STM32 F4 series

High-performance Cortex™-M4 MCU

Presentation highlights

The STM32 F4 series brings to the market the **world's highest performance** Cortex™-M microcontrollers

168 MHz F_{CPU}/210 DMIPS

363 Coremark score

The STM32 F4 series extends the STM32 portfolio
250+ compatible devices already in production, including the F1 series, F2 series and ultra-low-power L1 series

The STM32 F4 series reinforces ST's current leadership in Cortex-M microcontrollers, **with 45% world market share** by units in (2010 or cumulated 2007 to Q1/11) according to ARM reporting

STMicroelectronics

STM32 F4 series
High-performance digital signal controller

ARM

Cortex
Low-Power Leadership from ARM

FPU
Single precision
Ease of use
Better code efficiency
Faster time to market
Eliminate scaling and saturation
Easier support for meta-language tools
   (Matlab…)

STM32 F4

What is Cortex-M4?

MCU
Ease of use of C programming
Interrupt handling
Ultra-low power

Cortex-M4

DSP
Harvard architecture
Single-cycle MAC
Barrel shifter

STM32 F4 Series highlights 1/4

- ST is introducing STM32 products based on Cortex M4 core. Over 30 new part numbers pin-to-pin and software compatible with existing STM32 F2 Series.

- The new DSP and FPU instructions combined to 168Mhz performance open the door to a new level of Digital Signal Controller applications and faster development time.

- STM32 Releasing your creativity

STMicroelectronics

STM32 F4 Series highlights 2/4

Advanced technology and process from ST:

- Memory accelerator: ART Accelerator™

- Multi AHB Bus Matrix

- 90nm process

Outstanding results:

- 210DMIPS at 168Mhz.

- Execution from Flash equivalent to 0-wait state performance up to 168Mhz thanks to ST ART Accelerator

STM32 F4 Series highlights 3/4

More Memory

- Up to 1MB Flash,
- 192kB SRAM: 128kB on bus matrix + 64kB on data bus dedicated to the CPU usage

Advanced peripherals shared with STM32 F2 Series

- USB OTG High speed 480Mbit/s
- Ethernet MAC 10/100 with IEEE1588
- PWM High speed timers: Now 168Mhz max frequency!
- Crypo/hash processor, 32-bit random number generator (RNG)
- 32-bit RTC with calendar: Now with sub 1 second accuracy, and <1uA typ!

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Further improvements

- Low voltage: 1.8V to 3.6V VDD , down to 1.7*V on most packages

- Full duplex I2S peripherals

- 12-bit ADC: 0.41µs conversion/2.4Msps (7.2Msps in interleaved mode)

- High speed USART up to 10.5Mbits/s

- High speed SPI up to 37.5Mbits/s
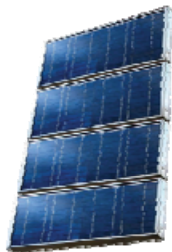
- Camera interface up to 54MBytes/s

*external reset circuitry required to support 1.7V

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STM32 F4 series – applications served

- Points of sale/inventory management

- Industrial automation and solar panels

- Transportation

- Medical

- Building

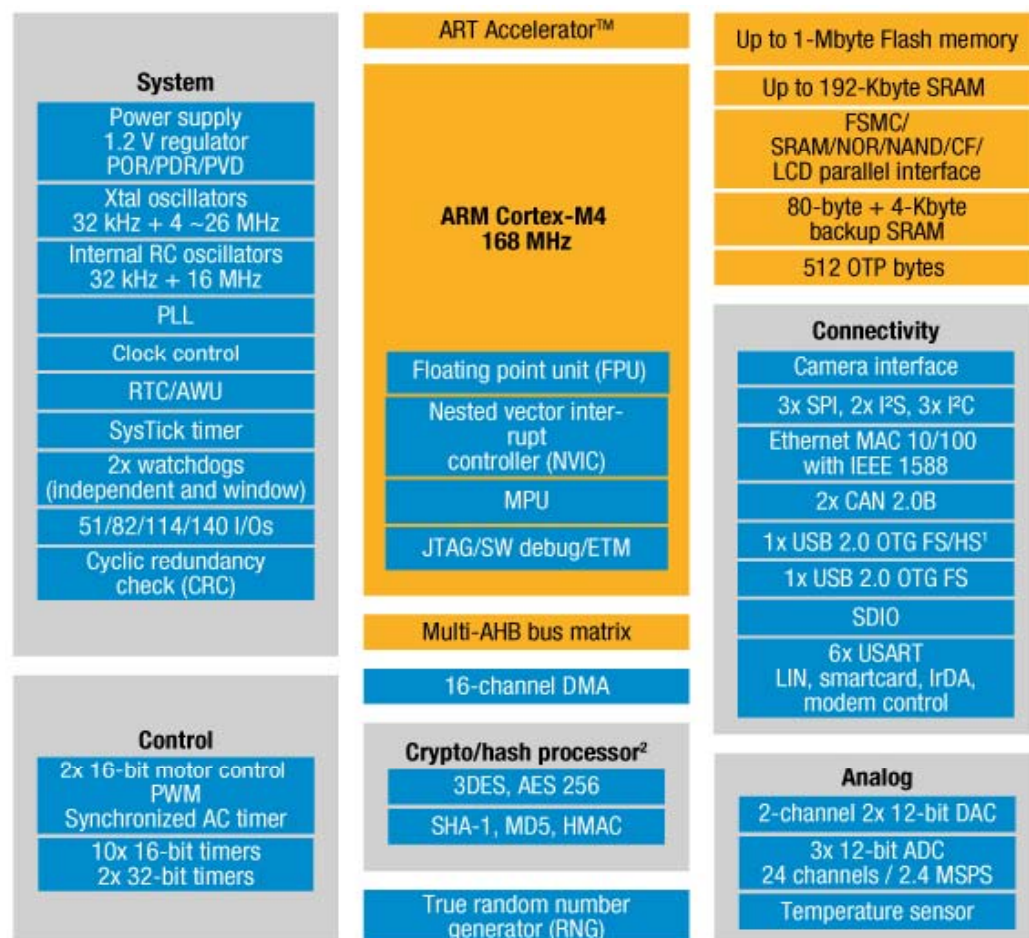- Security/fire/HVAC

- Test and measurement

- Consumer

- Communication

2

STM32 F4 block diagram

Feature highlight

- 168 MHz Cortex-M4 CPU
  - Floating point unit (FPU)
  - ART Accelerator ™
  - Multi-level AHB bus matrix
- 1-Mbyte Flash, 192-Kbyte SRAM
- 1.7 to 3.6 V supply
- RTC: <1 µA typ, sub second accuracy
- 2x full duplex I²S
- 3x 12-bit ADC 0.41 µs/2.4 MSPS
- 168 MHz timers

System
- Power supply 1.2 V regulator POR/PDR/PVD
- Xtal oscillators 32 kHz + 4 ~26 MHz
- Internal RC oscillators 32 kHz + 16 MHz
- PLL
- Clock control
- RTC/AWU
- SysTick timer
- 2x watchdogs (independent and window)
- 51/82/114/140 I/Os
- Cyclic redundancy check (CRC)

ART Accelerator™

ARM Cortex-M4 168 MHz
- Floating point unit (FPU)
- Nested vector inter-rupt controller (NVIC)
- MPU
- JTAG/SW debug/ETM

Multi-AHB bus matrix

16-channel DMA

Control
- 2x 16-bit motor control PWM Synchronized AC timer
- 10x 16-bit timers 2x 32-bit timers

Crypto/hash processor²
- 3DES, AES 256
- SHA-1, MD5, HMAC

True random number generator (RNG)

- Up to 1-Mbyte Flash memory
- Up to 192-Kbyte SRAM
- FSMC/ SRAM/NOR/NAND/CF/ LCD parallel interface
- 80-byte + 4-Kbyte backup SRAM
- 512 OTP bytes

Connectivity
- Camera interface
- 3x SPI, 2x I²S, 3x I²C
- Ethernet MAC 10/100 with IEEE 1588
- 2x CAN 2.0B
- 1x USB 2.0 OTG FS/HS¹
- 1x USB 2.0 OTG FS
- SDIO
- 6x USART LIN, smartcard, IrDA, modem control

Analog
- 2-channel 2x 12-bit DAC
- 3x 12-bit ADC 24 channels / 2.4 MSPS
- Temperature sensor

Notes:
1. HS requires an external PHY connected to the ULPI interface
2. Crypto/hash processor on STM32F417 and STM32F415

