Chapter 1

# Overview of Real-Time Digital Signal Processing

## Introduction

In this first chapter we provide motivation for the topics to be addressed in this course. Before going any further let us first give a short description of the course and the assumed background for the course

### A Brief Description of the Course

- A course in real-time DSP brings together the following:
  - Continuous- and discrete-time systems theory (in particular knowledge from a first DSP course)
  - Software engineering concepts
  - Microprocessor programming and hardware interfacing
- The interest in doing this stems from the increase in real-time DSP applications headed for the consumer market, and the ever improving device VLSI designs for implementing powerful DSP microprocessors

- Many years ago, Texas Instruments created the following long list of DSP real-time application areas

| Automotive | Consumer | Control |
|---|---|---|
| Adaptive ride control | Digital radios/TVs | Disk drive control |
| Antiskid brakes | Educational toys | Engine control |
| Cellular telephones | Music synthesizers | Laser printer control |
| Digital radios | Pagers | Motor control |
| Engine control | Power tools | Robotics control |
| Navigation and global positioning | Radar detectors | Servo control |
| Vibration analysis | Solid-state answering machines | |
| Voice commands | | |
| Anticollision radar | | |
| **General-Purpose** | **Graphics/Imaging** | **Industrial** |
| Adaptive filtering | 3-D rotation | Numeric control |
| Convolution | Animation/digital maps | Power-line monitoring |
| Correlation | Homomorphic processing | Robotics |
| Digital filtering | Image compression/transmission | Security access |
| Fast Fourier transforms | Image enhancement | |
| Hilbert transforms | Pattern recognition | |
| Waveform generation | Robot vision | |
| Windowing | Workstations | |
| **Instrumentation** | **Medical** | **Military** |
| Digital filtering | Diagnostic equipment | Image processing |
| Function generation | Fetal monitoring | Missile guidance |
| Pattern matching | Hearing aids | Navigation |
| Phase-locked loops | Patient monitoring | Radar processing |
| Seismic processing | Prosthetics | Radio frequency modems |
| Spectrum analysis | Ultrasound equipment | Secure communications |
| Transient analysis | | Sonar processing |
| **Telecommunications** | | **Voice/Speech** |
| 1200- to 33 600-bps modems | Faxing | Speaker verification |
| Adaptive equalizers | Line repeaters | Speech enhancement |
| ADPCM transcoders | Personal communications systems (PCS) | Speech recognition |
| Cellular telephones | Personal digital assistants (PDA) | Speech synthesis |
| Channel multiplexing | Speaker phones | Speech vocoding |
| Data encryption | Spread spectrum communications | Text-to-speech |
| Digital PBXs | Video conferencing | Voice mail |
| Digital speech interpolation (DSI) | X.25 packet switching | |
| DTMF encoding/decoding | | |
| Echo cancellation | | |

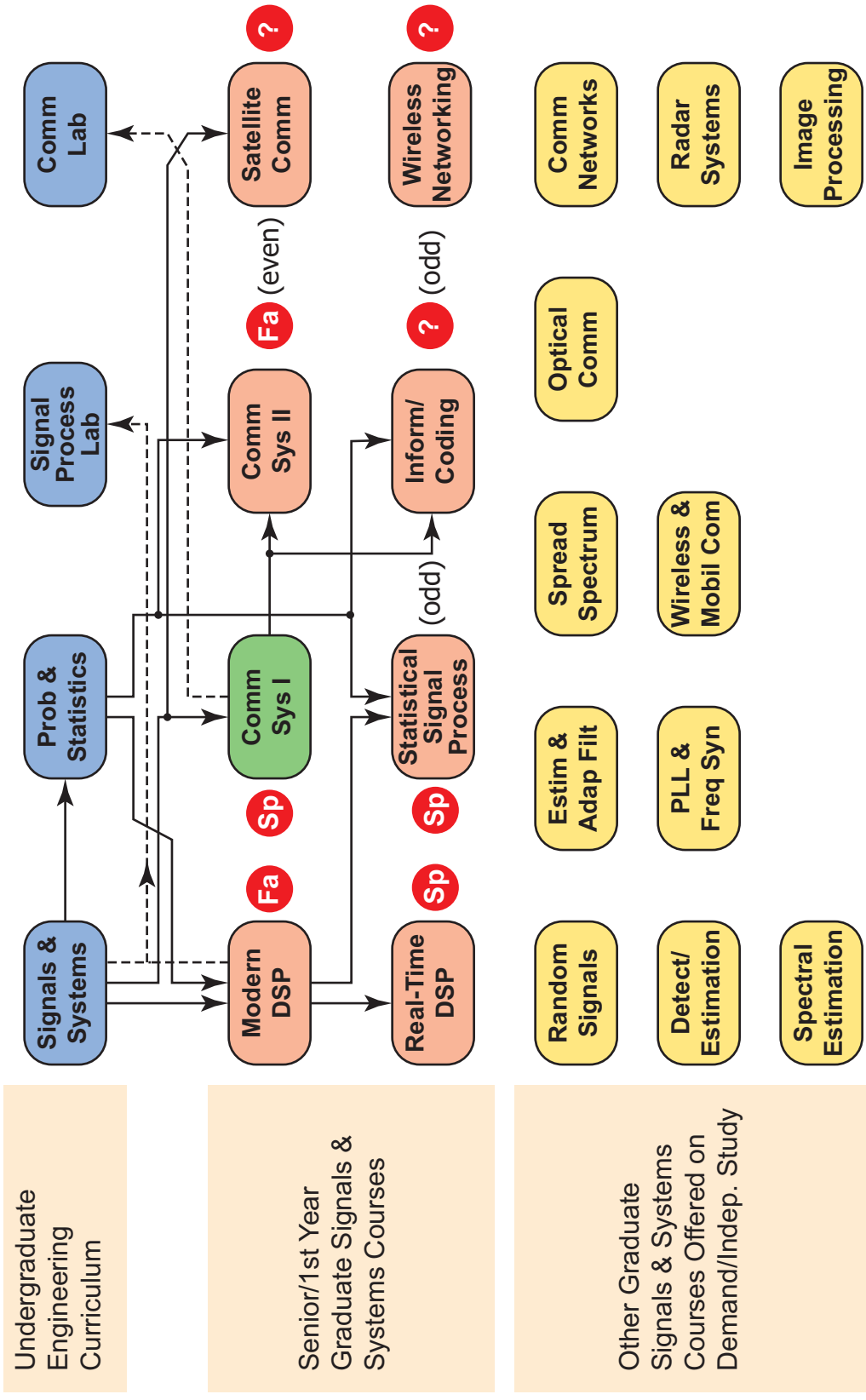
- Today (2020) the list is longer, but some of the above DSP applications are no longer a going concern, e.g., 1200 to 33600-bps telephone modems
  - Do you remember using telephone channel modems, or too young?

