

FPGA Technology and Industry Experience

Guest Lecture in the context of the VLSI III course at D-ITET, ETH Zurich

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 - Company Profile
- FPGA Basics
 - Programmable Logic History
 - FPGA Architecture
 - FPGA Design Flow
 - Market Overview
- The Case for FPGAs
 - Unique Selling Points
 - FPGA vs. ASIC
 - FPGA vs. DSP
 - FPGA vs. uC
- Real-World FPGA Applications
 - Software Defined Radio
 - Linux on FPGA
- Example Project
 - Motion Control
- Conclusions
 - Field Update
 - „Featuritis“
 - Outsourcing
 - Skills
 - How to Stand Out
- Outlook & Trends

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- **Outlook & Trends**

- Quick Facts
 - Founded in 2004
 - Located at Technopark Zurich
 - Currently 6 FPGA Engineers
 - Vendor-Independent
- FPGA Design Center
 - FPGA-Related Design Services
 - Firmware (VHDL/Verilog)
 - Hardware (incl. analog and digital interfaces)
 - Embedded Software (for FPGA soft processors)
- FPGA Solution Center
 - FPGA Modules
 - Mars, Mercury and Saturn
 - IP Cores
 - TFT Display Controller
 - Universal Drive Controller
 - Etc.



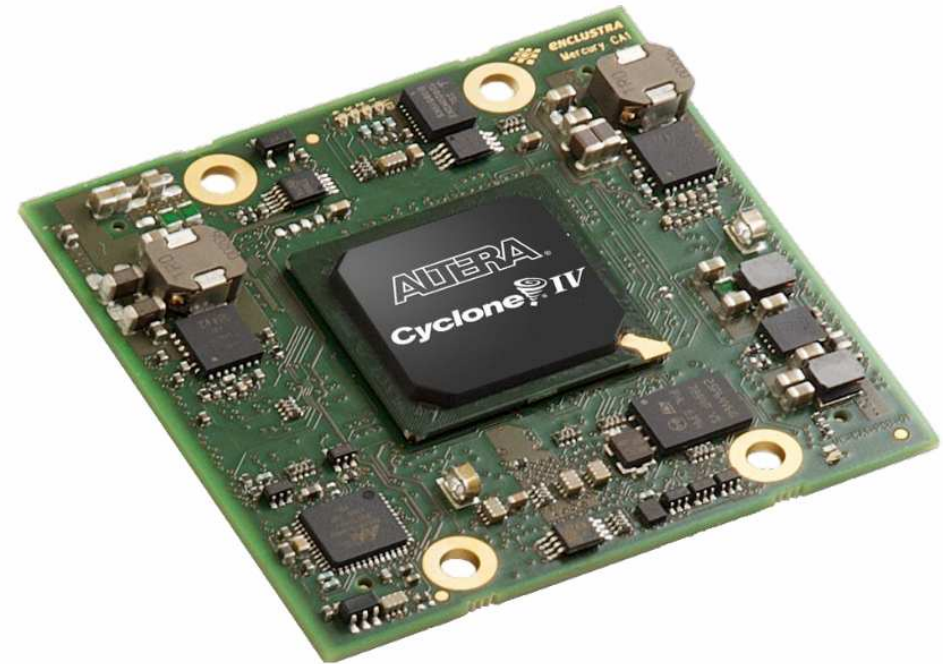
Mars MX1/MX2 FPGA Module

- Low-cost, low-power Spartan-6 FPGA
- SO-DIMM form factor
- Single supply voltage
- 16 MB quad SPI Flash
- 256 MB DDR2 SDRAM
- Dual Fast Ethernet (MX1 only)
- Real time clock (MX1 only)
- Gigabit Ethernet (MX2 only)
- Dual multi-gigabit transceivers (MX2 only)
- PCIe endpoint (MX2 only)