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STM32 F4 portfolio
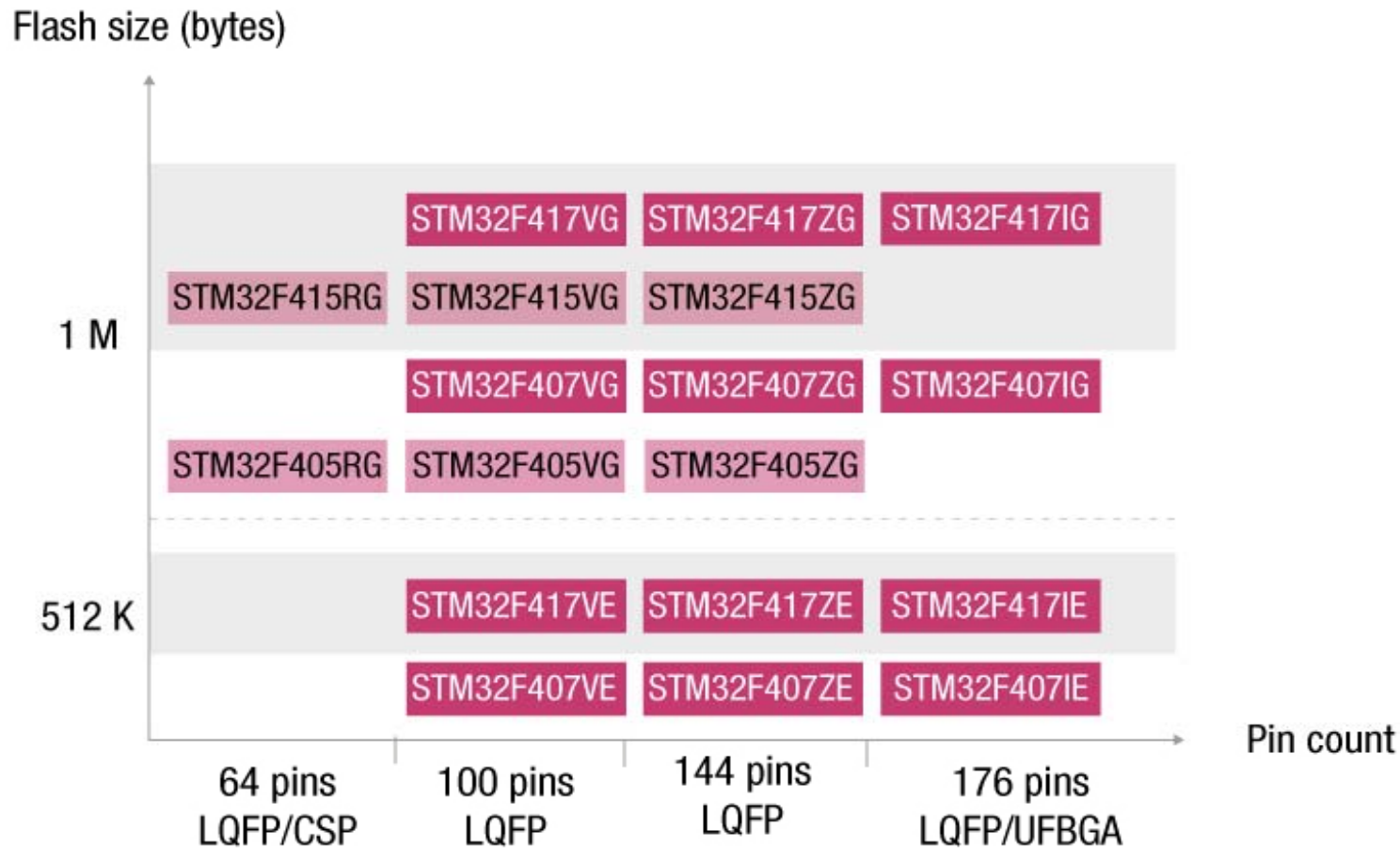
STM32 product series

4 product series

Common core peripherals and architecture:

| Communication peripherals: USART, SPI, I²C |
| Multiple general-purpose timers |
| Integrated reset and brown-out warning |
| Multiple DMA |
| 2x watchdogs Real-time clock |
| Integrated regulator PLL and clock circuit |
| External memory interface (FSMC) |
| Dual 12-bit DAC |
| Up to 3x 12-bit ADC (up to 0.41 µs) |
| Main oscillator and 32 kHz oscillator |
| Low-speed and high-speed internal RC oscillators |
| -40 to +85 °C and up to 105 °C operating temperature range |
| Low voltage 2.0 to 3.6 V or 1.65/1.7 to 3.6 V (depending on series) 5.0 V tolerant I/Os |
| Temperature sensor |

+

STM32 F4 series - High performance with DSP (STM32F405/415/407/417)

| 168 MHz Cortex-M4 with DSP and FPU | Up to 192-Kbyte SRAM | Up to 1-Mbyte Flash | 2x USB 2.0 OTG FS/HS | 3-phase MC timer | 2x CAN 2.0B | SDIO 2x I²S audio Camera IF | Ethernet IEEE 1588 | Crypto/hash processor and RNG |

STM32 F2 series - High performance (STM32F205/215/207/217)

| 120 MHz Cortex-M3 CPU | Up to 128-Kbyte SRAM | Up to 1-Mbyte Flash | 2x USB 2.0 OTG FS/HS | 3-phase MC timer | 2x CAN 2.0B | SDIO 2x I²S audio Camera IF | Ethernet IEEE 1588 | Crypto/hash processor and RNG |

STM32 F1 series - Connectivity line (STM32F105/107)

| 72 MHz Cortex-M3 CPU | Up to 64-Kbyte SRAM | Up to 256-Kbyte Flash | USB 2.0 OTG FS | 3-phase MC timer | 2x CAN 2.0B | 2x I²S audio | Ethernet IEEE 1588 |

STM32 F1 series - Performance line (STM32F103)

| 72 MHz Cortex-M3 CPU | Up to 96-Kbyte SRAM | Up to 1-Mbyte Flash | USB FS device | 3-phase MC timer | CAN 2.0B | SDIO 2x I²S |

STM32 F1 series - USB Access line (STM32F102)

| 48 MHz Cortex-M3 CPU | Up to 16-Kbyte SRAM | Up to 128-Kbyte Flash | USB FS device |

STM32 F1 series - Access line (STM32F101)

| 36 MHz Cortex-M3 CPU | Up to 80-Kbyte SRAM | Up to 1-Mbyte Flash |

STM32 F1 series - Value line (STM32F100)

| 24 MHz Cortex-M3 CPU | Up to 32-Kbyte SRAM | Up to 512-Kbyte Flash | 3-phase MC timer | CEC |

STM32 L1 series - Ultra-low-power (STM32F151/152)

| 32 MHz Cortex-M3 CPU | Up to 48-Kbyte SRAM | Up to 384-Kbyte Flash | USB FS device | Data EEPROM up to 12 Kbytes | LCD 8x40 4x44 | Comparator | BOR MSI VScal | AES 128-bit |

STM32 F1

STM32 F2

STM32 F1

STM32 L1

STM32 – leading Cortex-M portfolio

Flash size (bytes)

	36 pins QFN	48 pins LQFP/QFN	64 pins LQFP/BGA/CSP	100 pins LQFP/BGA	144 pins LQFP	176 pins LQFP/UFBGA

1 M
- STM32F407VG | STM32F417VG | STM32F407ZG | STM32F417ZG | STM32F407IG | STM32F417IG
- STM32F405RG | STM32F415RG | STM32F405VG | STM32F415VG | STM32F405ZG | STM32F415ZG
- STM32F207VG | STM32F217VG | STM32F207ZG | STM32F217ZG | STM32F207IG | STM32F217IG
- STM32F205RG | STM32F215RG | STM32F205VG | STM32F215VG | STM32F205ZG | STM32F215ZG
- STM32F101RG | STM32F103RG | STM32F101VG | STM32F103VG | STM32F101ZG | STM32F103ZG

768 K
- STM32F205RF | | STM32F205VF | STM32F207VF | STM32F205ZF | STM32F207ZF | STM32F207IF
- STM32F101RF | STM32F103RF | STM32F101VF | STM32F103VF | STM32F101ZF | STM32F103ZF

512 K
- STM32F407VE | STM32F417VE | STM32F407ZE | STM32F417ZE | STM32F407IE | STM32F417IE
- STM32F207VE | STM32F217VE | STM32F207ZE | STM32F217ZE | STM32F207IE | STM32F217IE
- STM32F205RE | STM32F215RE | STM32F205VE | STM32F215VE | STM32F205ZE | STM32F215ZE
- STM32F101RE | | STM32F101VE | | STM32F101ZE |
- STM32F100RE | STM32F103RE | STM32F100VE | STM32F103VE | STM32F100ZE | STM32F103ZE