- This course is about the use of general purpose digital signal processing microprocessors for solving signal processing problems in real-time
- The course focus will be on using the ARM Cortex M series, specifically the M4 processor for general purpose DSP
- Prior to 2015 this course was taught using the Texas Instruments (TI) C6x family fixed/floating processors
- The course will start out considering general signal processing applications of real-time DSP and the associated programming issues
  - Later in the course, a focus applications area will be wireless communication system design using DSP algorithms
- The books chosen for the course, Reay and Yiu focus on real-time DSP using an Cortex-M4 device and the intimate details of Cortex-M3 & M4programming, respectively
- The course meeting time will be used for lecturing and laboratory time (about 60/40) using hardware/software development tools
  - Tools: MDK–ARM development environment for Cortex and ARM devices
  - Specifically MDK-ARM v5.x (also denoted as µVision) is a product of the ARMKEIL microcontroller tools group in Germany
  - Note: I have considered switching to an Eclipse IDE such as STM32CubeIDE or MCUXpressoIDE

## Background Requirements

- The required background for all students taking the course is an introductory graduate or junior/senior level undergraduate course in DSP and experience programming in ANSI C
- Knowledge of ANSI C is required in order to develop real-time algorithm in a high level language (HLL)
- At this point it is unlikely that we do any assembly language programming (I'm looking at my options in this area)
- Eventually, and in practice, you use a combination of C and assembly, e.g., mixed language programming
- That said, for the Coretex M we have at our disposal the CMSIS-DSP
- Programming the PC host in C/C++, or perhaps some other language, may be useful for developing a user interactive application for the final project
- Familiarity with test equipment e.g., signal generators, digital scopes, and a spectrum/network analyzer would be helpful

# Course Perspective



# The *Way-back* History of DSP in the Context of Real-Time Processing

- From a systems engineering point of view DSP stands for digital signal processing, but in the world of real-time hardware, systems people often refer to digital signal processing solutions (DSPS)
- The decades of DSP/DSPS have brought the following[1]

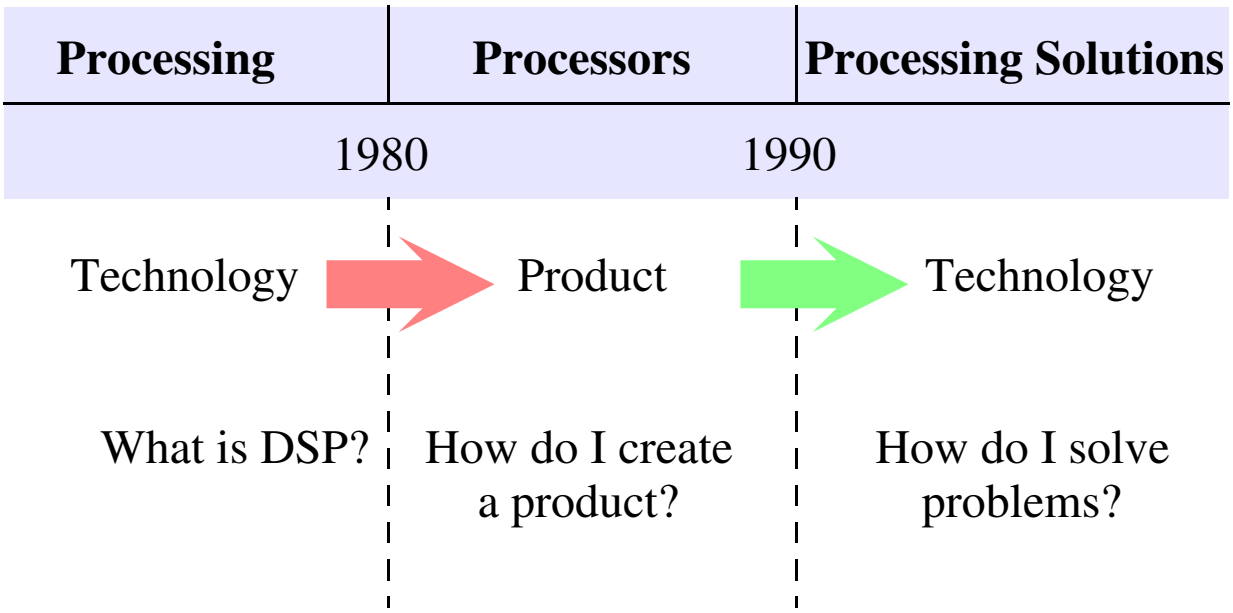
Table 1.1: Decades of DSP

| Decade | Characteristic | $/MIPS |
|---|---|---|
| ‘60s | University Curiosity | $100–$1,000 |
| ‘70s | Military Advantage | $10–$100 |
| ‘80s | Commercial Success | $1–$10 |
| ‘90s | Consumer Enabler | $0.10–$1 |
| Beyond | Expected Part of Daily Life? | $0.01–$0.10 |

