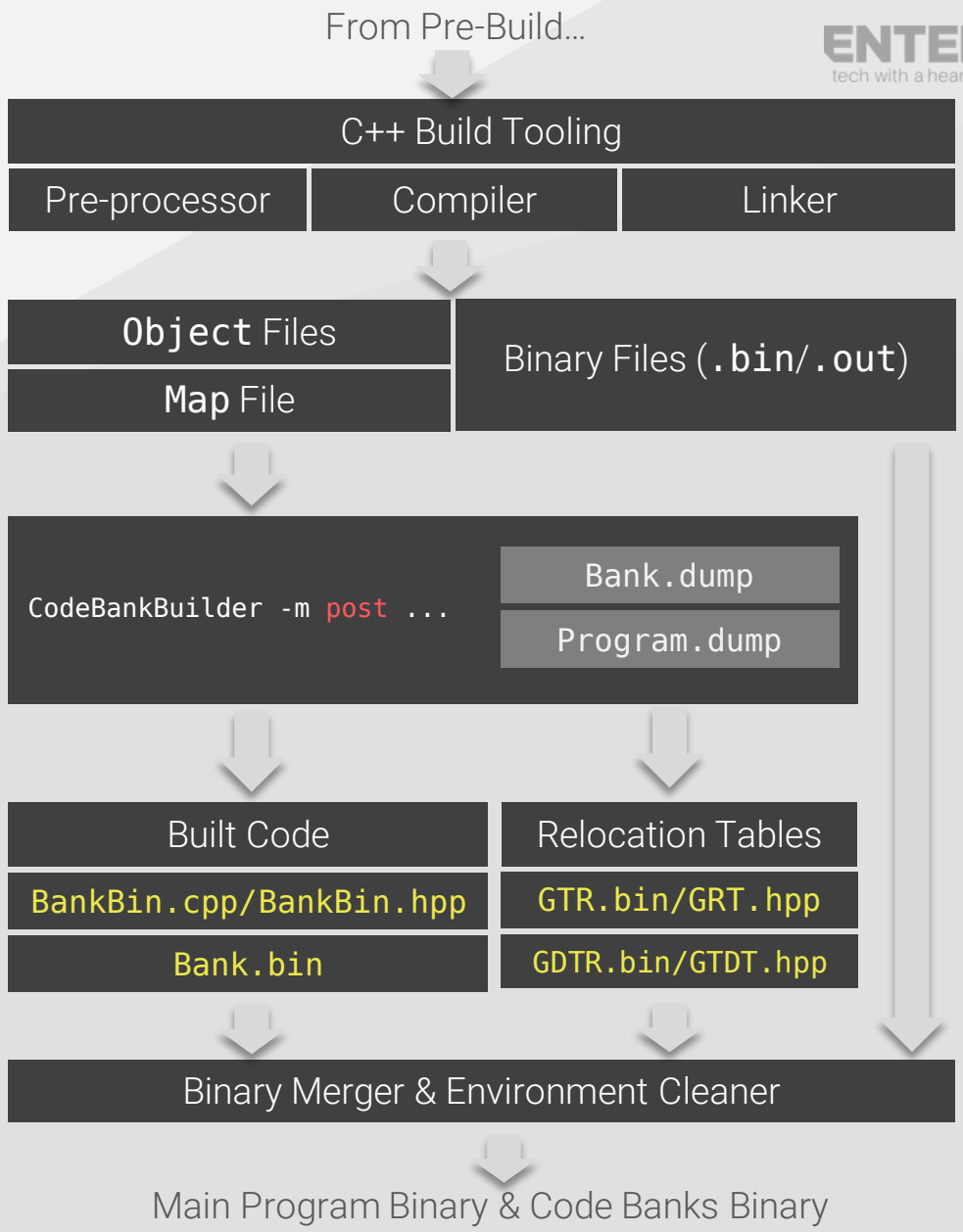
- Both build steps are processed by the **BankedCodeBuilder** tool, developed for the project using C#;
  - The tool requires a JSON input file, describing the project's structure and some output files.
  - Multiple temporary (source, object etc.) files are generated during the build process.



BUILDING CODE BANKS

UNDER THE HOOD: **PRE-BUILD**

- Remove the keywords and operators are processed during the pre-build step
  - Extra code information is acquired during this stage.
  - **In a nutshell**: adjust the code to be properly built.

BUILDING CODE BANKS

UNDER THE HOOD: **PRE-BUILD**

- `BankedCodeBuilder` has to:
  1. Generate a ***symbol table*** containing all *banked-types*, as well as `RESTRICTED` and `EXPOSED` methods;
  2. Update the linker file, to place the *code banks* **outside** of the initial 128KB of flash, and ensure that no PC-relative branches are used;
  3. Generates code for `CodeRunner`;
  4. Injects code wherever `CODE_BANK`, `@` or `of` operators are used;

BUILDING CODE BANKS

UNDER THE HOOD: **STANDARD COMPILATION**

- With all **non-standard structures out of the code**, and with all the appropriate source/configuration adjustments, the C++ build tools are free to do their job:
  - The build follows that standard flow of pre-processing, compilation, (multiple) optimizations and linking;

- If the build is successful, the resulting **object files** and **binaries** will be used in the post-build steps;

BUILDING CODE BANKS

UNDER THE HOOD: **POST-BUILD**

- Generate the *code banks* binary code to create the infrastructure needed for proper execution;
  - It makes use of the **fully built** *main application* assembly code and the **pre-linked** *code banks* code.

- **In a nutshell**: **resolves *main application* dependencies** found in *the code bank* and **outputs the bank's binary code** including relevant metadata.

BUILDING CODE BANKS

UNDER THE HOOD: **POST-BUILD**

- `BankedCodeBuilder` has to:
  1. Locate all *main application* dependencies used in the *code banks;*
  2. Map the dependencies found step 1 with symbols defined in the *main application;*
  3. Generate the **relocation tables** (GRT/GRDT);
  4. Patch the *code banks* code to make use of the tabled from step 3;
  5. Emit the binary code of each *code bank*

BUILDING CODE BANKS

UNDER THE HOOD: **WRAPPING UP BUILD**

- A few extra steps are performed during the post-build:
  - The new content of GRT and GRDT gets re-injected into the binary of the *main application;*
  - Any temporary file is deleted and the original source code is restored.
    - This is specially valid for the pre-build artifacts

PART II.C

RUNNING CODE BANKS

```
0x20d8: 0x4e18          LDR.N R6, [PC, #0x60]  ; .text_8
0x20da: 0x9801          LDR   R0, [SP, #0x4]
0x20dc: 0x42b0          CMP   R0, R6
0x20de: 0xd00e          BEQ.N @20fe
0x20e0: 0x2280          MOVS  R2, #128
0x20e2: 0x0152          LSLS  R2, R2, #5
0x20e4: 0x2004          MOVS  R0, #4
0x20e6: 0x9000          STR   R0, [SP]
0x20e8: 0xab01          ADD   R3, SP, #0x4
0x20ea: 0x2112          MOVS  R1, #18
0x20ec: 0x6868          LDR   R0, [R5, #0x4]
0x20ee: 0xf00c 0xfc45   BL ; 0xe97c
0x20f2: 0x9801          LDR   R0, [SP, #0x4]
0x20f4: 0x42b0          CMP   R0, R6
0x20f6: 0xd102          BNE.N @20fe
0x20f8: 0x2001          MOVS  R0, #1
0x20fa: 0x8028          STRH  R0, [R5]
0x20fc: 0xe000          B.N   @2100
        @20fe:
0x20fe: 0x802c          STRH  R4, [R5]
        @2100:
0x2100: 0x2280          MOVS  R2, #128
0x2102: 0x0192          LSLS  R2, R2, #6
0x2104: 0x2004          MOVS  R0, #4
0x2106: 0x9000          STR   R0, [SP]
0x2108: 0xab01          ADD   R3, SP, #0x4
0x210a: 0x2112          MOVS  R1, #18
0x210c: 0x6868          LDR   R0, [R5, #0x4]
0x210e: 0xf00c 0xfc35   BL ; 0xe97c
0x2112: 0x2402          MOVS  R4, #2
0x2114: 0x9801          LDR   R0, [SP, #0x4]
0x2116: 0x42b0          CMP   R0, R6
0x2118: 0xd00c          BEQ.N @2134
0x211a: 0x22c0          MOVS  R2, #192
```