384 K
- STM32L162RD[1] | STM32L162VD[1] | STM32L162ZD[1]
- STM32L151RD[1] | STM32L152RD[1] | STM32L151VD[1] | STM32L152VD[1] | STM32L151ZD[1] | STM32L152ZD[1]
- STM32F101RD | STM32F101VD | STM32F101ZD
- STM32F100RD | STM32F103RD | STM32F100VD | STM32F103VD | STM32F100ZD | STM32F103ZD

256 K
- STM32F205RC | | STM32F205VC | STM32F207VC | STM32F205ZC | STM32F207ZC | STM32F207IC
- STM32L151RC[1] | STM32L152RC[1] | STM32L151VC[1] | STM32L152VC[1] | STM32L151ZC[1] | STM32L152ZC[1]
- STM32F105RC | | STM32F105VC
- STM32F101RC | STM32F107RC | STM32F101VC | STM32F107VC | STM32F101ZC
- STM32F100RC | STM32F103RC | STM32F100VC | STM32F103VC | STM32F100ZC | STM32F103ZC

128 K
- STM32F205RB | | STM32F205VB
- STM32L151CB | STM32L152CB | STM32L151RB | STM32L152RB | STM32L151VB | STM32L152VB
- STM32F105RB | STM32F107RB | STM32F105VB
- STM32F103TB | STM32F101CB | STM32F103CB | STM32F101RB | STM32F103RB | STM32F101VB | STM32F107VB
- STM32F101TB | STM32F100CB | STM32F102CB | STM32F100RB | STM32F102RB | STM32F100VB | STM32F103VB

64 K
- STM32L151C8 | STM32L152C8 | STM32L151R8 | STM32L152R8 | STM32L151V8 | STM32L152V8
- STM32F105R8 | STM32F105V8
- STM32F103T8 | STM32F101C8 | STM32F103C8 | STM32F101R8 | STM32F103R8 | STM32F101V8 | STM32F103V8
- STM32F101T8 | STM32F100C8 | STM32F102C8 | STM32F100R8 | STM32F102R8 | STM32F100V8

32 K
- STM32L151C6 | STM32L152C6 | STM32L151R6 | STM32L152R6
- STM32F103T6 | STM32F101C6 | STM32F103C6 | STM32F101R6 | STM32F103R6
- STM32F101T6 | STM32F100C6 | STM32F102C6 | STM32F100R6 | STM32F102R6

16 K
- STM32F103T4 | STM32F101C4 | STM32F103C4 | STM32F101R4 | STM32F103R4
- STM32F101T4 | STM32F100C4 | STM32F102C4 | STM32F100R4 | STM32F102R4

Pin count

Over 250 pin-to-pin compatible part numbers

Legend:
STM32 L1 | STM32 F1 | STM32 F2 | STM32 F4

Note:
1. Available in 04/2011 for all 256- and 384-Kbyte STM32L devices

2

# The cheapest and quickest way to discover the STM32F4

- Everything included for a quick start with the STM32F4 serie
    - **Price: $ 14.90 (RRP)**
    - **DCPL : $ 11.90**
    - **Order code: STM32F4DISCOVERY**
    - **Available in ST stock** from October 2011

- In circuit ST-LINK/V2 debugger / programmer included to debug Discovery kit applications or other target board applications.

- Dedicated web site www.st.com/stm32F4discovery
    - Large number of examples ready to run
    - Schematics
    - Forums and more

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STM32F4 Discovery Board

- On-board ST-LINK/V2 with selection mode switch to use the kit as stand-alone ST-LINK with SWD connector

- Designed to be powered by USB or by external power 5V or 3.3V supply

- Can supply target application with 5 Volts or 3 Volts

- Two User LEDs (Green and Blue)
- Audio codec
- Mems Micro (MP45DT02)

- One user Push Button

- Extension header for all QFP64 I/Os for quick connection to prototyping board or easy probing

ST-LINK/V2

SWD connector

STM32F407VGT6

User button

Audio Jack
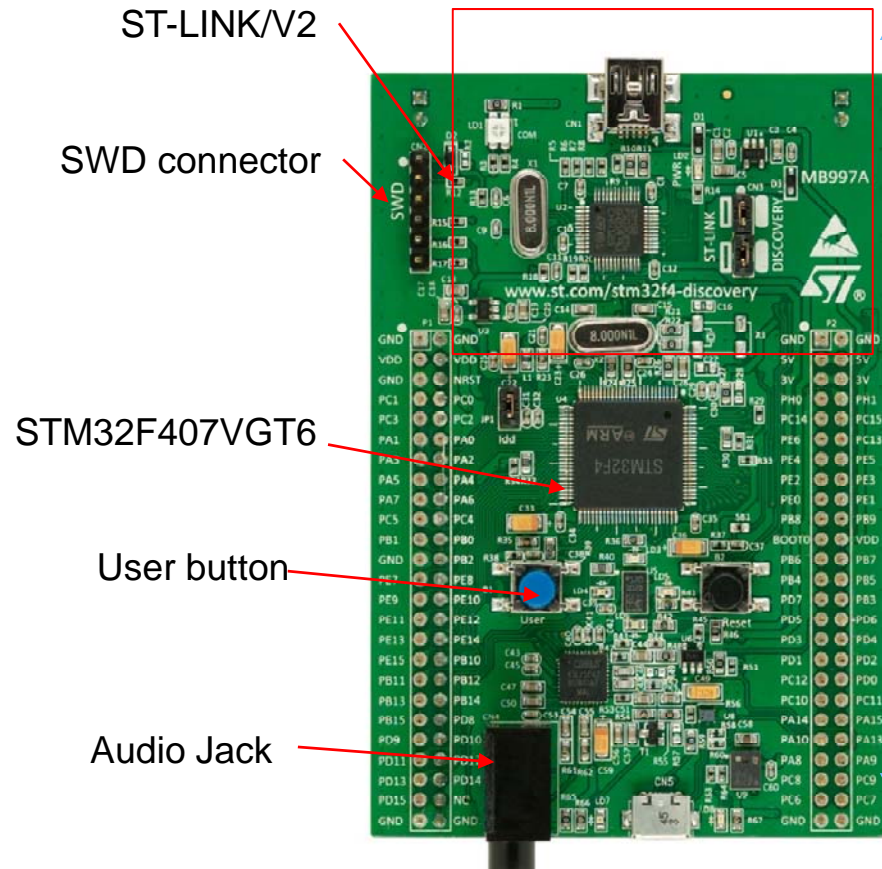
September : STM32F4 eval board

- Eval board : STM3240G-EVAL : 21st of September
  - For any needs before contact your local ST support
  - DCPL : $279
  - RRP : $349

Sample :