- The dates here are very old, but it is clear we arrived at the “Expected Part of Daily Life” a long time ago

1. Gene A. Frantz, “TI’s DSPS Future,” *Texas Instruments DSPS Fest ‘97*, Houston, TX, July 1997.

- Another way of looking at this is (Frantz)




- We are well beyond the time line shown above, so what has been happening in the last 22 years?
  - DSP is definitely mainstream in most everything electronic
  - general purpose DSP processors are only part of the picture; FPGA drives the government/military applications side, and ARM processors drive the consumer product side
  - In the last few years we have also seen more multi-core micro controller devices

## Great Moments in DSPS History[1]

- 1976 – DSP is used to simulate a voice in the educational product "Speak and Spell"
- 1982 – TI announces details on the TMS32010 which executes at 5 MIPS
- 1985 – DSP is used in a modem for the first time
- 1986 – Lotus automotive uses DSP in active suspension and noise abatement in racing cars
- 1988 – First DSP hearing aid introduced
- 1991 – First TI sponsored educators conference
- 1993 – Cadillac automotive introduces a DSP-based ride control system
- 1995 – TI implements the *On-line DSP Lab™* for Web based testing of DSP applications
- 1997 – 15 years of DSPs for TI and
  - The introduction of the TMS320C6x family of DSPs 1,600 MIPS performance (C62x)
  - The 1-v barrier in power consumption reached
  - In late 1997 the first C6x floating point part is announced (C67x) with 1 GFLOPS performance
- *Fast forward* to 2022?

1. "Great Moments in DSPS History," *Integration: An Update on Texas Instruments Semiconductors*, vol. 14, No. 4, June 1997.

## DSP Integration (Frantz)

Table 1.2: DSP Integration over three decades.

| | Typical 1982 DSP | Typical 1992 DSP (97) | Typical 2002 DSP |
|---|---|---|---|
| Die size | 50 mm | 50 mm | 50 mm |
| Technology size | 3 μ | 0.8 (.35) μ | 0.18 μ |
| MIPS | 5 | 40 (100) | 2000 |
| MHz | 20 | 80 (200) | 500 |
| RAM (words) | 144 | 1 K | 16 K |
| ROM (words) | 1.5 K | 4 K | 64 K |
| Price | $150.00 | $15.00 | $1.50 |
| Pwr. Dissp. | 250 mW/ MIP | 12.5 mW/ MIP (1) | 0.1 mW/MIP |
| Transistors | 50 K | 500 K | 5 M |
| Wafer Size | 3” (75 mm) | 6” (150 mm) | 12” (300 mm) |

- Where are we at in 2022?
  - Not an easy find comparison like the above, but here there is a nice Wiki page for the Cortex-M series: https://en.wikipedia.org/wiki/ARM_Cortex-M

## Communications and Wireless

- In the distant past two key application areas, telephone line modems and cellular voice/data communications, had a major impact on DSPS sales
- In 1994 when the V.34 modem standard (28.8 kbps) was approved fixed point (integer) DSPs became a popular design route
  - The V.34 standard allowed for data rates from 2400 to 28,800 bps
  - In late 1994 these modems cost ~$400, today we know that 28,800 modems (dial-up) are little used
- In the cellular telephone arena fixed point DSPs still have their place (more likely as cores in a larger ASIC)
- DSPs are also utilized in VoIP and cellular basestations
  - In a portable device market, such as cell phones, the efficiency of a particular processor can be measured in mW/algorithm, which is obtained via

$$\frac{\text{mW}}{\text{algorithm}} = \frac{\text{mA}}{\text{MIPS}} \times \frac{\text{MIPS}}{\text{algorithm}} \times \text{voltage}$$

- MIPS/algorithm requirements for an IS95 handset[1]

Table 1.3: MIPS requirements for an IS95 handset.

| Algorithm | Implement ation | MIPS |
|---|---|---|
| Correlator | Hardware | 5 |
| Automatic frequency control (AFC) | Hardware | 5 |
| Automatic gain control (AGC) | Hardware | 5 |
| Transmit filter | Hardware | 30 |
| 128-pt FFT | Software | 1 |
| Viterbi decoder (length 9, rate 1/2) | Software | 6 |
| Vocoder (8-Kbps Qualcomm code excited linear prediction (QCELP)) | Software | 20 |
| Vocoder (enhanced variable rate coder (EVRC)) | Software | 30 |