RUNNING CODE BANKS
DYNAMIC COMPONENTS

- The `CodeRunner` is the essential component when dealing with *code banks* in runtime.
  - It is responsible to **allocate and deallocate** resources in the **program RAM**;
  - It must **properly branch to any** `EXPOSED` method;
  - It must properly **return** from the *code bank;*
- All operations performed by the `CodeRunner` should be executed as efficiently as possible and must appear seamless to the programmer;

RUNNING CODE BANKS

BRANCHING TO/FROM CODE BANKS

- When the execution moment comes, the `CodeRunner` will use a **function pointer** to perform the branch **to** the *code bank* in RAM;
  - Registers `R0` through `R3` are used to pass the arguments and the return address is stored in the **link register**;
  - Braches are performed with the `BLX` instruction, forcing **Thumb-mode** (using a 32-bit address);
  - Return values are stored in `R0`;

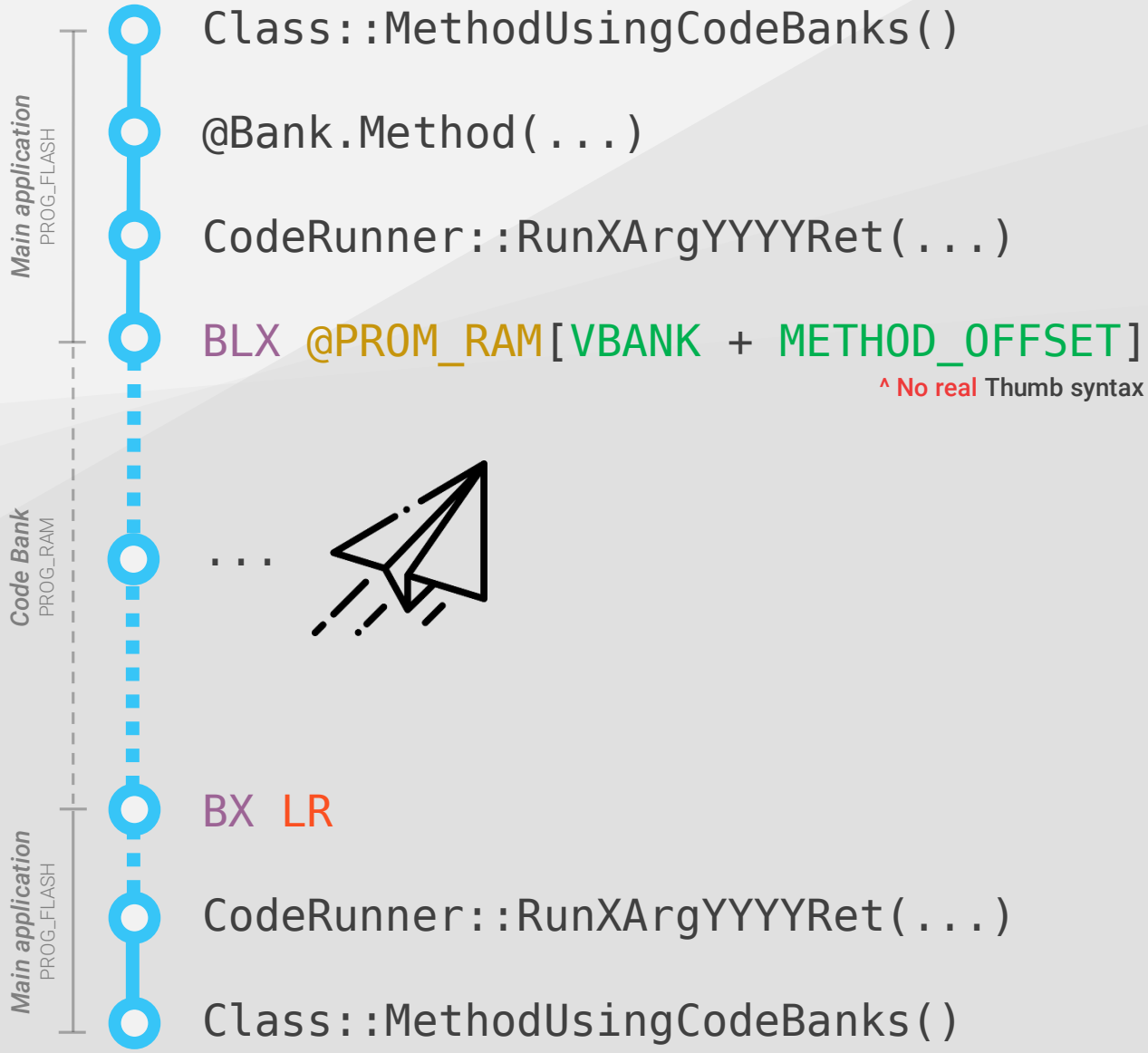
- Branches **from** the *code bank* to the *main application* use **veneering** with absolute 32-bit addresses (as discussed in the previous section);

- Branches **from** *code banks* **to** *other code* banks are indirectly performed through the `CodeRunner` (which ends up as a special case of veneering branch);

RUNNING CODE BANKS

JOURNEY TO CODE BANKS

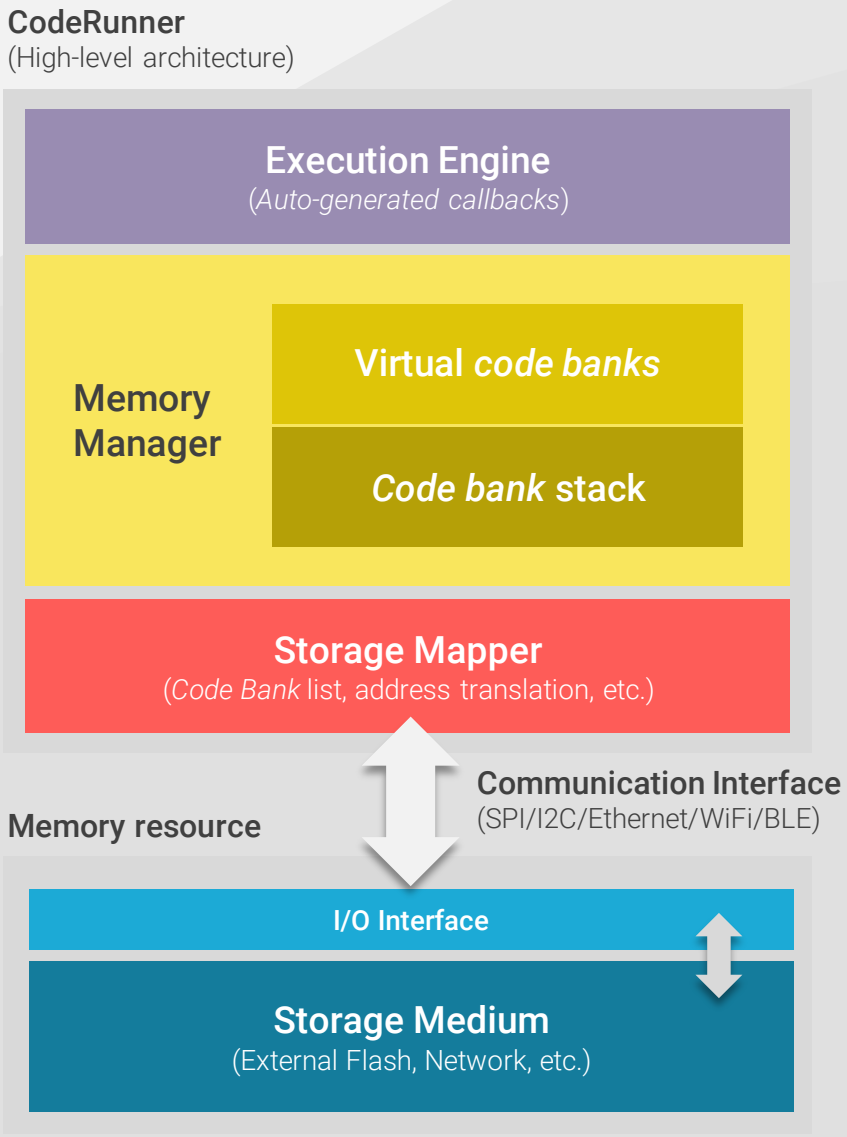
- Within the code bank, anything can happen:
  - Branches to ***the main application***;
  - Branches to the **internal** `RESTRICTED` methods;
  - Indirect **branches to other *code banks***;
  - Execution of **IRQs**