21st of September

LQFP100	STM32F407VGT6
LQFP144	STM32F457ZGT6
LQFP176	STM32F457IGT6
BGA176	STM32F457IGH6
LQFP64	STM32F455RGT6

Full production November 2011

Key messages to remember

- ## STM32 F4 series

  - **World's highest performance**

  - **Extends the STM32 portfolio to over 250+ compatible devices**

  - **One-in-two Cortex-M MCUs shipped worldwide is an STM32**
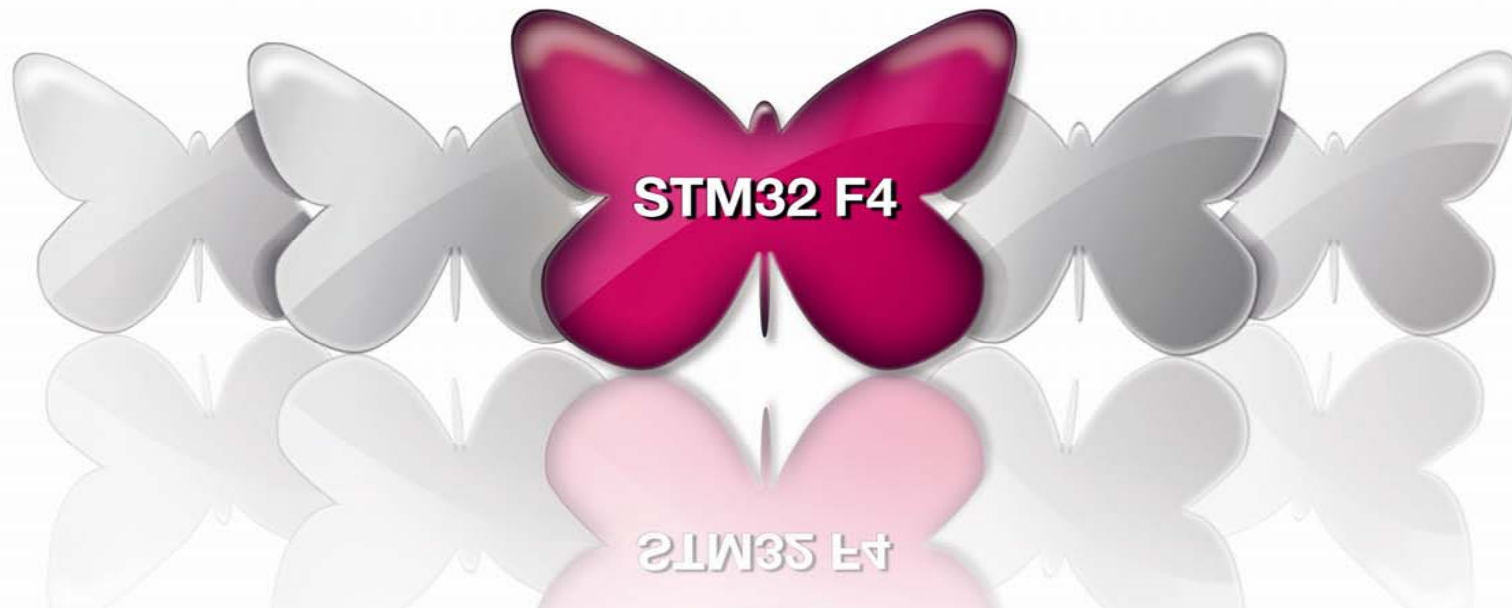
  Discovery kits available now