# DSP Hardware Design Issues[2]

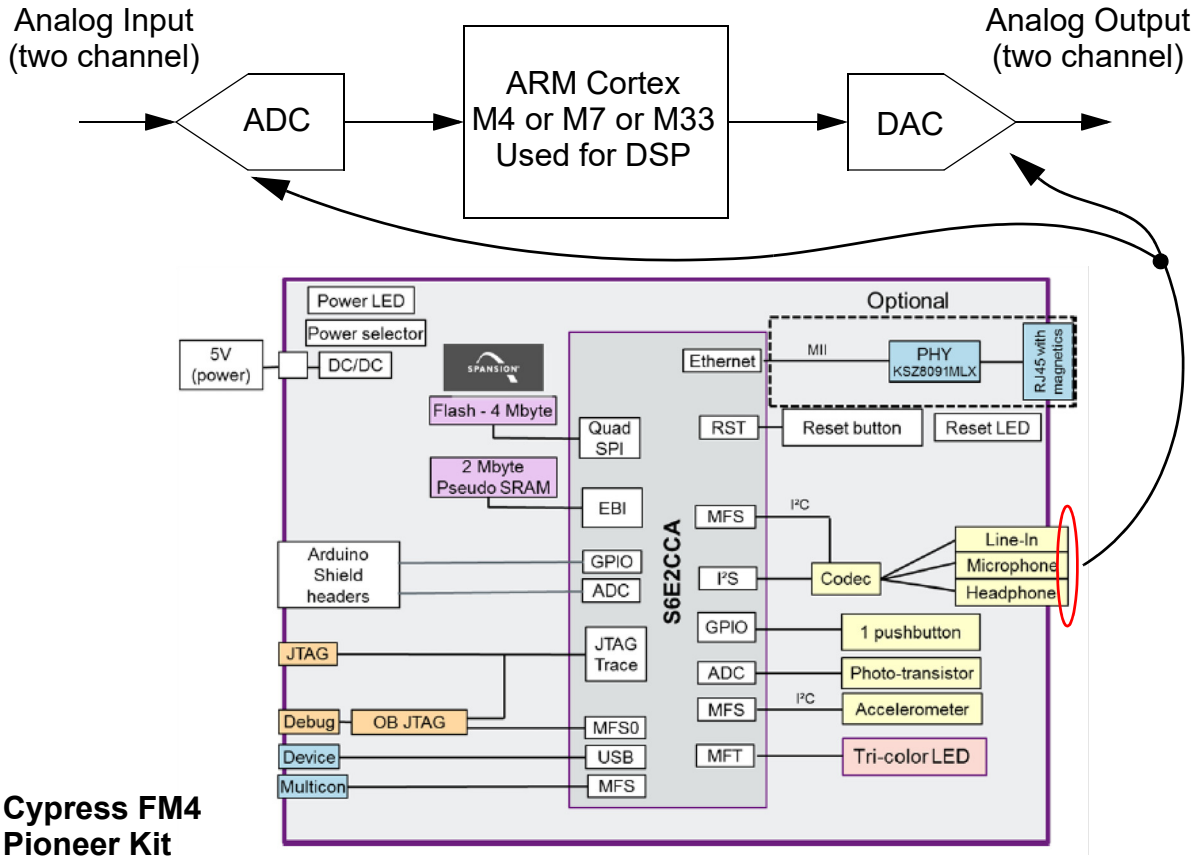
- Hardware alternatives, FPGA, ASIC
- Using a general purpose DSP
- Fixed-Point DSPS
  - Fixed-point arithmetic

1. John Groe and Lawrence Larsen, *CDMA Mobile Radio Design*, Artech House, Boston, MA, 2000.
2. Craig Marven and Gillian Ewers, *A Simple Approach to Digital Signal Processing*, John Wiley, 1996. ISBN 0-471-15243-9.

  - Quantization effects and scaling in fixed point
  - Typically a lower power design
  - Typically a lower cost design
- Floating Point DSPS
  - A more rapid design due to the ease of floating point algorithm implementation
  - The Cortex M4 can have one hardware multiply and accumulate function to allow rapid prototyping of algorithms
  - The Cortex M7 can have two hardware multiply and accumulate functions in hardware
  - The CMSIS-DSP library includes fixed and floating point algorithms
- Accessing memory resources
- Integration of peripheral devices
- A very practical alternative today is to consider a hybrid FPGA/general purpose DSP architecture
- Application Design
  - Software design
  - Generating assembler source and using C where possible
  - Testing the code
  - Hardware design
  - System integration

# Systems Level M4 or M7 or M33 Hardware

- Many hardware/dev kit options available:
  - The Reay focuses on the TI Tiva TM4C123G (M4) + Audio Booster Pak (~80MHz), but this did not take-off
  - From 2016 to 2021 Cypress/Infineon FM4 (M4) (200 MHz clock) has been a great platform and Reay added support for it (the platform of choice for this course)
  - The STM32F746 (M7) (~212 MHz) is now used by ARM for DSP Education Kit on GitHub (availability)
  - Others? Yes! More discussion at the end of this chapter
- FM4 (`FM4-176L-S6E2CC-ETH`) detail:




**Cypress FM4 Pioneer Kit**

# Course Laboratory Foundations

- Beyond DSP math, you need to work with a variety of software and hardware, including measurement equipment

## Software

- MDK–ARM (Keil) development platform
  - Most of the time the free version is sufficient
  - Can easily switch to the full version using the license server (see the link on the right column of the course home page)
  - There are also open-source GCC based integrated development environments available for the M4/M7/M33
- Jupyter notebook, in browser or VS Code, for all calculation needs
  - There is a learning curve to get going with Python, but the fact that the tools are readily available is powerful motivation to *take the plunge*
  - Real-time DSP using *pyaudio_helper* running in *Jupyter*
- *GoldWave* or *Audacity* shareware for .wav audio file manipulation