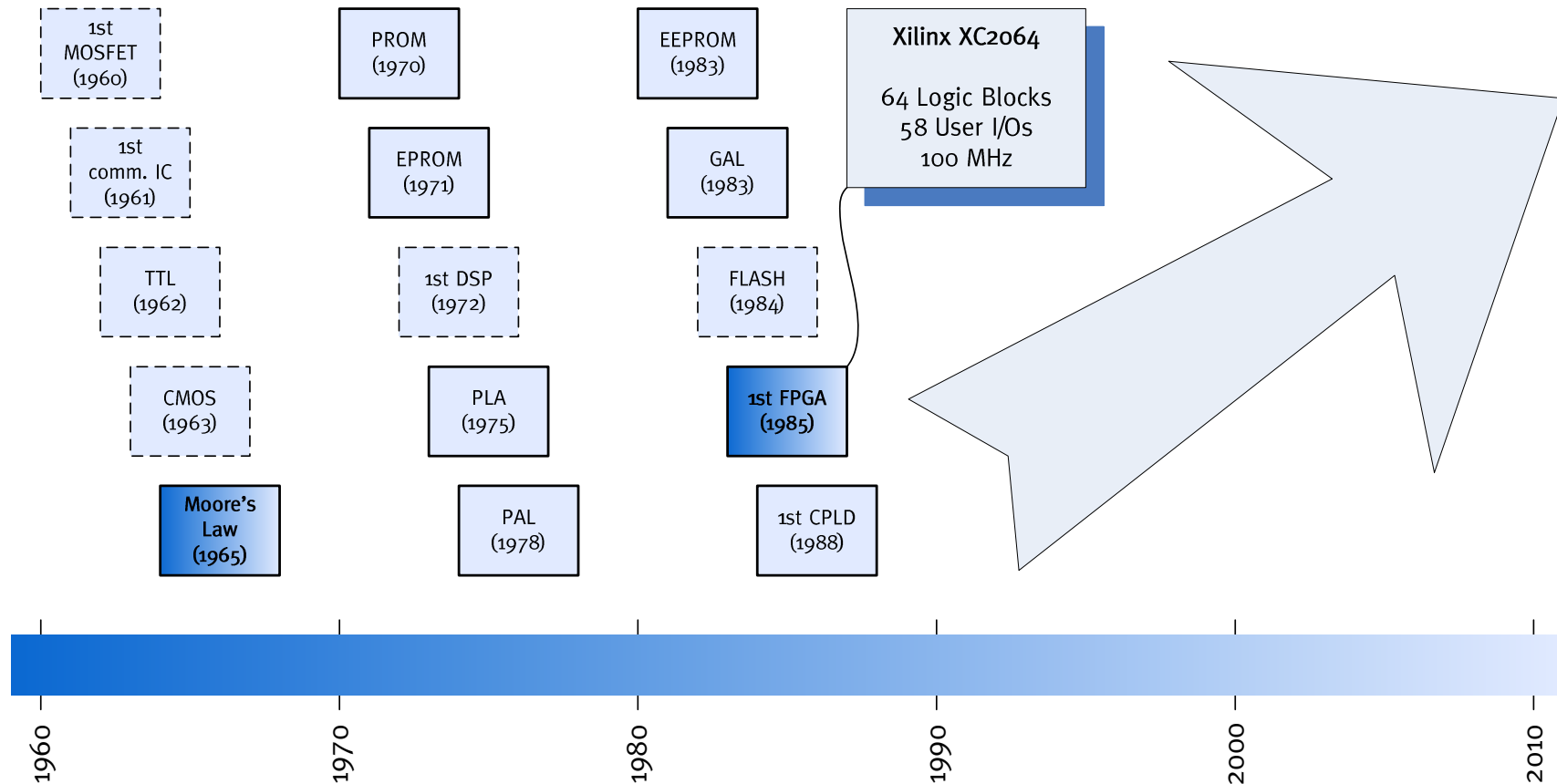
Mercury CA1 FPGA Module

- Low-cost Cyclone IV FPGA
- Single supply voltage
- 16 MB SPI Flash
- 256 MB DDR2 SDRAM
- Gigabit Ethernet PHY
- USB 2.0 High-Speed interface
- High-power 8A core power supply