  STM32F4DISCOVERY

STMicroelectronics

Thank you

STM32 Releasing your **creativity**

STM32 F4

www.st.com/stm32f4

STM32F roadmap

STM32F series short term roadmap

STM32F4 series

Cortex-M4 @ 168 MHz

STM32F2 series

Cortex-M3 @ 120 MHz

STM32F1 series

Cortex-M3 @ 72 MHz

STM32F0 series
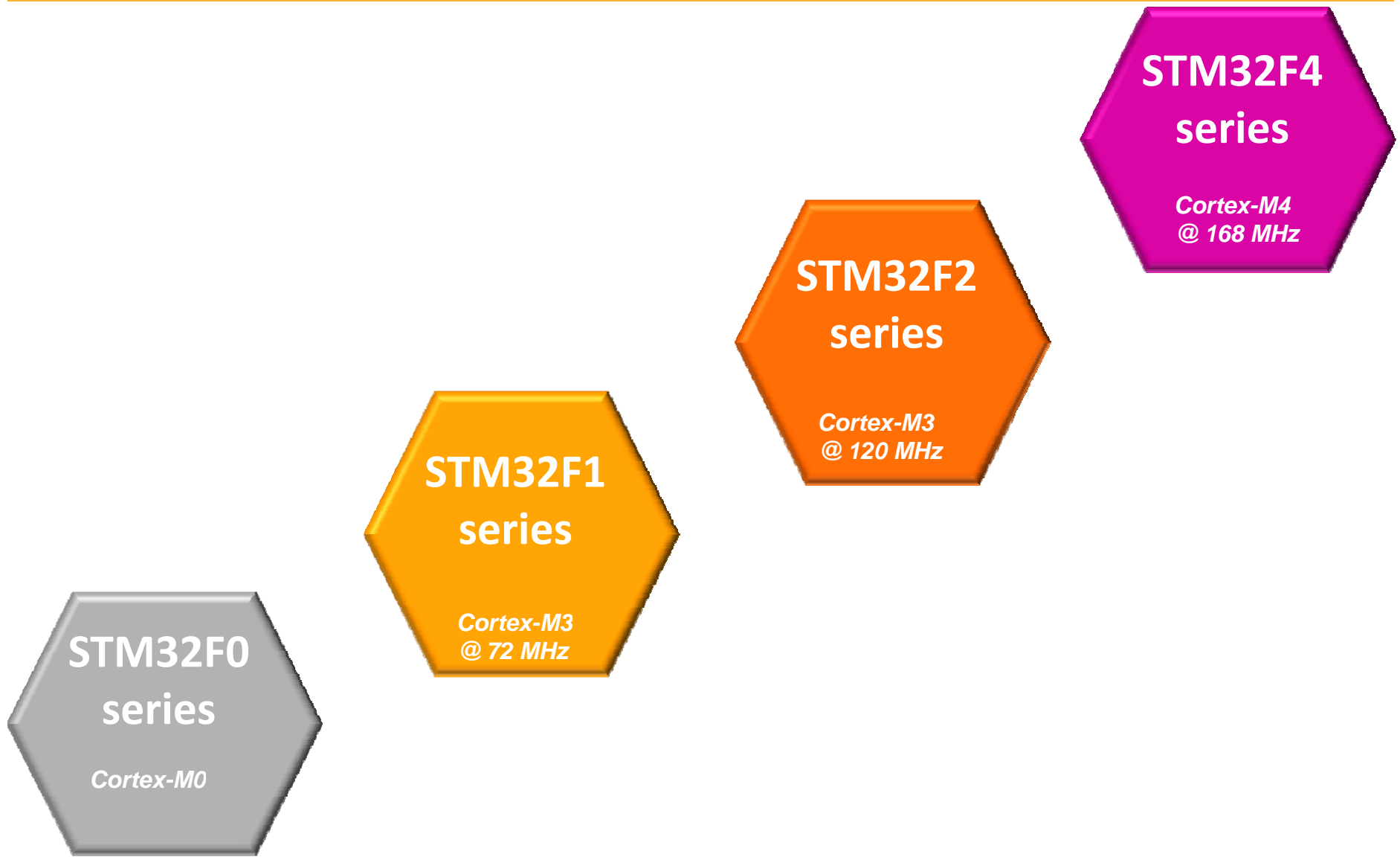
Cortex-M0

STM32 Next 2 Major Launch

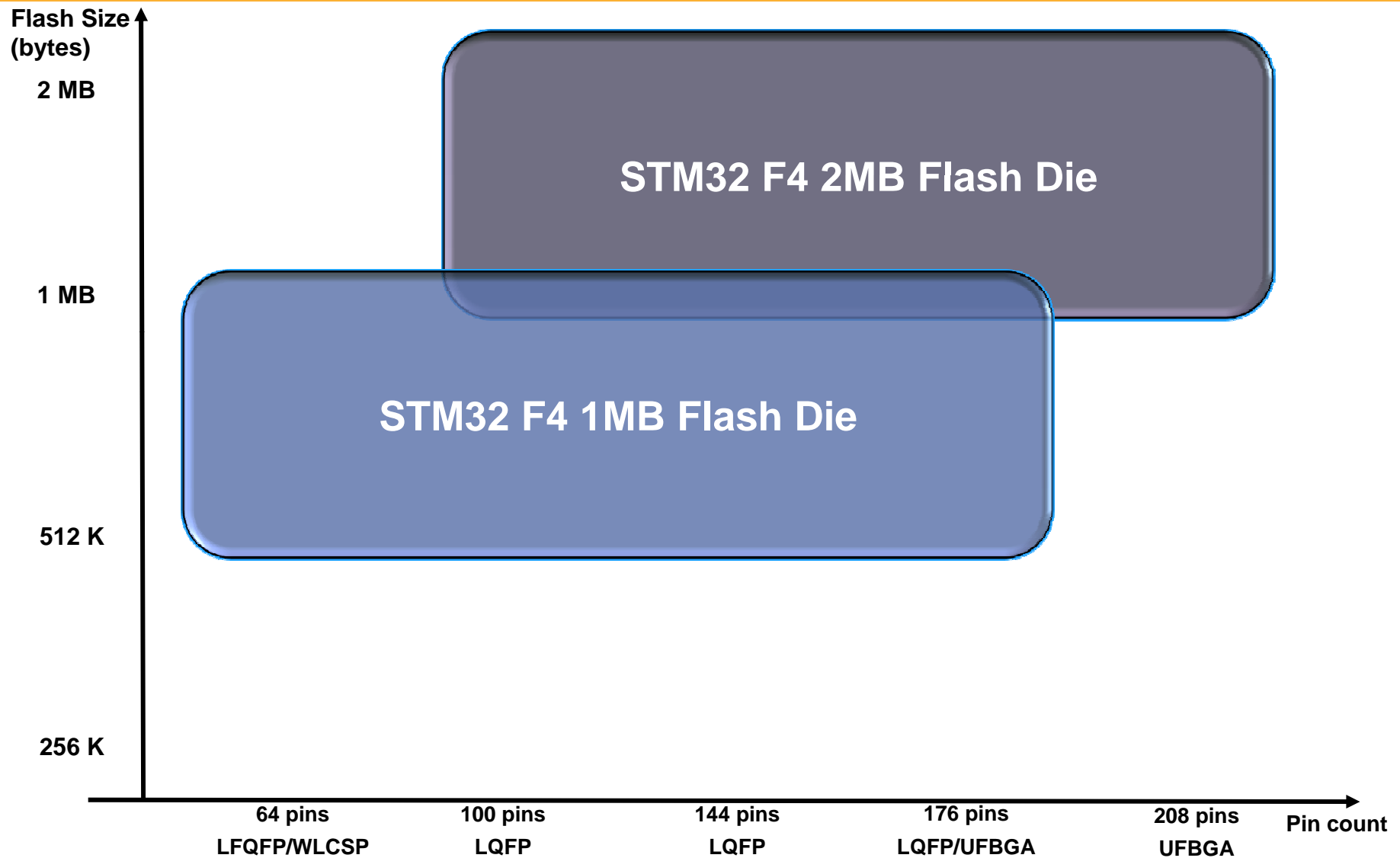**STM32F4 series**

Cortex-M4 @ 168 MHz

STM32F4 → Cortex M4
Increasing ST leadership
in the performance race
PR September 2011

STM32F0 → Cortex M0
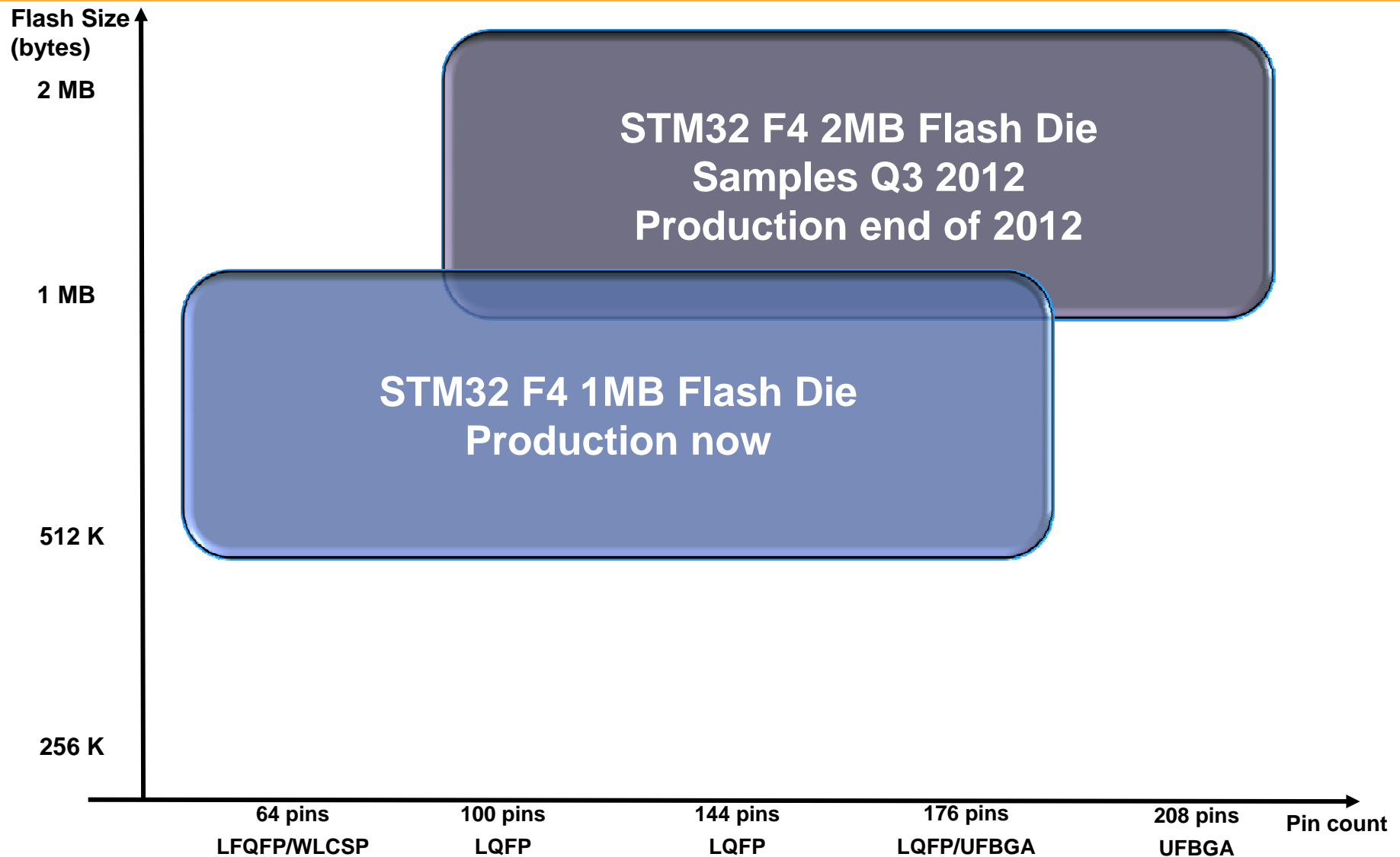Expanding Market Reach
towards 8-16 bit
Early 2012

STM32F0 series

Cortex-M0

STM32 F4 Roadmap

STMicroelectronics

STM32 F4 Roadmap

Flash Size (bytes)

2 MB

**STM32 F4 2MB Flash Die
Samples Q3 2012
Production end of 2012**

1 MB

**STM32 F4 1MB Flash Die
Production now**

512 K

256 K

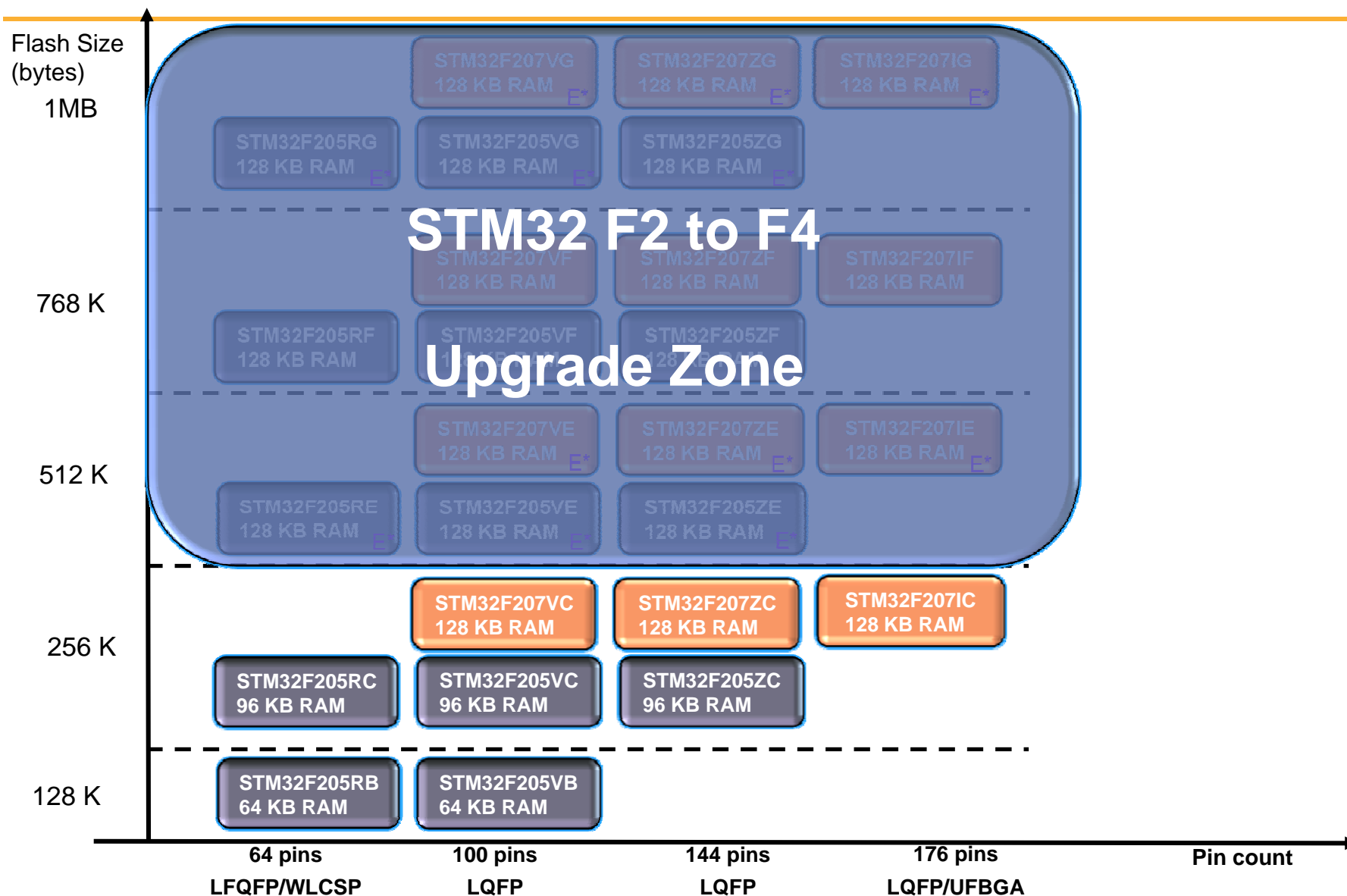| 64 pins	100 pins	144 pins	176 pins	208 pins
LFQFP/WLCSP	LQFP	LQFP	LQFP/UFBGA	UFBGA