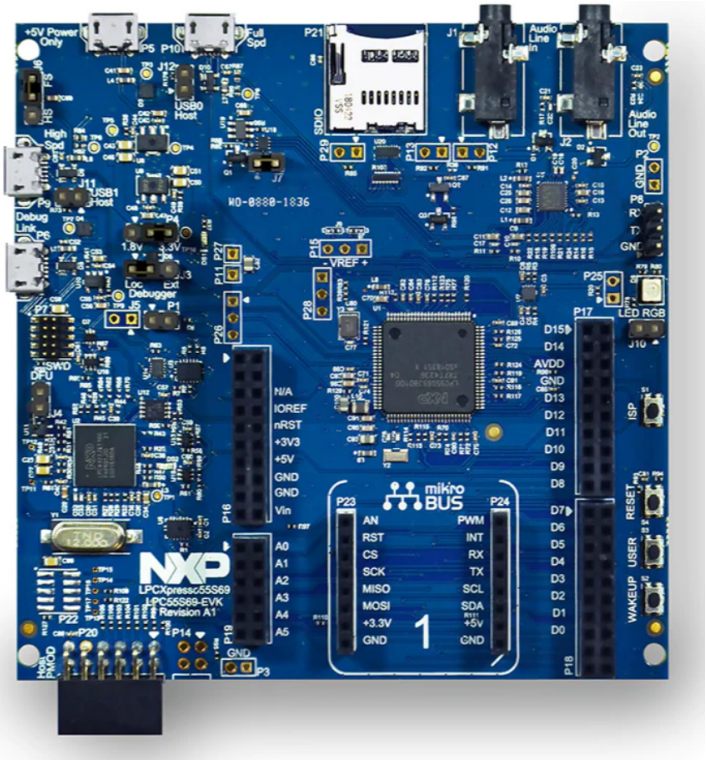
### Test Equipment

- For all of your measurement needs the Digilent *Analog Discovery* (or the new version 2) may be adequate (see in-class demo and syllabus for details)
  - With the Analog Discovery 2 you have a highly portable set of instruments with the software running on a PC/Mac/Linux
  - This would allow you to work from home
- Keysight DSOX6004A four-channel 1 GHz digital scopes (20 Gsps)
- Agilent function/arbitrary waveform generators; 15 MHz and 80 MHz models, and the new Keysight 33600A True*f*orm, two channel generators
- Agilent 10 Hz – 500 MHz spectrum/vector network analyzers
- For RF/microwave front-ends we have the Keysight FieldFox N9914A, 100 kHz – 6.5 GHz spectrum/vector network analyzers

## Interesting Boards Beyond the Cypress FM4

- New dev-kit boards are appearing all the time
- During my Fall 2020–Spring 2021 sabbatical I began to invest serious time a few new boards, knowing the FM4 would soon be gone
- Early Fall 2021 I acquired yet another board

# NXP LPC55S69-EVK with PowerQuad co-processor




## NXP EVK Description

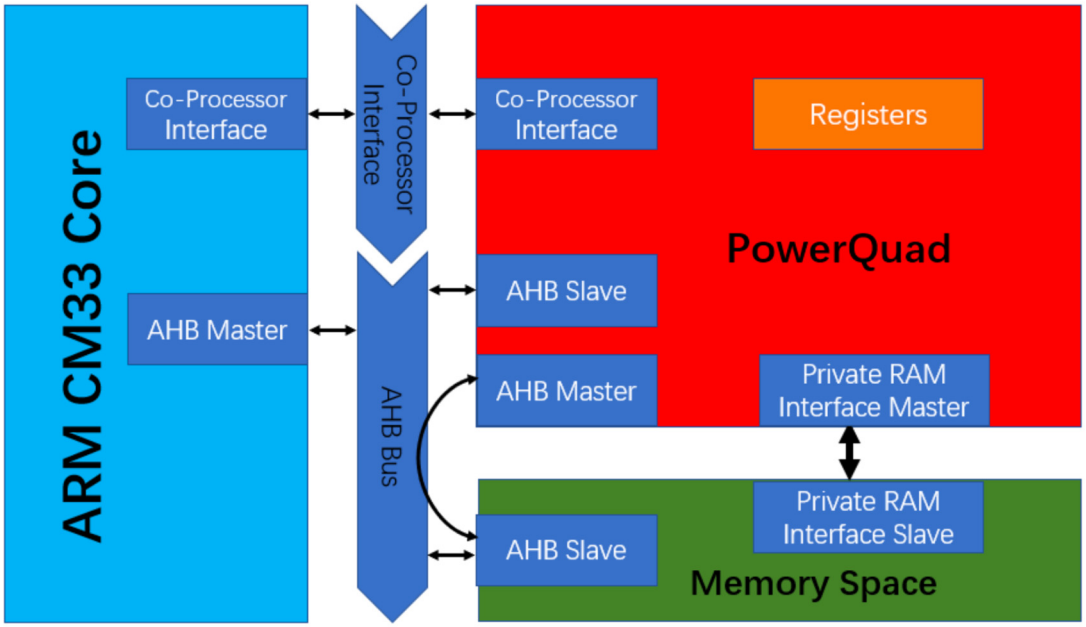
The LPC55S69 development board provides the ideal platform for evaluation of and development with the LPC55S6x MCU based on the Arm® Cortex®-M33 architecture. The board includes a high performance onboard debug probe, audio subsystem and accelerometer, with several options for adding off-the-shelf add-on boards for networking, sensors, displays, and other interfaces.

The LPC55S69 is fully supported by the MCUXpresso suite of tools, which provides device drivers, middleware and examples to allow rapid development, plus configuration tools and an optional free IDE. MCUXpresso software is compatible with the open source MCU operating system FreeRTOS, tools from popular tool vendors such as Arm and IAR, and the LPCXpresso55S69 may also be used with the popular debug probes available from SEGGER and P&E Micro.