RUNNING CODE BANKS

CODERUNNER INTERNAL ORGANIZATION

- Internally, the code runner is subdivided into three major components:
  - The `ExecutionEngine` is responsible to prepare and perform branches to *code banks*;
  - The `MemoryManager` keeps track of the program RAM resources and virtual banks;
  - The `StorageMapper` is responsible to locate and load *code banks* from an external memory resource;



RUNNING CODE BANKS

CODERUNNER'S EXECUTION ENGINE

- The `ExecutionEngine` is a collection of *callbacks* used to jump to *code banks* loaded in the program RAM;
  - It is composed of **<<N>>** *callbacks* where: each *callback* **<<N_i>>** maps to a **distinct** `EXPOSED` **method signature** (`i ⊆ [0, N)`);
  - Each *callback* **<<N_i>>** will have its unique **input arguments list** or **return types** (`i ⊆ [0, N)`).

Generated based on (example):

```
// Code bank MyBank1
EXPOSED: bool IsComplete();
```

CodeRunner.hpp

```
#ifndef CODE_RUNNER_HPP_
#define CODE_RUNNER_HPP_

#include <cstdint>
#include "BankedCodeUtils.hpp"

class CodeRunner
{
  ...
  // Auto-generated methds
public:
  void Run0ArgVoidRet(uint8_t bankID, uint8_t methodID, void* ctx);
  bool Run0ArgBoolRet(uint8_t bankID, uint8_t methodID, void* ctx);
  char Run0ArgCharRet(uint8_t bankID, uint8_t methodID, void* ctx);
  uint8_t Run0ArgCharRet(uint8_t bankID, uint8_t methodID, void* ctx);

  void Run1ArgVoidRet(uint8_t bankID, uint8_t methodID, void* ctx, void* arg1);
  bool Run1ArgBoolRet(uint8_t bankID, uint8_t methodID, void* ctx, void* arg1);
  char Run1ArgCharRet(uint8_t bankID, uint8_t methodID, void* ctx, void* arg1);
  uint8_t Run1ArgUint8Ret(uint8_t bankID, uint8_t methodID, void* ctx, void* arg1);

  ...
};

#endif
```

Generated based on (example):

```
// Code bank MyBankX
EXPOSED: uint8_t NumberOfEntries(bool update);
```

RUNNING CODE BANKS

MEMORY MANAGEMENT

- Originally, banks were *monolithic* chunks of code taking ownership of the entire program RAM resources when loaded;
  - Only one *code bank* was allowed to be loaded at a time and no *reentrant calls* were allowed.

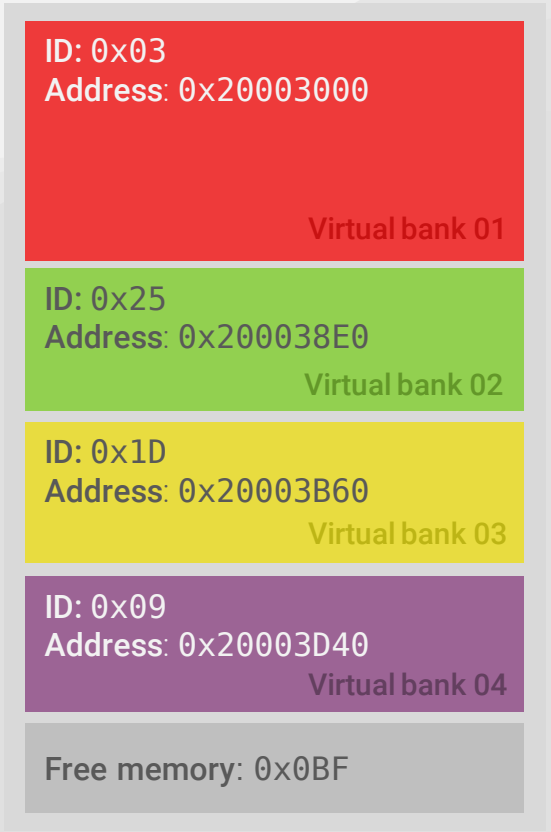
- That's a not very efficient approach:
  - As *code banks* were more frequently used in the project, it was clear that **the average bank size** was way **smaller than program RAM buffer**;
    - In general, banks were between 500 Bytes to 1.5KB while the buffer was as big as 3KB;
    - That lead to a sub-allocation of the program RAM (of about 1/3 to 1/2) leading to low-performance in some cases.
      - That was particularly noticeable in UI-driven *code banks;*

  - *Code banks* **were not allowed to call other *code banks***, or even **to call functions in the *main application* that would make use of *code banks***;

RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

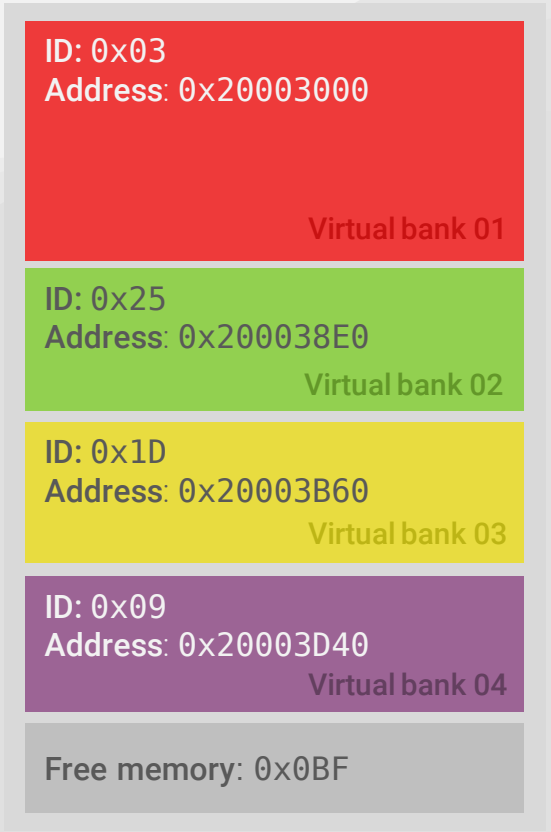
- To solve that problem, the concept of **virtual *code banks*** was developed:
  - A virtual *code bank* is a slice of the Program RAM, holding one *code bank*;
  - Virtual *code banks* can be loaded at any **contiguous memory range** where they fit;



RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

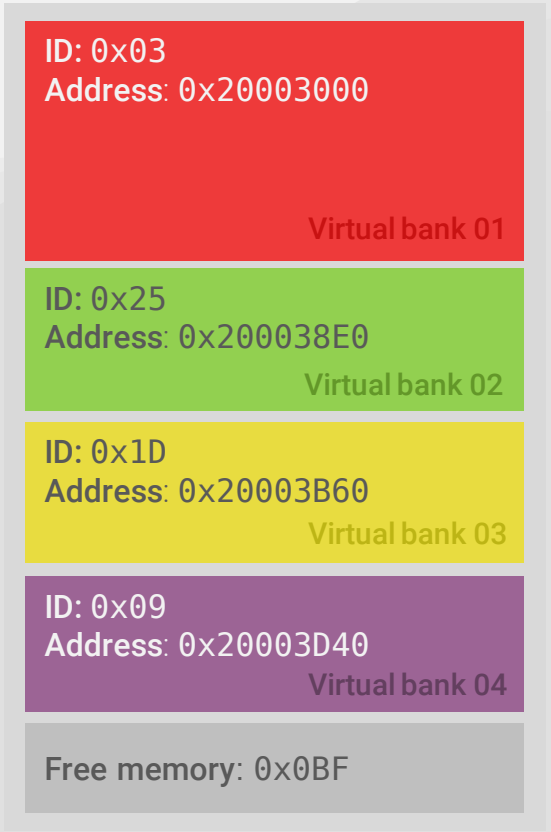
- The stack is used when **suspending** or **resuming** *code banks*:
  - Upon requests, banks can be suspended (i.e. lack of memory) and later resumed, in an operation called **context switching**;



RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

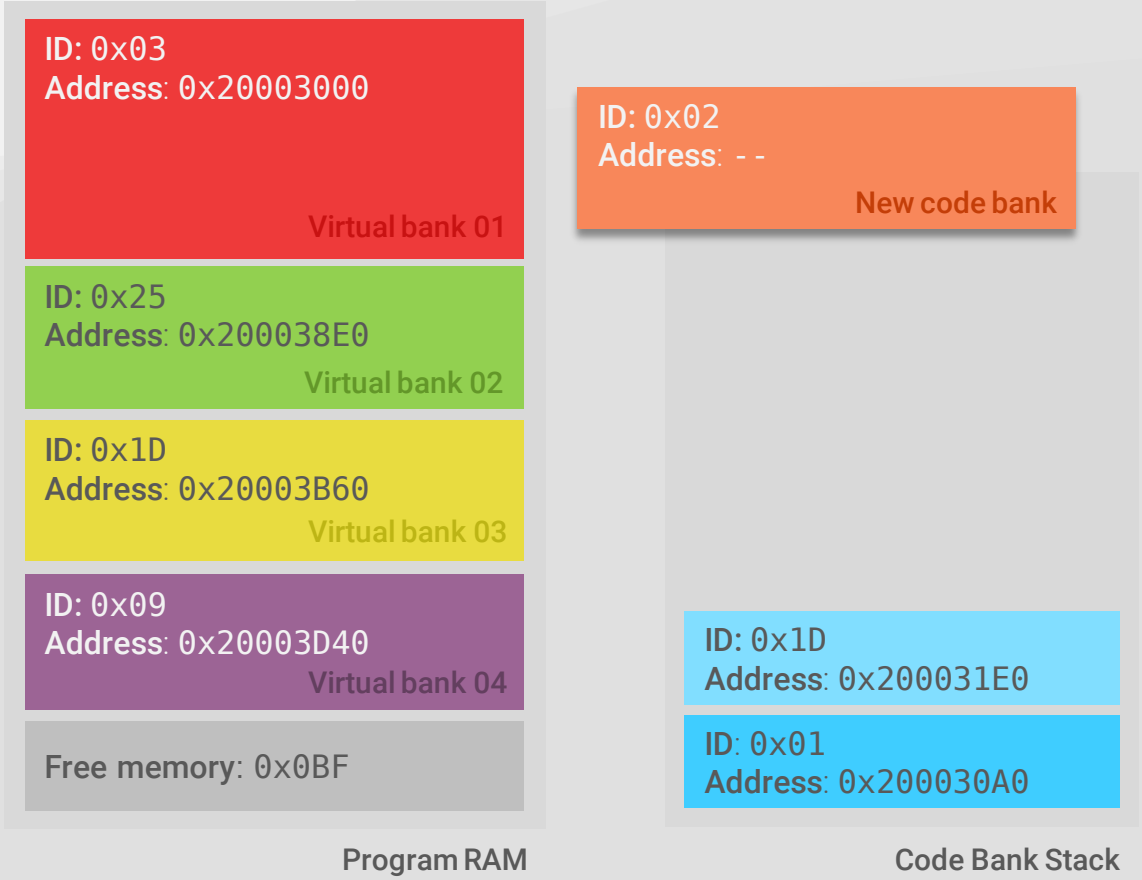
- **4 banks** loaded at the same time;
  - 2 banks were suspended at some point in the past.



RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

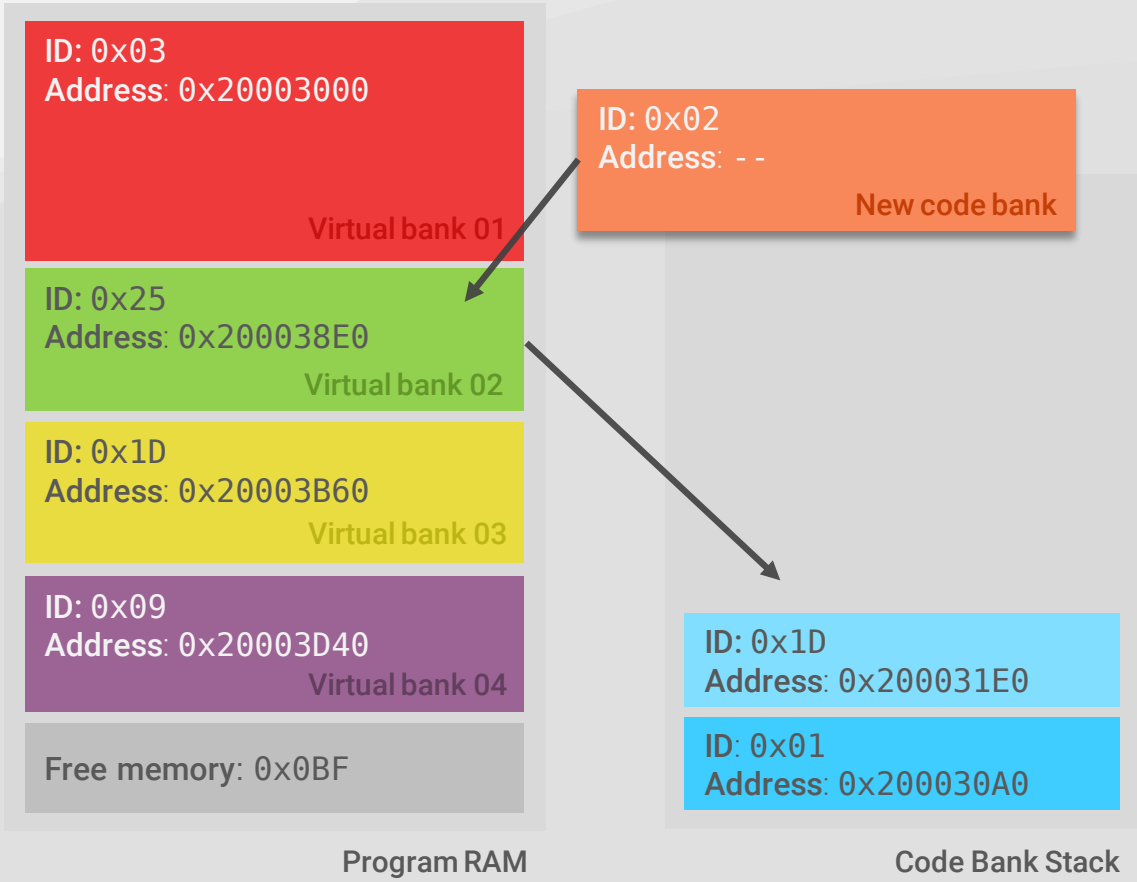
- A new *code bank* is must be **loaded in memory**;
  - But there is **no room** for it!



RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

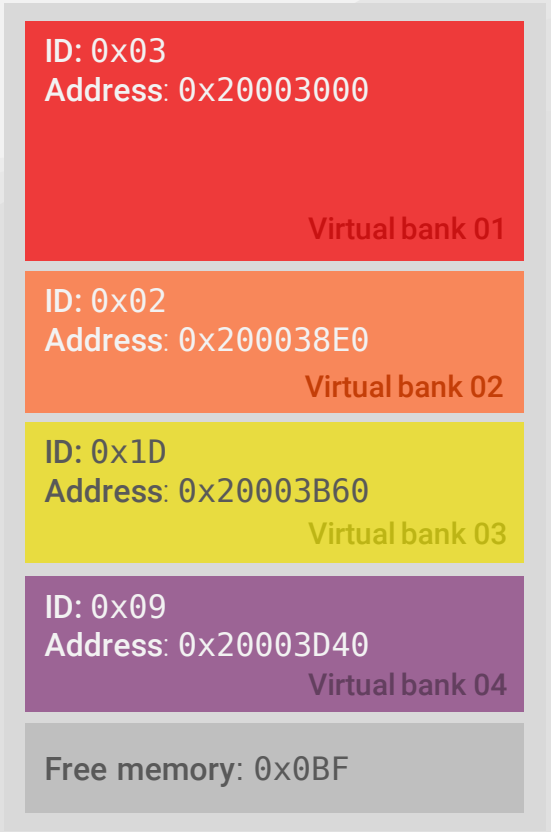
- No problem! **Unload `0x25`** and **load `0x02`** in its place;
  - `0x25` goes to the *code bank* stack for a while;
  - We say that `0x25` has been **suspended**;

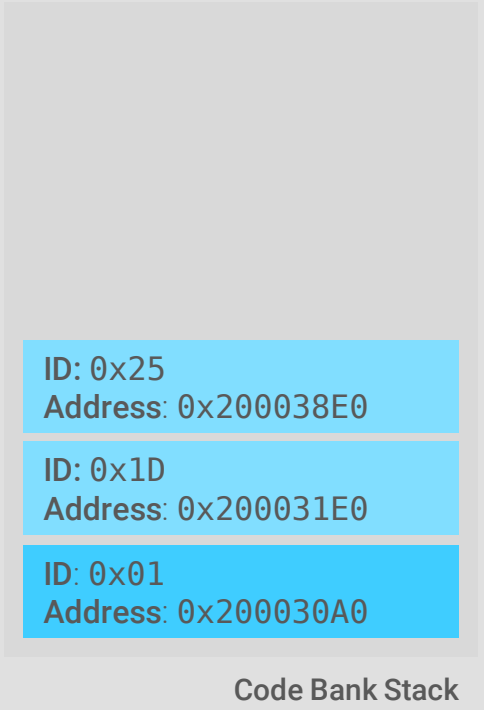


RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

- Now we can run `0x02`!

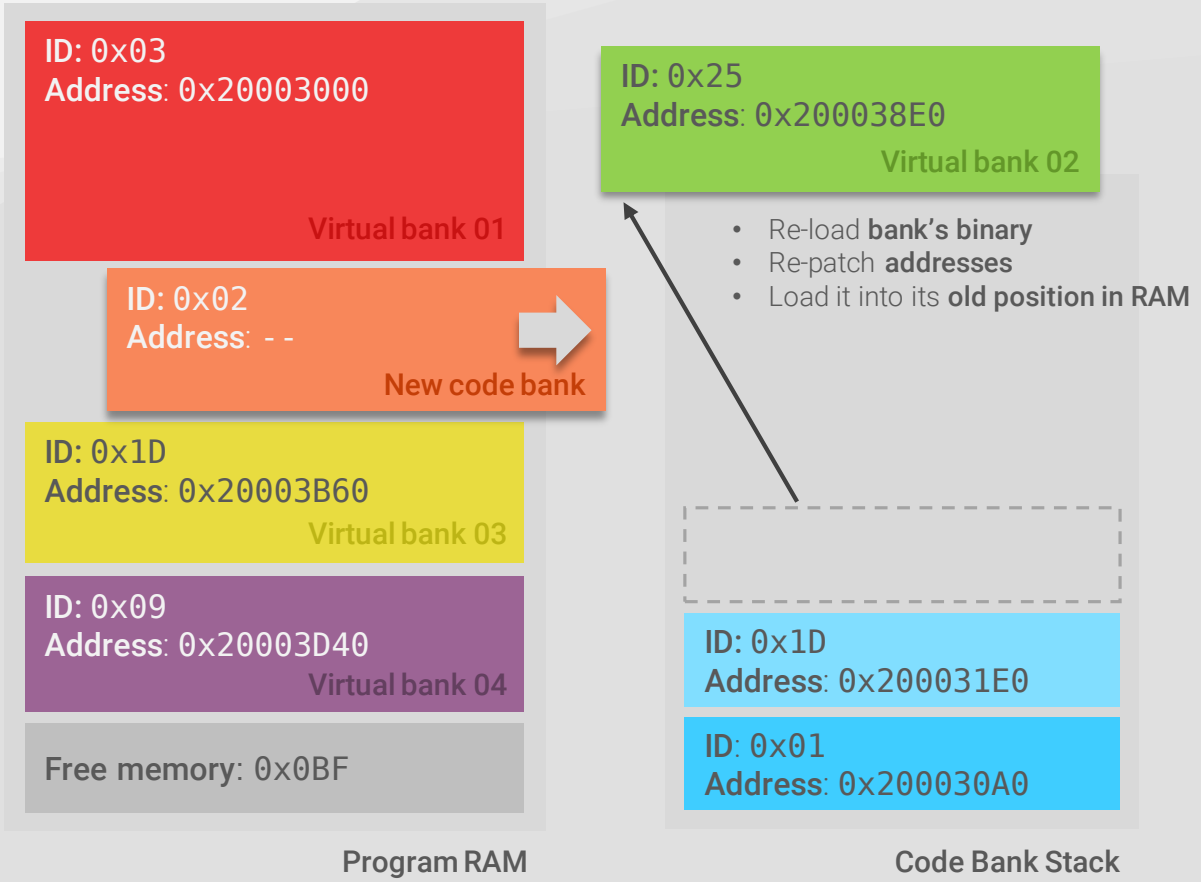




RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

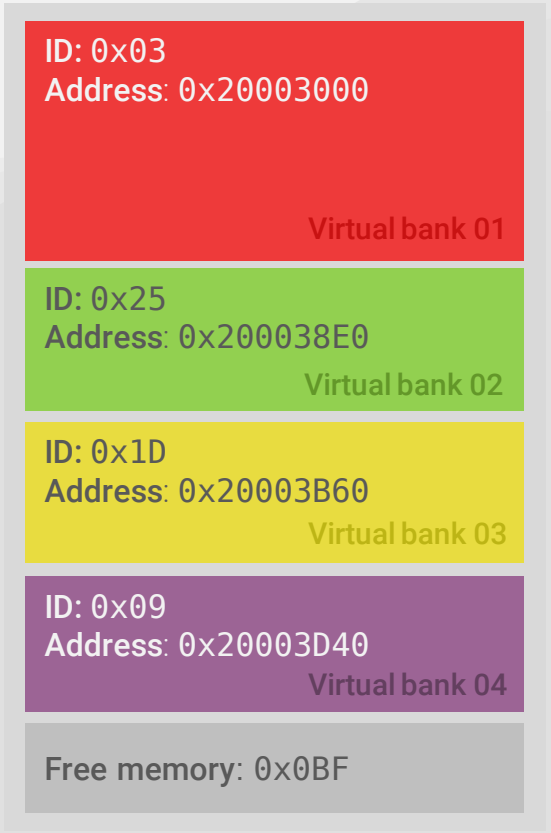
- Done `0x02`! `0x25` can be **resumed**. A full **context switching** is needed.
  - Request and reload `0x25`'s binary code;
  - Re-patch `0x25`'s code
  - Reload it into RAM and update the virtual code bank's house keeping;



RUNNING CODE BANKS

MEMORY MANAGEMENT: VIRTUAL CODE BANKS AND CODE BANK STACK

- Back to the beginning…



RUNNING CODE BANKS

CODE EXECUTION: INS-AND-OUTS

- The execution of a *code bank* is carried over exactly as you would expect:
  - **Stack** and **Heap** usage is shared among the *main application* and the *code banks;*
  - **Exceptions** will trigger a call stack unrolling as they would normally do;
  - *(local)* Variable scope follows the usual rules;
    - Member attributes depend on the life-cycle of the bank's context!