Pin count

STMicroelectronics

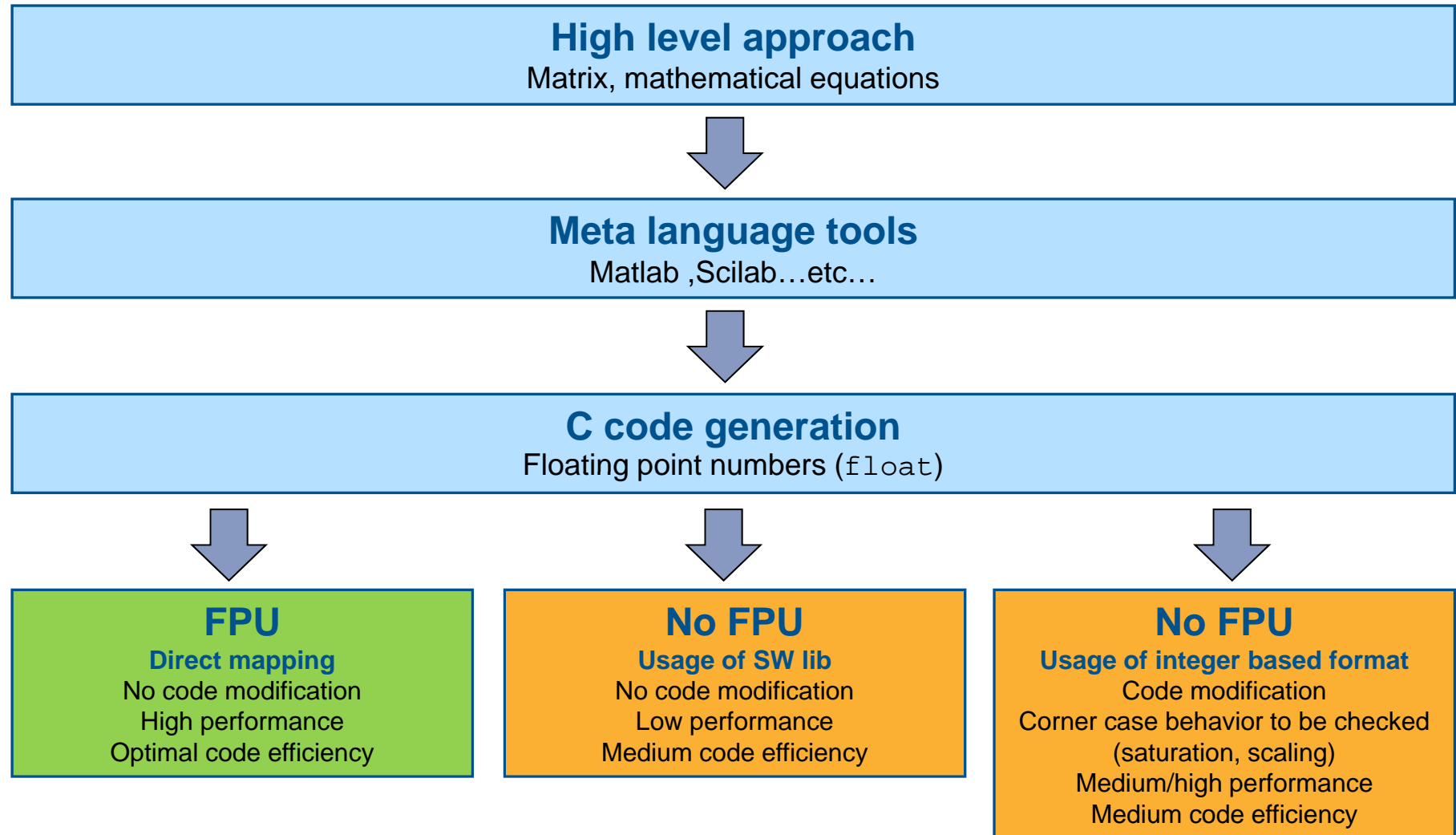# Backup Slides

ARM

STM32 F2 and F4 Series coverage

Starter kits from 3rd parties

- **STM32F4 starter kits from IAR and Keil available in Q4 2011**

- **Order codes:**
  - IAR: STM3240G-SK/IAR
 - KEIL: STM3240G-SK/KEI

FPU benefits and performance

FPU benefits in real life applications

High level approach
Matrix, mathematical equations

Meta language tools
Matlab ,Scilab…etc…

C code generation
Floating point numbers (`float`)

FPU	**No FPU**	**No FPU**
Direct mapping	**Usage of SW lib**	**Usage of integer based format**
No code modification	No code modification	Code modification
High performance	Low performance	Corner case behavior to be checked
Optimal code efficiency	Medium code efficiency	(saturation, scaling)
		Medium/high performance
		Medium code efficiency

Floating point benchmark

- Time execution comparison for a 29 coefficient FIR on float 32 with and without FPU (CMSIS library)