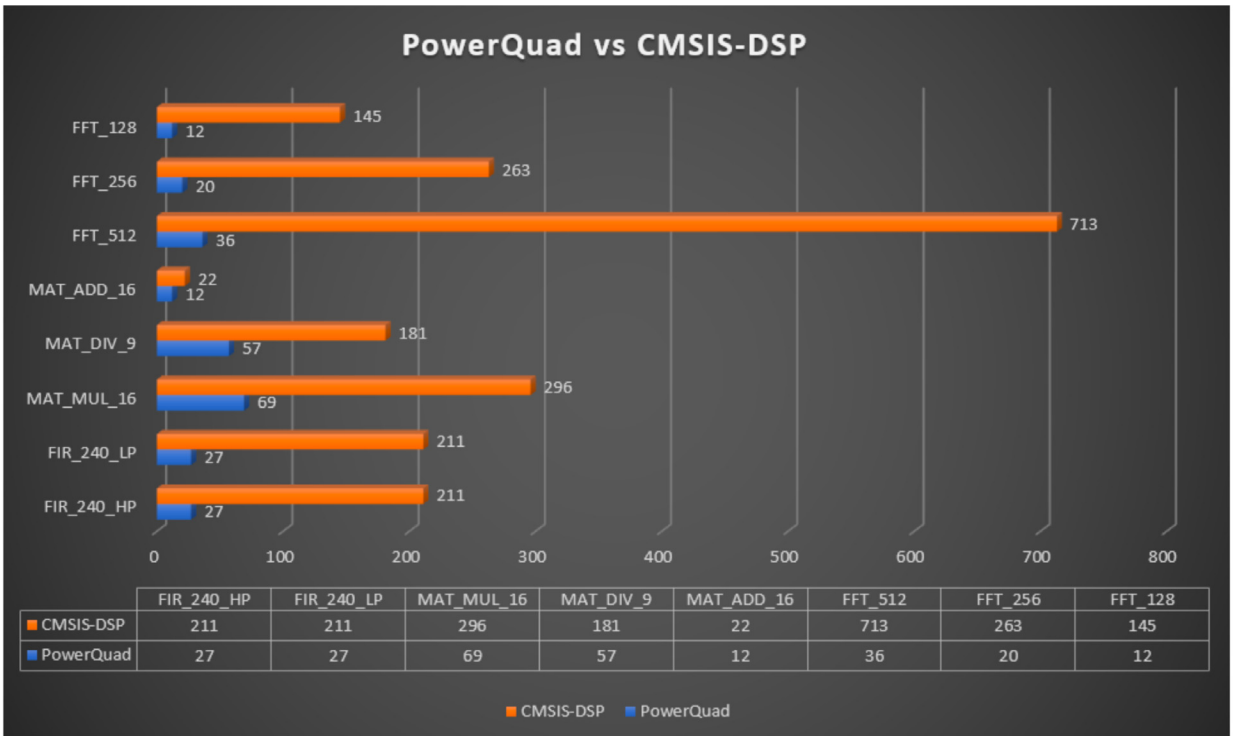
| | |
|---|---|
| **Microcontroller** | ▪ LPC55S69 dual core Arm Cortex-M33 microcontroller running at up to 150 MHz. |
| **Memory Expansion** | ▪ Micro SD card slot (4-bit SDIO). |
| **Connectivity** | ▪ UART and SPI port bridging from LPC55S69 target to USB via the onboard debug probe.<br>▪ High and full speed USB ports with micro A/B connector for host or device functionality. |
| **Debug** | ▪ Onboard, high-speed USB, Link2 debug probe with CMSIS-DAP and SEGGER J-Link protocol options.<br>▪ Hardware support for external debug probe. |
| **Sensors** | ▪ NXP MMA8652FCR1 accelerometer |
| **Audio** | ▪ Stereo audio codec with a line in/out |
| **Expansion Options** | ▪ MikroEletronika Click expansion option<br>▪ LPCXpresso-V3 expansion connectors compatible with Arduino® UNO Rev3<br>▪ PMod compatible expansion / host connector |
| **User Interface** | ▪ RGB user LED, plus Reset, ISP, Wake, and user buttons |

– The PowerQuad hardware functions and block diagram:

| Class | Function | Comments |
|---|---|---|
| Math | 1/x, ln(x), sqrt(x), 1/sqrt(x), e^(x), e^(-x), (x1) / (x2), sin(x), cos(x) | coprocessor instruction |
| | arctan(x), arctanh(x) | |
| Filter | • 2nd order IIR filter | coprocessor instruction |
| | • FIR filter<br>• FIR filter incremental<br>• Correlation<br>• Convolution | |
| Matrix | • Scale<br>• Addition<br>• Subtraction<br>• Invert<br>• Profuct<br>• Hadamard product (elementwise product)<br>• Transpose<br>• Dot product | - |
| Transform | • Complex FFT (complex-valued input sequence)<br>• Real FFT (real-valued input sequence)<br>• Inverse FFT<br>• Complex DCT (complex-valued input sequence)<br>• Real DCT (real-valued input sequence)<br>• Inverse DCT | - |