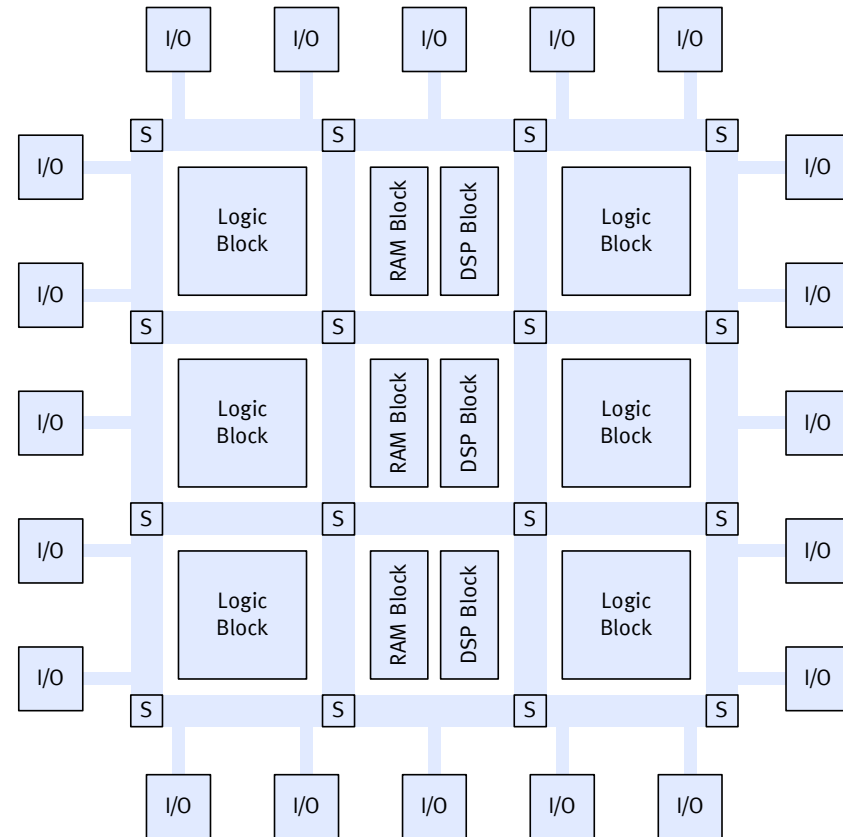


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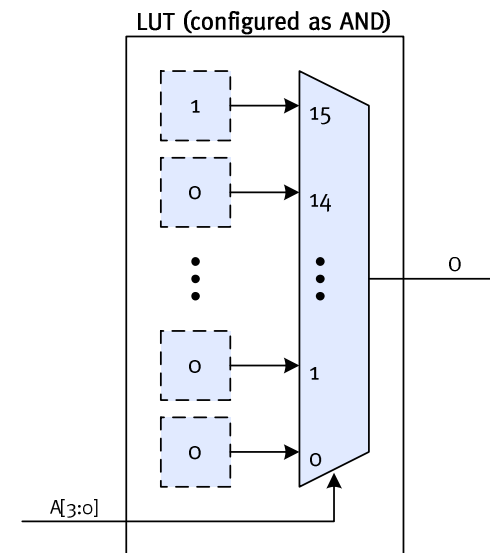
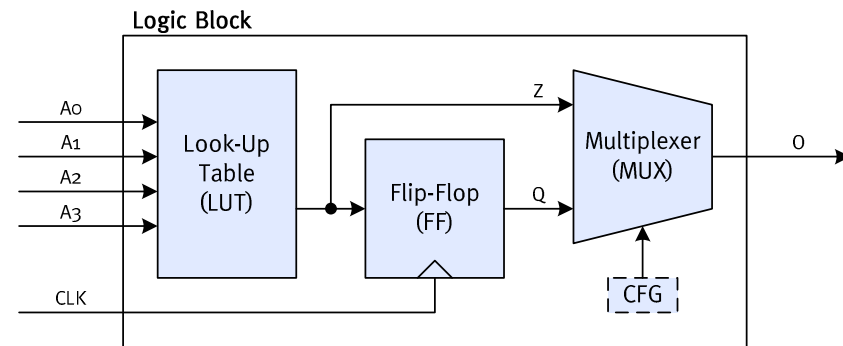
FPGA Basics – Programmable Logic History