Execution Time

10x improvement
Best compromise
Development time vs.
performance

No FPU   FPU
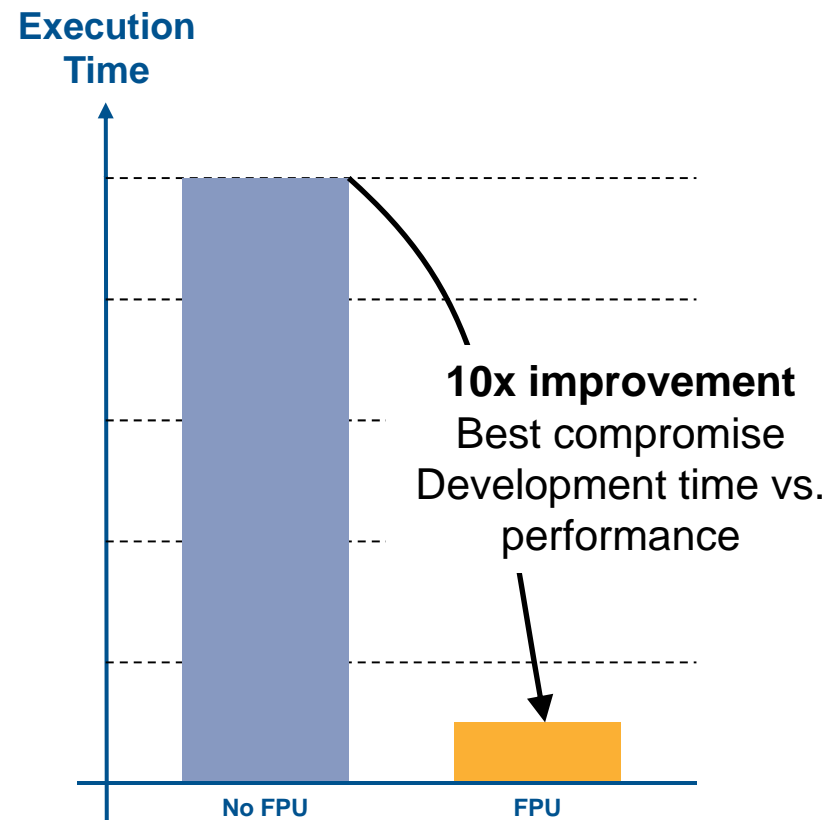
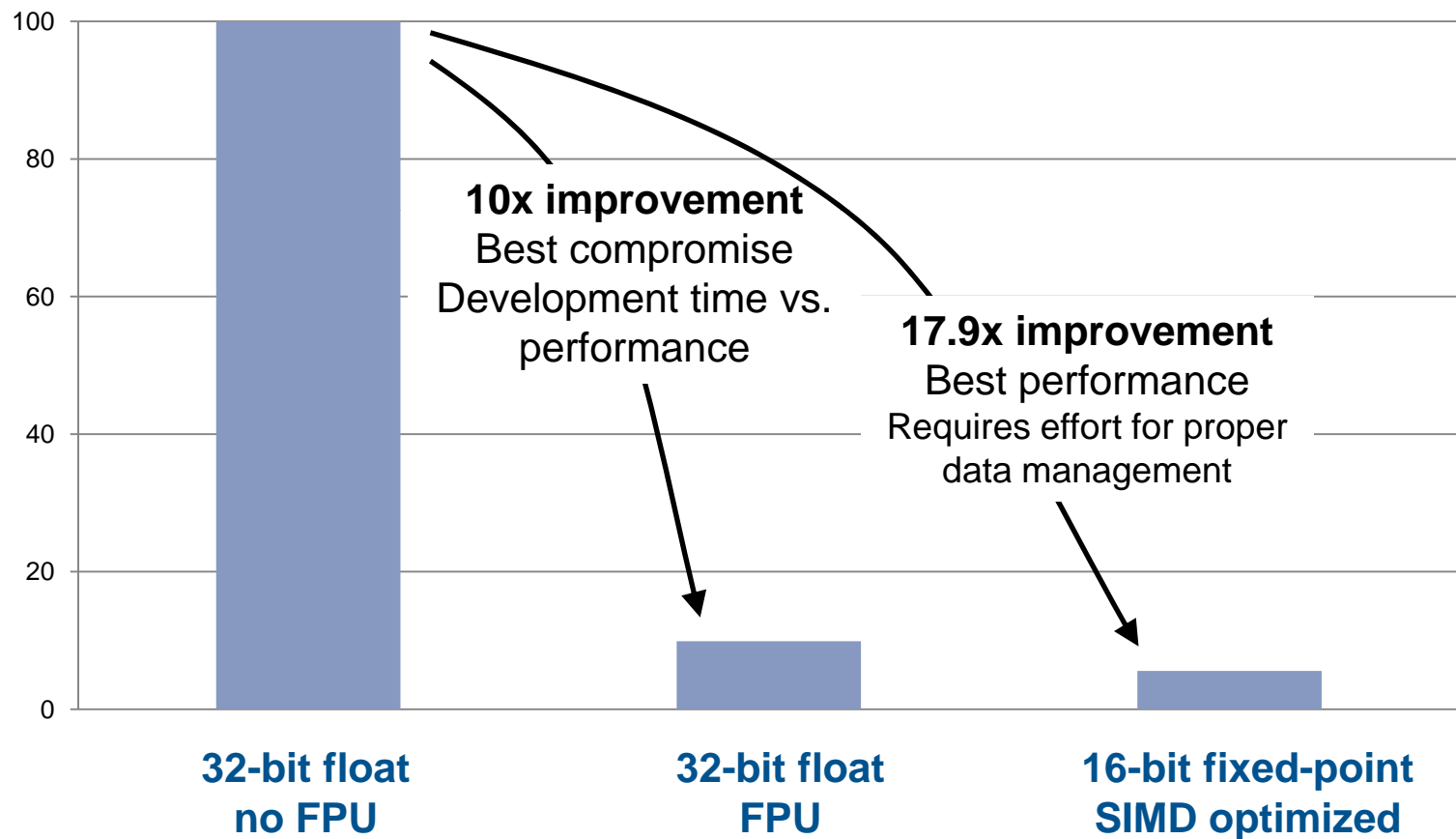# DSP benefits and performance

Single-cycle multiply-accumulate (MAC)

- The multiplier unit allows any MUL or MAC instructions to be executed in a single cycle
    - Signed/Unsigned Multiply
    - Signed/Unsigned Multiply-Accumulate
    - Signed/Unsigned Multiply-Accumulate Long (64-bit)

- **Benefits** : Speed improvement vs. Cortex-M3
    - 4x for 16-bit MAC (dual 16-bit MAC)
    - 2x for 32-bit MAC
    - up to 7x for 64-bit MAC

DSP performances for filtering applications

- **FIR filter** execution time (CMSIS library)

10x improvement
Best compromise
Development time vs.
performance

17.9x improvement
Best performance
Requires effort for proper
data management

**32-bit float
no FPU**

**32-bit float
FPU**

**16-bit fixed-point
SIMD optimized**

ARM Cortex M4 in few words

ARM

Cortex-M processors

- **Forget traditional 8/16/32-bit classifications**
  - Seamless architecture across all applications
  - Every product optimised for ultra low power and ease of use

Cortex-M0	Cortex-M3	Cortex-M4
"8/16-bit" applications	"16/32-bit" applications	"32-bit/DSC" applications

Binary and tool compatible →

Cortex-M processors binary compatible

CORTEX-M0/M1

CORTEX-M3

Cortex-M4

Cortex-M4F

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Cortex — Low-Power Leadership from ARM

ARM Cortex M4 Core

FPU

Single precision
Ease of use
Better code efficiency
Faster time to market
Eliminate scaling and saturation
Easier support for meta-language tools

What is Cortex-M4?

MCU

Ease of use of C
programming
Interrupt handling
Ultra-low power

Cortex-M4

DSP

Harvard architecture
Single-cycle MAC
Barrel shifter

Cortex-M feature set comparison

	Cortex-M0	Cortex-M3	Cortex-M4
Architecture Version	V6M	v7M	v7ME
Instruction set architecture	Thumb, Thumb-2 System Instructions	Thumb + Thumb-2	Thumb + Thumb-2, DSP, SIMD, FP
DMIPS/MHz	0.9	1.25	1.25
Bus interfaces	1	3	3
Integrated NVIC	Yes	Yes	Yes
Number interrupts	1-32 + NMI	1-240 + NMI	1-240 + NMI
Interrupt priorities	4	8-256	8-256
Breakpoints, Watchpoints	4/2/0, 2/1/0	8/4/0, 2/1/0	8/4/0, 2/1/0
Memory Protection Unit (MPU)	No	Yes (Option)	Yes (Option)
Integrated trace option (ETM)	No	Yes (Option)	Yes (Option)
Fault Robust Interface	No	Yes (Option)	No
Single Cycle Multiply	Yes (Option)	Yes	Yes
Hardware Divide	No	Yes	Yes
WIC Support	Yes	Yes	Yes
Bit banding support	No	Yes	Yes
Single cycle DSP/SIMD	No	No	**Yes**
Floating point hardware	No	No	**Yes**
Bus protocol	AHB Lite	AHB Lite, APB	AHB Lite, APB
CMSIS Support	Yes	Yes	Yes

Cortex™
Low-Power Leadership from ARM

DSP lib provided for free by ARM

- **The benefits of software libraries for Cortex-M4**
    - Enables end user to develop applications faster
        - Keeps end user abstracted from low level programming
    - Benchmarking vehicle during system development
    - Clear competitive positioning against incumbent DSP/DSC offerings
    - Accelerate third party software development

- **Keeping it easy to access for end user**
    - Minimal entry barrier - very easy to access and use

- **One standard library – no duplicated efforts**
    - ARM channels effort/resources with software partner
    - Value add through another level of software – eg: filter config tools

Cortex
Low-Power Leadership from ARM

DSP lib function list snapshot

- Basic math – vector mathematics

- Fast math – sin, cos, sqrt etc

- Interpolation – linear, bilinear

- Complex math

- Statistics – max, min,RMS etc

- Filtering – IIR, FIR, LMS etc

- Transforms – FFT(real and complex) , Cosine transform etc

- Matrix functions

- PID Controller

- Support functions – copy/fill arrays, data type conversions etc

Cortex

Low-Power Leadership from ARM

STM32 F4
vs.
STM32 F2

Differences in Core and System Architecture

	STM32 F2	STM32 F4
Core	ARM Cortex M3 (r2p0)	ARM Cortex M4F * (r0p1)
Floating point calculation	s/w	Single precision h/w
Performance / with ART ON	"0ws like" performance thanks to ART Accelerator: 120MHz:1.65V-3.6V	"0ws like" performance thanks to ART Accelerator: 168Mhz: 2.1V–3.6V 144MHz:1.8V–2.1V 128MHz:1.7V–1.8V
SRAM internal capacity	128KB of system memory	192KB (128KB system memory + 64KB dedicated to CPU data)

Differences in Core and System Architecture

	STM32 F2	STM32 F4
Internal Regulator Bypass	Available only on WLCSP64 (IRR_OFF pin) and BGA176 (BYPASS_REG pin) packages On WLCSP64 this functionality can not be dissociated from BOR OFF	Available only on WLCSP64 and BGA176 (BYPASS_REG pin) packages BOR OFF and Internal regulator bypass are non exclusive on the above packages
VDD min extension from 1.8V down to 1.65V (requires BOR OFF) on F2 1.7V (requires BOR OFF) on F4	Available only on WLCSP64 package (IRR_OFF pin) This functionality can not be dissociated from Regulator bypass	Available on all packages (PDR_ON pin) except on LQFP64 pin package This functionality can be dissociated from Regulator bypass
Voltage Scaling (Internal regulator output)	None	Performance Optimization (150 MHz max) Power Optimization (120MHz max)

Differences in Peripheral System Architecture

	STM32 F2	**STM32 F4**
FSMC (improvements)	Remap capability on bank1-NE1/NE2, but no capability to access other banks while remapped	Remap capability on bank1-NE1/NE2, with access to other FSMC banks while remapped.
I2S	2x I2S Half duplex	2x I2S Full duplex.