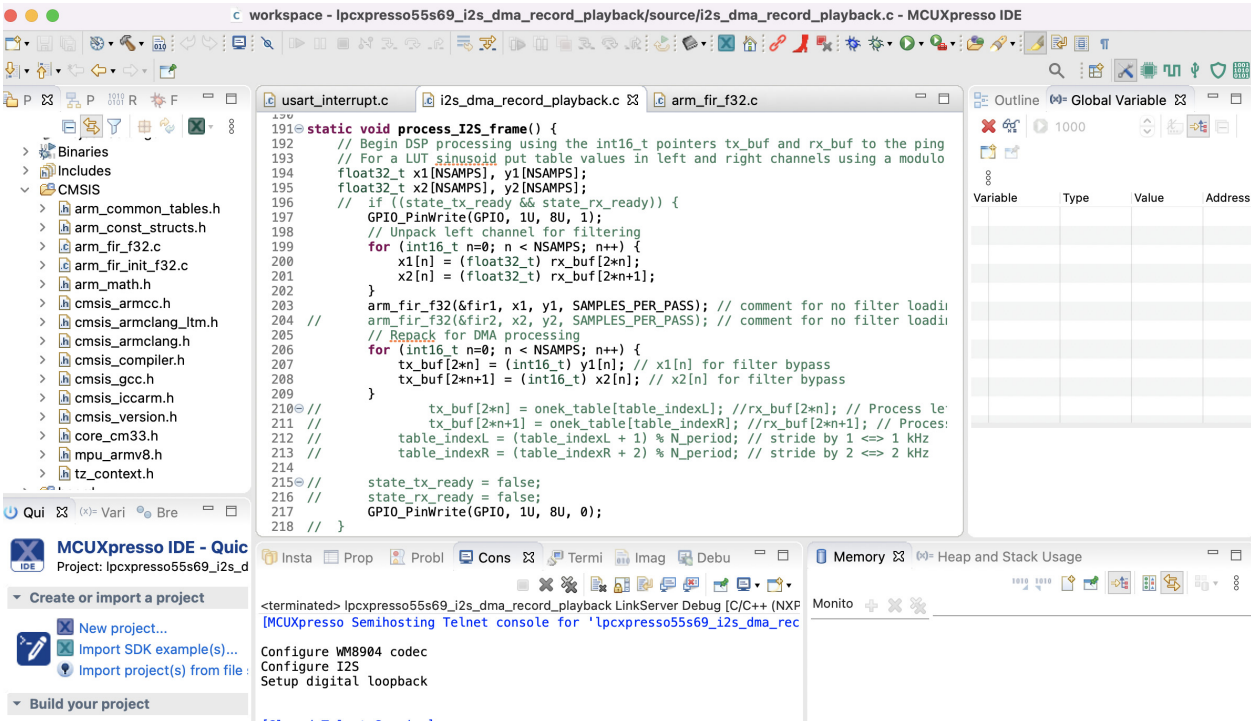


– The PowerQuad performance over pure CMSIS-DSP is amazing



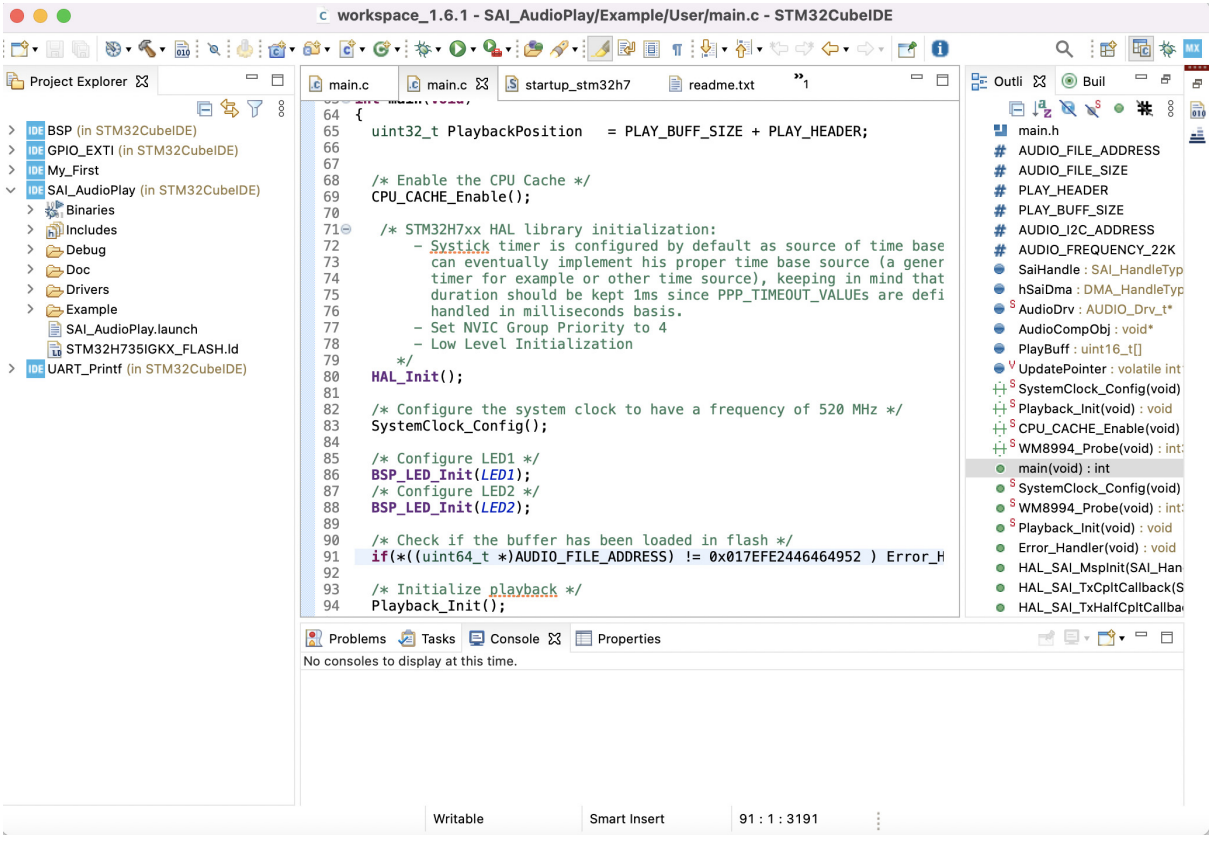

| | FIR_240_HP | FIR_240_LP | MAT_MUL_16 | MAT_DIV_9 | MAT_ADD_16 | FFT_512 | FFT_256 | FFT_128 |
|---|---|---|---|---|---|---|---|---|
| CMSIS-DSP | 211 | 211 | 296 | 181 | 22 | 713 | 263 | 145 |
| PowerQuad | 27 | 27 | 69 | 57 | 12 | 36 | 20 | 12 |

- Availability and price $49.95
- DMA code for DSP is written and tested at 48 ksps