- Some points should be taken into account:
  - Running **virtual methods require proper initialization** of VPTR table;
    - The bank's **constructor** is responsible for doing so: remember that your code must do it explicitly!
  - Similarly, **destructors** need to be called explicitly (if needed);
  - There is no real use of **RTTI** (thus, no use for `dynamic_cast`) with *banked-types*;

RUNNING CODE BANKS

CODE EXECUTION: INS-AND-OUTS

- The `CodeRunner`'s house keeping must be taken into account when integrating it in your application:
  - All algorithms in the `CodeRunner` are of complexity $O(n)$, **mostly I/O-bound**;
  - That means, *the bigger the number of banks, and the size of those banks, the slower the* `CodeRunner` *becomes*;
    - The **speed of the interface** between the CPU and the storage medium, *plays a huge role* in the overall runtime performance;

- *Code banks* place some **pressure over stack size**: every call to a *code bank* requires intermediate steps which can get up to 5 levels (worst case scenario);
  - *Furthermore, re-entrant code banks* **multiply that cost by the amount of nesting calls** *they perform;*
  - Careful stack management is advised!
    - This is also valid when dimensioning the *code bank*'s stack;

PART III

GENERAL TOPICS

This section *quickly* covers:

DEBUG

TESTING

SECURITY

WHAT'S NEXT

DEBUGGING CODE BANKS

- Your success on debugging directly depends on the building/debug tools you are using:
  - In any case, there is **no** *C++ level* debug support;
  - Your tool must be able to **disassemble ARM/Thumb code in RAM** space (IAR can't, btw);
    - Set breakpoints in RAM are also desirable;
- **Forget about debug symbols**:
  - The code loaded in RAM **has been patched** (both in build and runtime);
  - The header will also ruin any addresses mentioned in the dbs files, making the **binary inconsistent** with the compiler-generated debug data;

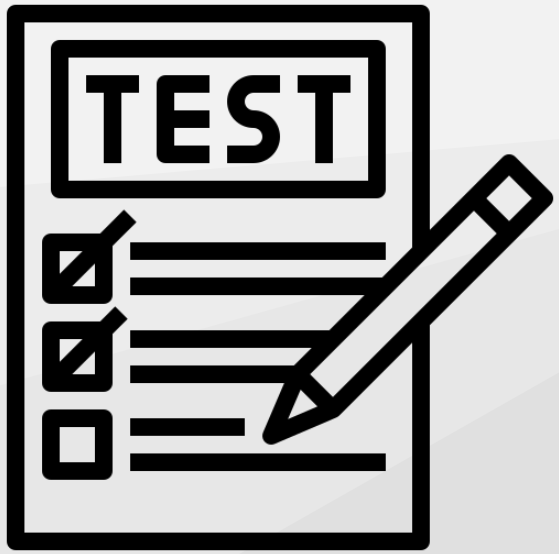
DEBUGGING CODE BANKS

- Be ready to learn ARM binary code…
- That's what I would usually debug with:

```
20000420: 8c3e 0020 f8b5 0400 0d00 a068 0028 05d1  .>. .......h.(..
20000430: fff7 1afe fff7 28fe a060 f1bd fff7 14fe  ......(..`......
20000440: fa21 4900 a068 fff7 17fe 0028 35d0 fff7  .!I..h.....(5...
20000450: 0bfe fff7 19fe a060 794e 3068 2a21 405c  .......`yN0h*!@\
20000460: 0700 0321 0328 08d1 207b 421c 2273 0022  ...!.(.. {B."s."
20000470: 0092 2b00 0322 0240 1ce0 3800 01d0 022f  ..+.."."@..8..../
20000480: 09d1 207b 421c 2273 0022 0092 fff7 e4fd  .. {B."s."......
20000490: 2b00 cab2 0de0 042f 07d1 3068 fff7 0cfe  +....../..0h....
200004a0: 0090 2b00 0022 0421 04e0 0020 0090 2b00  ..+.."."!... ..+.
200004b0: 0022 3900 2000 00f0 11f8 f8bd 6c2e 0020  ."9. .......l..
200004c0: c42e 0020 f81e 0020 2564 0020 242f 0020  ... ... %d..$/.
200004d0: 3b28 0020 3928 0020 3c28 0020 10b5 1400  ;(. 9(. <(. ....
200004e0: 1a00 0529 01d1 2421 33e0 0729 00d0 0329  ...)..$!3..)...)
200004f0: 0bd1 2100 28d0 012c 01d1 2621 29e0 022c  ..!.(..,..&!)..,
20000500: 01d1 2721 25e0 2e21 23e0 0b00 01d0 0229  ..'!%..!#......)
20000510: 09d1 2100 01d1 1821 1be0 012c 01d1 1a21  ..!....!...,...!
```

You are here!

TESTING CODE BANKS



- **Unit testing *code banks* is possible** using code banks, but require some *getting-used to:*
- The new syntax elements **must not be included**. That means:
  - Include a **special testing header** to your code-bank (`BankTestUtils.hpp`);
  - Surround special code (using `@` and `of`) with `#ifdef/#ifndef` conditional compilation statements;
  - Use a `CodeRunner` mock object in the test body;

- Admittedly needs more work to get to an acceptable level;
  - Only *toyed* around with this idea;

SECURITY & CODE BANKS

- *Code banks are usually stored* in *(potentially)* **exposed storage media**;
- That may open room for hackers to **extract the application code** and **reverse-engineer your product**;
  - This could lead to IP leaks;
  - Code injection, leading to misuse of the host hardware;

- Code **encryption is a *must have***:
  - Secure Flash (in the case of external Flash chips);
  - Encrypted communication channels (i.e. Https, in the case of remote code storage);
  - Discuss this with your hardware/production teams;

WHAT'S NEXT

- **Port** to other platforms/compilers;
  - GCC and Keil would be a good start;
- **Simplify** the build flow;
  - Remove the lots of temporary files;
  - Reduce build times (multithread support)
- **Empower** debugging:
  - Generate new debug symbols based on the information acquired during build;
- **Improve** testing infrastructure;

QUESTIONS?

```
// Include required information to allow us
#include "BankDefinitions.hpp"
#include "infrastructure/CodeRunner.hpp"

//Declare code bank and places it at a spec
int main()
{
    ...
    // The code runner should be initialized
    CodeRunner::Initialize(&storageControlle
    ...

    BankContext context of FactorialCalculat

    uint32_t factorial = @FactorialCalculato
);

    std::cout<<"Factorial of 5: "<<factorial
    ...
}

#endif // BANK_HPP_
```

```
#ifndef FACTORIAL_CALCULATOR_HPP_
#define FACTORIAL_CALCULATOR_HPP_

#include <cstdint>
#include "BankedCodeUtils.hpp"

CODE_BANK FactorialCalculator
{
   // Only one Exposed Method
   EXPOSED: uint32_t Calculate(uint8_t number)
     {
       uint32_t result = 1;

       for(auto i = 1; i <= number; i++)
       {
         result = result * i;
       }
```

$ {040}_

FACTORIAL.BANK

FactorialCalculator.hpp

```
#ifndef FACTORIAL_CALCULATOR_HPP_
#define FACTORIAL_CALCULATOR_HPP_

#include <cstdint>
#include "BankedCodeUtils.hpp"

CODE_BANK FactorialCalculator
{
      // Only one Exposed Method
      EXPOSED: uint32_t Calculate(uint8_t number)
      {
          uint32_t result = 1;

          for(auto i = 1; i <= number; i++)
          {
              result = result * i;
          }

          return result;
      }
};

#endif // FACTORIAL_CALCULATOR_HPP_
```