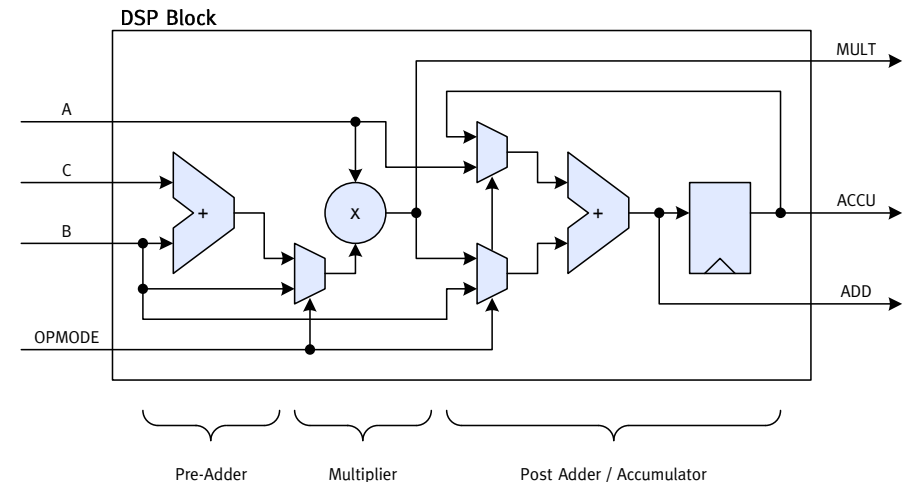
- **F**ield **P**rogrammable **G**ate **A**rray
- Regular array of configurable logic blocks
- Embedded RAM blocks
- DSP blocks
- Configurable I/O blocks
- Dedicated clock management blocks
- Connected through configurable routing resources
 - Global routing (long, fast, few lines)
 - Local routing (short, abundant)
 - Switch boxes
- Configuration data stored in distributed SRAM cells



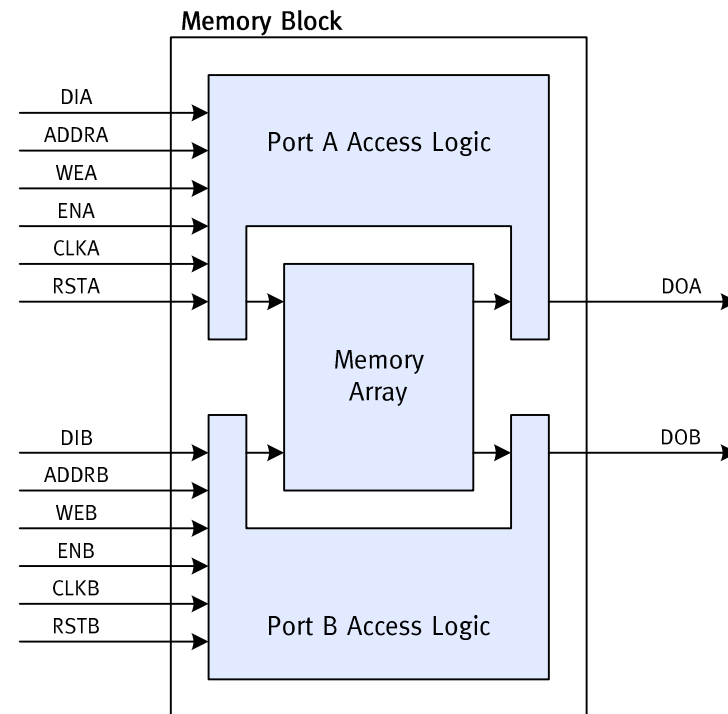
- LUTs are used for implementing logic functions
 - 1-4 input functions in a single LUT
 - LUT trees or carry chain architectures for more complex logic functions
 - LUTs are in fact small SRAMs
- FFs are used for storing data and for pipelining
 - Increasing logic levels result in increased propagation time
 - Routing delay is dominant over LUT delay
 - Pipelining helps to break long paths
 - FFs are expensive in ASICs but are cheap in FPGAs
 - Up to 500 MHz for real-world designs
- ~1500 .. 950'000 (1.5 Mio) per FPGA