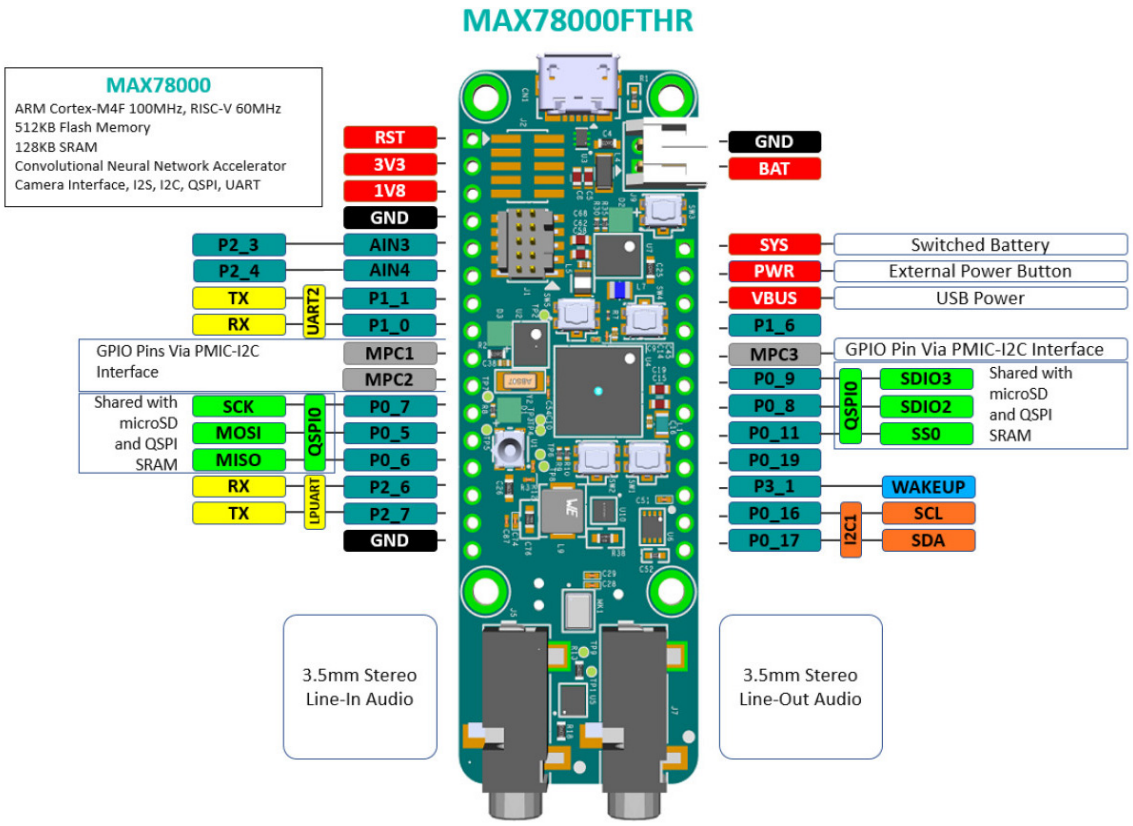


## The STM32H735G

- This board came out Fall 2020 and is available for $107.40
- Being an M7 is has two MACs per clock and is clocked at a very fast 520 MHz
- I have not been abale to find an easy -out-of-the-box audio loop through example
- STMicroelectronics does maintain a Git repo for all of its ortex M boards:
- Given more time I think this board could be a nive replace-ment for the FM4



# The Maxim MAX78000 FTHR



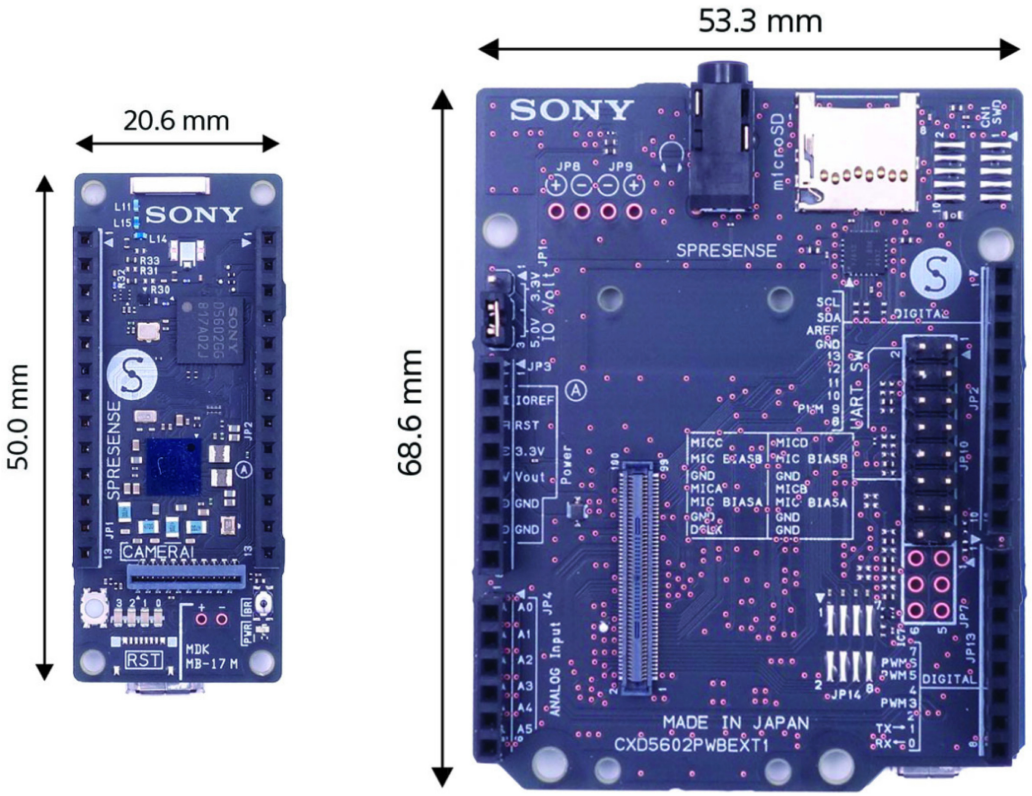

# The Sony SPRESENSE 6-core Cortex-M4 with baseboard

## Spresense combines multi-core and power efficiency

Spresense is a compact development board based on Sony's power-efficient multicore microcontroller CXD5602. It allows developers to create applications in a very short time and is supported by the Arduino IDE as well as the more advanced NuttX based SDK.

- **Integrated GPS** - The embedded GNSS with support for GPS, QZSS and GLONASS enables applications where tracking is required.
- **Hi-res audio output and multi mic inputs** - Advanced 192kHz/24 bit audio codec and amplifier for audio output, and support for up to 8 mic input channels.
- **Multicore microcontroller** - Spresense is powered by Sony's CXD5602 microcontroller (ARM® Cortex®-M4F × 6 cores), with a clock speed of 156 MHz.

– Potential usage in ECE 4655/5655 is the main board + extension board




Main Board Extension Board

– Development