Example Program

```
// C++ std headers
#include <iostream>
#include <cstdint>

// Include required information to allow use of code banks
#include "BankDefinitions.hpp"
#include "infrastructure/CodeRunner.hpp"

//Declare code bank and places it at a specific address.
int main()
{
      ...
      // The code runner should be initialized at some point
      CodeRunner::Initialize(&storageController);
      ...

      BankContext context of FactorialCalculator;
      uint32_t factorial = @FactorialCalculator.Calculate(context, 5);

      std::cout<<"Factorial of 5: "<<factorial<<std::endl;
      ...
}

#endif // BANK_HPP_
```

After properly building:

Output

```
cso@op040 /projects/programs
$ ./Factorial
$ Factorial of 5: 120
```

$ {040}_

040coders.nl

BACKUP

CODERUNNER

CodeRunner.cpp

```
bool CodeRunner::Run2ArgBoolRet(uint8_t bankID, uint8_t methodID, void* ctx, void* arg1, void* arg2)
{
        // Check whether code bank with ID bankID is in memory; If not, load it.
        auto virtualBank = LoadCodeBankIfNeeded(bankID);

        // Get a pointer to the first bank's address in the program RAM and get the Exposed method Offset offset from the bank's header.
        uint8_t *bankPointer = reinterpret_cast<uint8_t*>(reinterpret_cast<uint32_t>(executableMemory) + virtualBank->bankAddress);
        uint16_t methodOffset = GetExposedMethodOffset(bankPointer, methodID);

        // Sanity Check.
        if (methodOffset == 0xFFFF) { SetFailure(UnknownMethod); return; }

        // Create a function pointer to the exact address of the Exposed method and force it to be taken in Thumb mode.
        uint32_t exposedMethodAddress = methodOffset + reinterpret_cast<uint32_t> (bankPointer) + GetHeaderSize(bankPointer);
        bool (*method)(void *, void *, void *) = reinterpret_cast<bool(*)(void *, void *, void *)>(exposedMethodAddress | 0x01);

        // Ensure this bank cannot be unloaded.
        virtualBank->Lock();

        // Branch and acquire return value
        bool returnValue = (*method)(ctx, arg1, arg2);

        // Restore any possible bank suspended during the execution of the Exposed method.
        RestoreSuspendedBanksIfNeeded();
        virtualBank->Unlock();

        return returnValue;
}
```

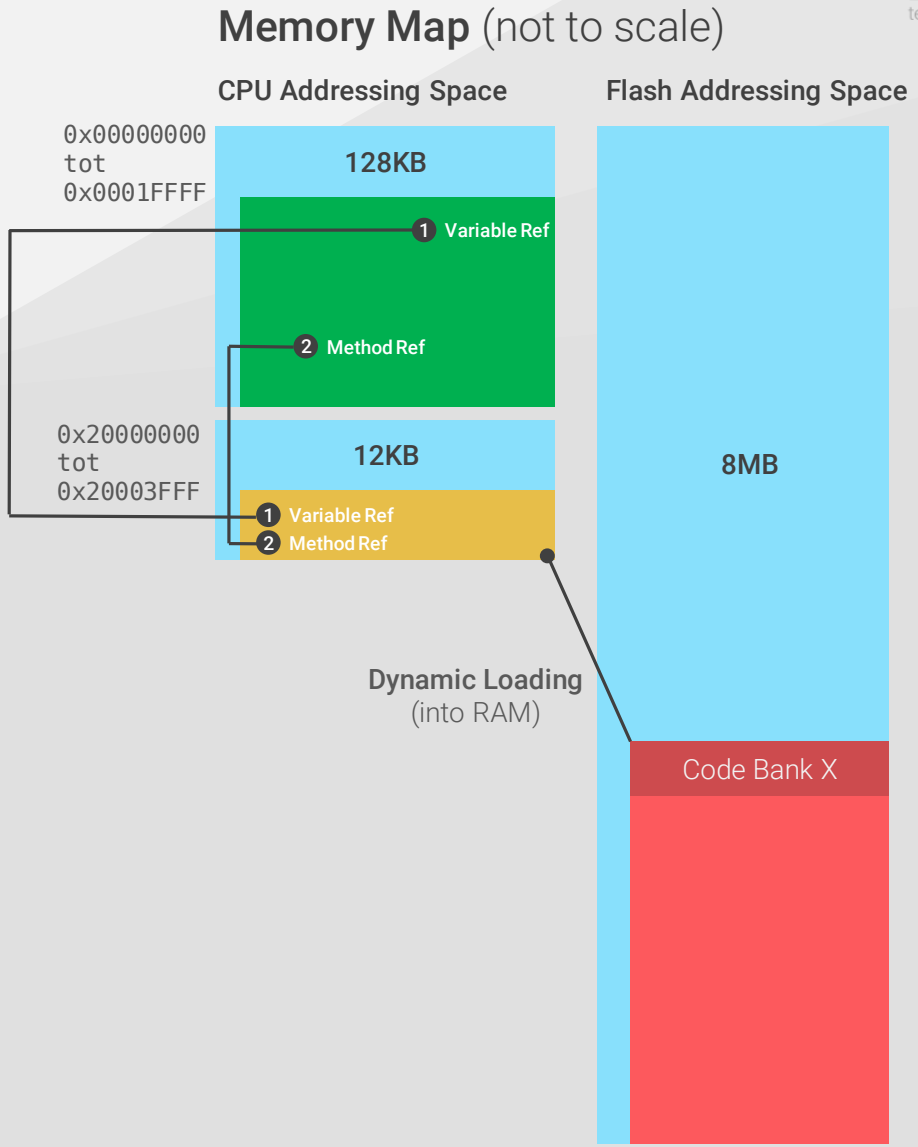
PRE-BUILD::SYMBOL TABLE

- The `BankedCodeBuilder` symbol table is a simple data structure holding the name of each *code bank*, its header file path and a list of each `RESTRICTED` or `EXPOSED` methods.
  - The tool will sweep every file in the project containing `CODE_BANK`, looking for *code banks* declarations.

PRE-BUILD::LINKER FILE UPDATE

- Ensuring that the *code bank* gets built, is just one part of the riddle:
  - *It must be **built correctly***!

1. It places the code **outside the first 128KB** of the CPU addressing space;
   1. Give an unique code region for each code bank
2. It ensures that all references to *main application* variables/functions are **made using absolute addresses**;



PRE-BUILD::CODE GENERATION

- The second-last stage of pre-building consists of `CodeRunner` **generation**;
  - `CodeRunner` is the component capable of branching to *code banks;*
  - It needs **one function for each different *code bank* method signatur**e
    - That's due to the way function pointers and Arm's Procedure Call convention is defined;

PRE-BUILD::CODE GENERATION

```
<RET_TYPE> Run<N_ARGS>Arg<RET_TYPE>Ret(uint8_t bank_id, uint8_t method_id, void* context, void * arg0, ..., void * argN);
```

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PRE-BUILD::CODE GENERATION

- Since `@` is no standard C++ operator, it must be *patched-out* before the code is delivered to the compiler;
  - This is done during the **code injection** phase.
- The `@` operator is ultimately translated into a call to the `CodeRunner` providing:
  - the bank's location in the Flash;
  - the method location in the bank's header;
  - A reference to the context and the arguments;

- Likewise, The `of` operator is translated into the declaration of a `BankContext` array, used as the bank's context used during a method call;
  - `BankContext` is in fact an alias of `uint8_t`;