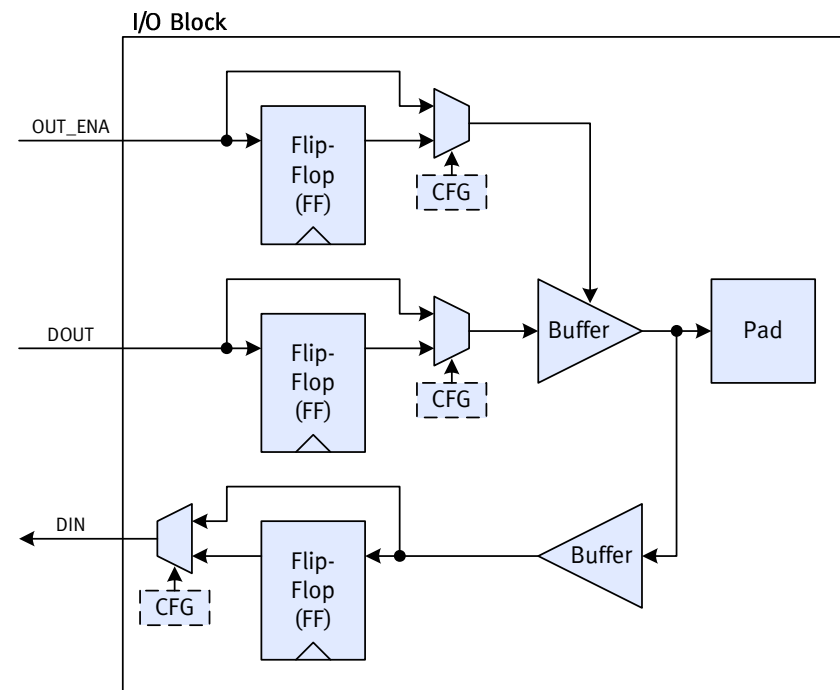
- DSP blocks are used to implement fixed-point arithmetic operations
 - Typically 18 x 18 bit multiplier
 - 48 + 48 bit adder/accumulator
 - Pre-adder for symmetric FIR filters
 - Dynamic configuration via OPMODE
 - Highly pipelined (configurable)
 - Up to 600 MHz clock frequency
 - Support for carry and adder chains
- ~4 .. 2000 (3600) per FPGA
- Up to 1200 (2160) GMAC/s per FPGA!!!