New RTC implementation

|	STM32 F2	STM32 F4
Calendar Sub seconds access	NO	**YES (resolution down to RTC clock)**
Calendar resolution	From RTCCLK/2 to RTCCLK/2^20	From RTCCLK/1 to RTCCLK/2^22
Calendar read and synchronization on the fly	NO	**YES**
Alarm on calendar	2 alarms Sec, Min, Hour, Date/day	2 alarms Sec, Min, Hour, Date/day, **Sub seconds**

	STM32 F2	STM32 F4
Calendar Calibration	Calib window : **64min** Calibration step: Negative:-2ppm Positive: +4ppm Range [-63ppm+126ppm]	Calib window : **8s/16s/32s** Calibration step: Negative or Positive: 3.81ppm/1.91ppm/**0.95 ppm** Range [-480ppm +480ppm]
Timestamp	YES Sec, Min, Hour, Date	YES Sec, Min, Hour, Date, **Sub seconds**
Tamper	YES (2 pins /1 event) Edge Detection only	YES (2 pins/ 2 events) **Level Detection with Configurable filtering**

Compatible board design for LQFP100-144-176 and BGA 176 packages

F2xx – RFU (reserved for future use) can be connected to VDD/VSS/NC

F4xx – PDR_ON can be connected to VDD or VSS (should be connected to VDD to maintain compatibility with the STM32 family
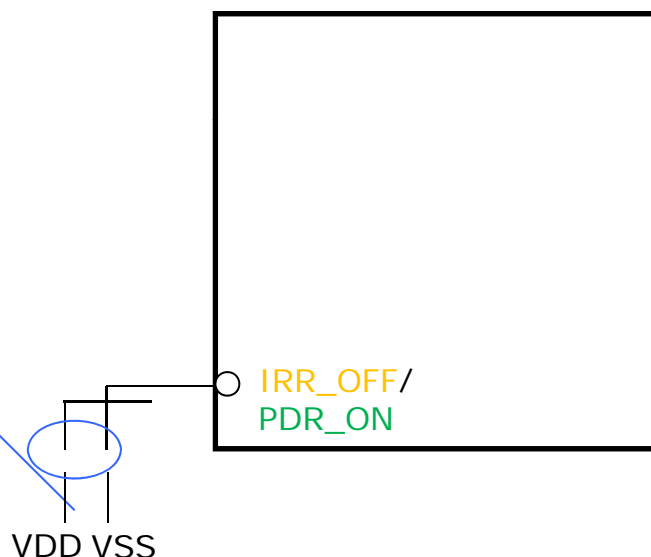
RFU / PDR_ON
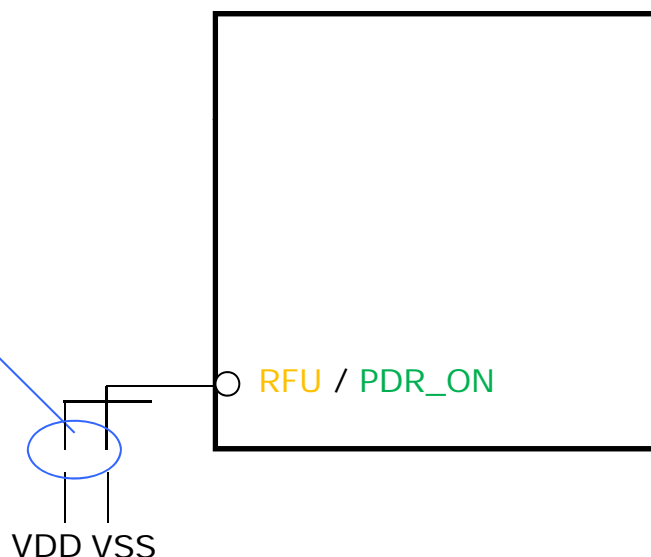
VDD VSS

Compatible board design for WLCSP64+2 package

F2xx – IRR_OFF(Internal Reset and Regulator OFF pin) can be connected to VDD/VSS. The BOR and the Internal Regulator is switched OFF when IRR_OFF is set to VDD.
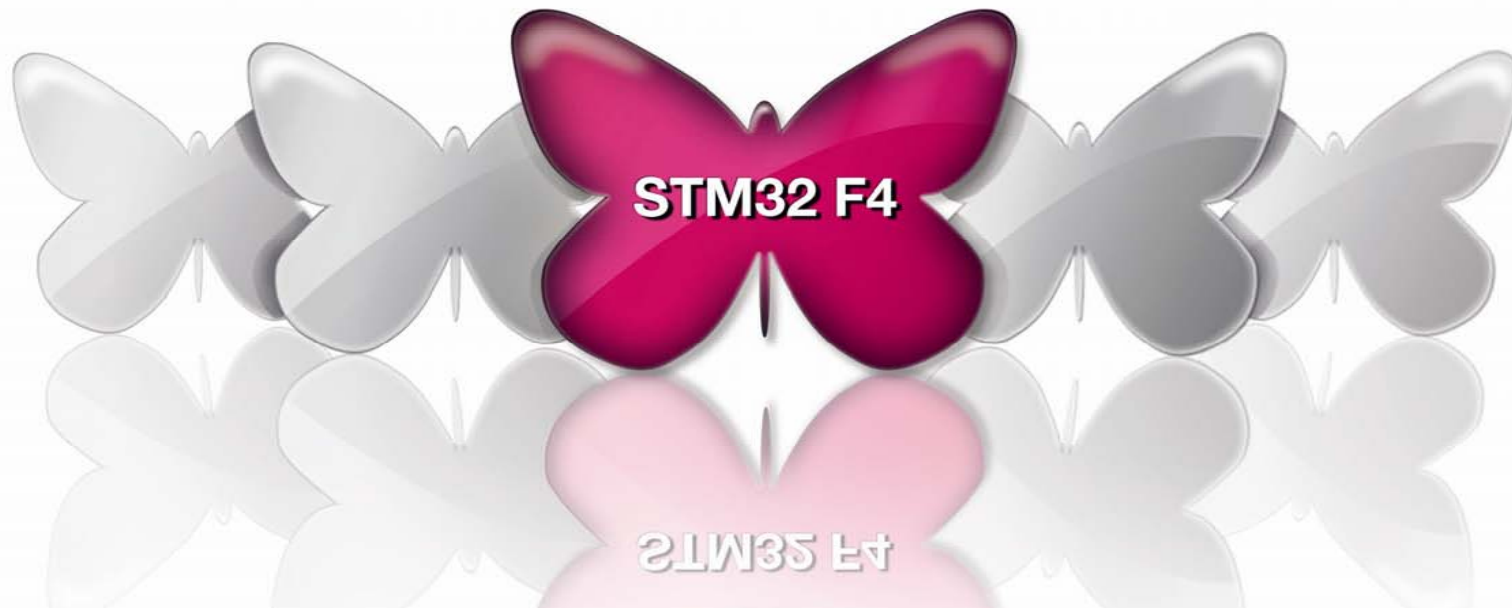
F4xx – PDR_ON (BOR OFF pin). The BOR is switched OFF when PDR_ON pin is set to VSS. (Internal regulator is controlled independently using the BYPASS_REG pin)

IRR_OFF/
PDR_ON

VDD VSS

Thank you

www.st.com/stm32f4

Glossary

- ART Accelerator ™ : ST's adaptive real-time accelerator

- CMSIS: Cortex™ microcontroller software interface standard

- MCU: microcontroller unit

- DSC: digital signal controller

- DSP: digital signal processor

- FPU: floating point unit

- RTC: real-time clock

- MPU: memory protection unit

- FSMC: flexible static memory controller

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