@ operator transformation

Original Source Code

```
@SampleBank.SampleMethod(NoContext, 0x10);
```

Pass 1: pre-build injection

```
CodeRunner::Instance().Run1ArgVoidRet
(
  BankedTypes.SampleBank,
  SampleBankMethods.SampleMethod,
  reinterpret_cast<void*>(&_noThis),
  reinterpret_cast<void*>(&_arg1)
);
```

of operator transformation

Original Source Code

```
BankContext context of SampleBank;
```

Pass 1: pre-build injection

```
BankContext context[sizeof(SampleBank)];
```

POST-BUILD::LOCATING DEPENDENCIES

- *Code banks unlinked assembly* are used to acquire all *main application* variables and functions referred in the *code bank*;
  - In the object file *dumps*, those references appear as unresolved symbols (such as `_ZN6ExternalCall1` or `_ZN8ExterbakVariable`).
  - A list of all symbols of every *code bank* is held by the `BankedCodeBuilder`.
    - Those symbol must be found in the *main application* (where their addresses can be extracted);

Code bank object dump

```
      $t:
...
0x3e: 0x6869         LDR   R1, [R5, #0x4]
0x40: 0x7d4a         LDRB  R2, [R1, #0x15]
0x42: 0x2a29         CMP   R2, #41              ; 0x29
0x44: 0xd111         BNE.N @6a
0x46: 0x1c48         ADDS  R0, R1, #1
0x48: 0xf7ff 0xfffe  BL    atoi
0x4c: 0x0001         MOVS  R1, R0
0x4e: 0x0600         LSLS  R0, R0, #24
0x50: 0xd020         BEQ.N @94
0x52: 0x48ff         LDR.N R0, REGION_BANK_21   ; _ZN8ExternalVariable
...
0x54: 0x6800         LDR   R0, [R0]
0x56: 0x22bd         MOVS  R2, #189             ; 0xbd
0x58: 0x5c82         LDRB  R2, [R0, R2]
0x5a: 0xb2cb         UXTB  R3, R1
0x5c: 0x429a         CMP   R2, R3
0x5e: 0xd319         BCC.N @94
0x60: 0x1e49         SUBS  R1, R1, #1
0x62: 0xb2c9         UXTB  R1, R1
0x64: 0xf7ff 0xfffe  BL    _ZN6ExternalCall1
...
      $d:
      REGION_BANK_21:
0x148: 0x00000000     DC32  _ZN8ExternalVariable
```

This step is specially interested in **static relocation symbols** such as those labeled with `R_ARM_THM_CALL` or `R_ARM_ABS32`. **No dynamic relocation** is expected to appear throughout the code.

POST-BUILD::ADDRESS MAPPING

- Mapping consists of **locating the symbols in the *main application dump*** (by name) and **extracting their 32-bit addresses**;
  - **Thumb-class relocation** symbols such as `R_ARM_THM_CALL` will map into *main application* function addresses and will be used as part of the **veneering patching** stage;
    - Those addresses will ultimately be added to **GRT**;
  - **Data-class relocation** symbols such as `R_ARM_ABS32` will map into *main application* variables and will be inserted in the *code bank*'s header to be used during the **address patching**;
    - Those addresses will ultimately be added to **GRDT**;

POST-BUILD::GLOBAL RELOCATION TABLES

- The Global Relocation Tables (GRT & GRDT) are a way to be **flexible with the dependencies** shared among the *main application* and the *code banks*;
  - It creates truly *position-independent* code, **allowing the main application to independently change**, without requiring a full re-build of the code banks.

- The content of the tables are used in two situations:
  - **Static Address Relocation** (SAR);
  - **Dynamic Address Patching** (DAP);

POST-BUILD::GLOBAL RELOCATION TABLES

- In the current implementation, GRT/GRDT is list of **128 32-bit void pointers** to methods in the *main application*.
  - GRT starts at address `0x1F8E0`;
  - GRDT starts at address `0x1F6E0`;
  - Each entry has a **well known address** (`base + (entry_index*4)`) and an appropriate label `GRT_ENTRY_XXX/GRDT_ENTRY_XXX`;

GRDT

```
...

// _variable1
#pragma location = 0x0001F6E0
__root const uint32_t GRDT_ENTRY_0001 = 0x200024e0;

// _variable2
#pragma location = 0x0001F6E4
__root const uint32_t GRDT_ENTRY_0002 = 0x20003e8c;

// _variable3
#pragma location = 0x0001F6E8
__root const uint32_t GRDT_ENTRY_0003 = 0x20002e6c;

// _variable4
#pragma locati
__root const u

// _variable5
#pragma locati
__root const u

...
```

GRT

```
...

// __aeabi_memcpy
#pragma location = 0x0001F8E0
__root const uint32_t GRT_ENTRY_0001 = 0x000059E9;

// __iar_small_idiv
#pragma location = 0x0001F8E4
__root const uint32_t GRT_ENTRY_0002 = 0x00006BD5;

// snprintf
#pragma location = 0x0001F8E8
__root const uint32_t GRT_ENTRY_0003 = 0x0000C6FB;

// _Z6ito02diPc
#pragma location = 0x0001F8EC
__root const uint32_t GRT_ENTRY_0004 = 0x0000C719;

...
```

POST-BUILD::VENEERS

- Veneers are small sections of code generated by the linker to **allow branching outside of the range of** BL instructions;
  - Veneers are required because the runtime address of a *code bank lies about 64MB away from the main application* (starting at `0x20003000`);
  - All veneers generated in *code banks* are thus **long branch veneers**;

Memcpy veneeer

```
; Linker-generated code
            $t:
            `?Veneer 14 (3) for __aeabi_memcpy`:
0x10000000: 0xb408          PUSH  {R3}
0x10000002: 0x4b02          LDR.N R3, [PC, #0x8] ; __aeabi_memcpy
0x10000004: 0x469c          MOV   R12, R3
0x10000006: 0xbc08          POP   {R3}
0x10000008: 0x4760          BX    R12
0x1000000a: 0x46c0          MOV   R8, R8
            $d:
0x1000000c: 0x00000000      DC32  __aeabi_memcpy
```

In-depth:

1. Push **R3** to (for temporary calculation)
2. Load the absolute address of **memcpy** into **R3** located 8 bytes away of the current PC value
3. Save the address into **R12** (note that **R12** content is allowed to be modified according to **APCS**)
4. Pop **R3** (restore argument)
5. Branch to the address in **R12** (in Thumb mode)
6. NOP

POST-BUILD::VENEER PATCHING

- After the Relocation Tables are generated, each veneer detected in the *code banks* **must branch to an address held by a GRT entry**;
- This is done by ***directly changing the absolute address stored in the veneer, by the address of the GRT entry holding the pointer to the to the function targeted by the veneer***;
  - Furthermore, due to the indirection introduced by GRT, the assembly code itself must be updated, to use the **indirect addressing mode** when loading the function address;

Original Veneer

```
; Linker-generated code
            $t:
            `?Veneer 14 (3) for __aeabi_memcpy`:
 0x10000000: 0xb408          PUSH  {R3}
 0x10000002: 0x4b02          LDR.N R3, [PC, #0x8]
 0x10000004: 0x469c          MOV   R12, R3
 0x10000006: 0xbc08          POP   {R3}
 0x10000008: 0x4760          BX    R12
 0x1000000a: 0x46c0          MOV   R8, R8
            $d:
 0x1000000c: 0x00000000      DC32  __aeabi_memcpy
```

Patched Veneer

```
; Patched veneer code
            $t:
            `?Veneer 14 (3) for __aeabi_memcpy`:
 0x10000000: 0xb408          PUSH  {R3}
 0x10000002: 0x4b02          LDR.N R3, [PC, #0x8]
 0x10000004: 0x1b68          LDR.N R3, [R3]
 0x10000004: 0x9c46          MOV   R12, R3
 0x10000008: 0xbc08          POP   {R3}
 0x1000000a: 0x4760          BX    R12
            $d:
 0x1000000c: 0x0001f8e0      DC32  GRT_ENTRY_0001
```

POST-BUILD::BINARY GENERATION

- The last post-build step is the generation of the binary code of each *code bank;*
  - The binaries generated in this state are ready to be programmed in the device's external flash and have the proper structure to be compatible with the `CodeRunner`;

- Each *code bank* binary holds an header providing metadata used by the `CodeRunner` to locate `EXPOSED` methods and to perform **address patching**;