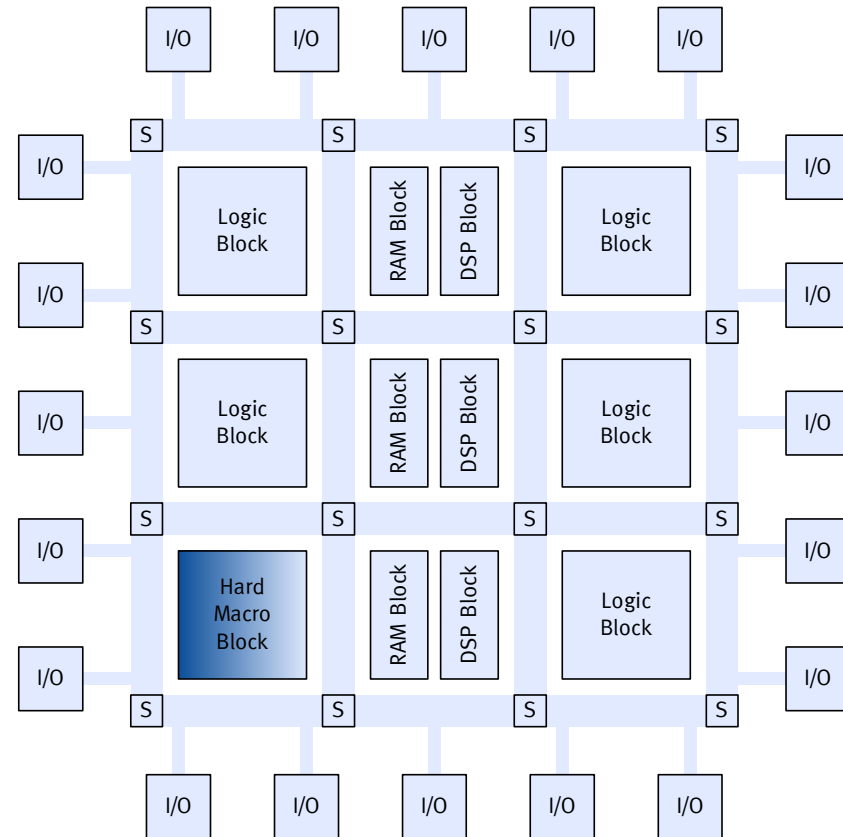
- Memory Blocks are used to implement
 - Simple data storage
 - Shared memory
 - Synchronous/asynchronous FIFOs
 - Configurable large delays
 - ROM (content is part of FPGA bitstream)
 - Data tap / coefficient storage for FIR filters
 - Program/data memory for embedded soft processors
- Widely configurable in
 - Width/depth aspect ratio
 - Size (cascadeable)
 - Read behaviour (registered/combinatorial)
- Granularities from 512 bit to 36 Kbit
- 72 kbit .. 38 Mbit per FPGA



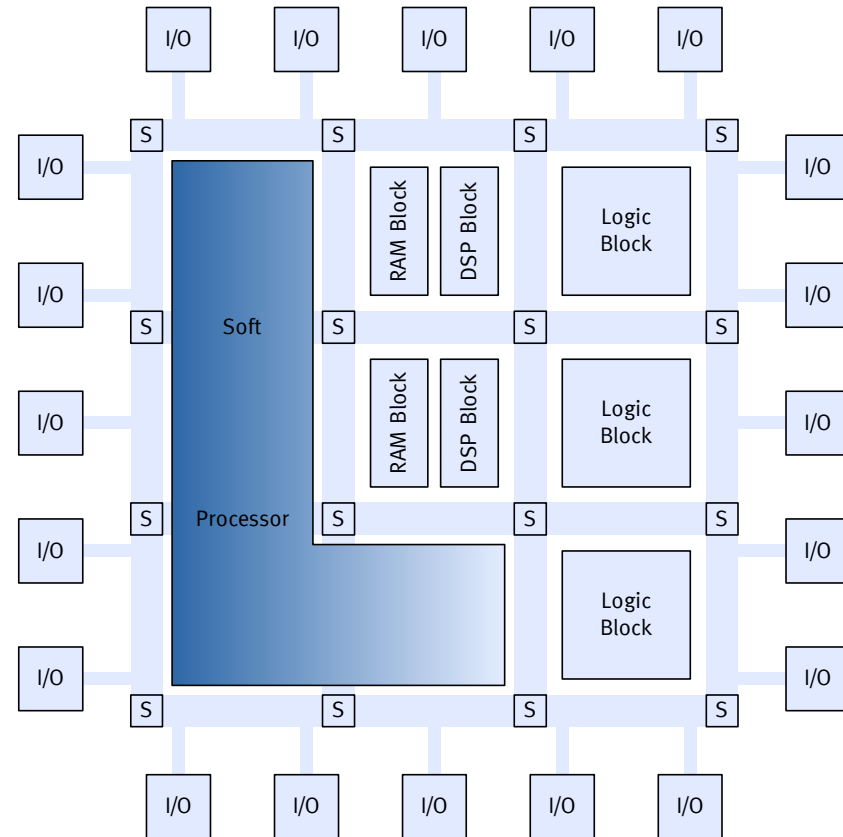
- I/O blocks are used to interface to the outside world
- Highly configurable in
 - Direction (input, output, bidirectional)
 - Data rate (SDR, DDR, SERDES)
 - I/O standard (single-ended, differential, referenced, etc.)
 - I/O voltage (1.2 V .. 3.3 V for single-ended standards)
- FFs in the I/O block guarantee a stable I/O timing
- ~100 .. 1200 per FPGA



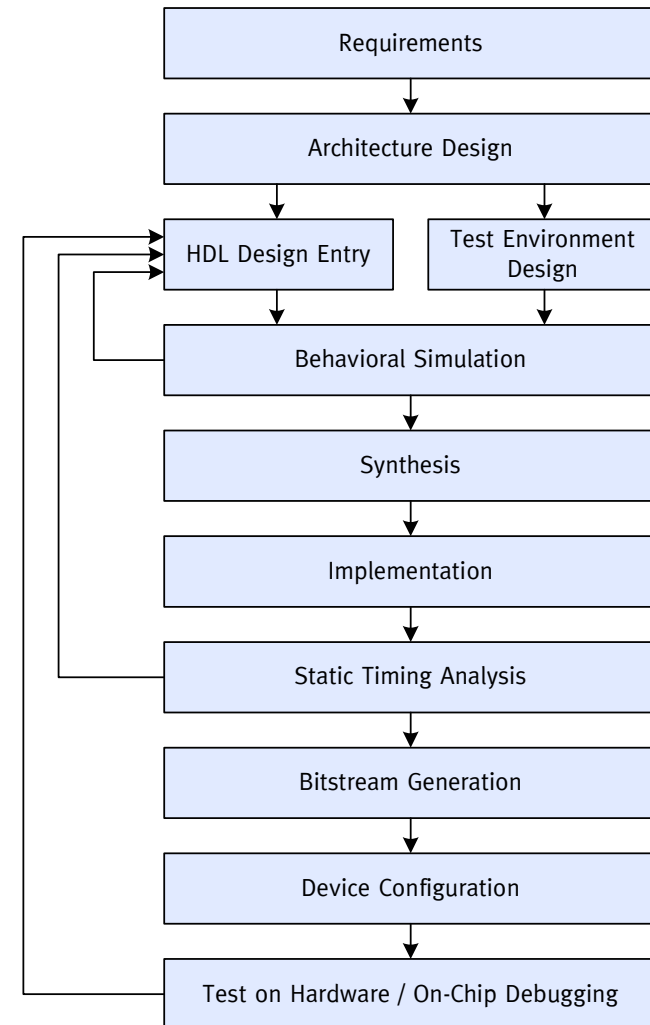
- Hard macro blocks provide complex functions like
 - Embedded processor cores (PowerPC, ARM, etc.)
 - External memory controllers (DDR, DDR2, DDR3, QDR, QDR II, etc.)
 - Triple-speed Ethernet MACs
 - Multi-gigabit serial transceivers
 - PCI-Express endpoints
 - Etc.
- Even low-cost FPGAs provide some hard macro blocks today
 - No hard macro CPU in low-cost FPGAs so far



- Embedded processor core implemented with FPGA logic, DSP and memory blocks
- Highly configurable
 - Starting with an ultra-simple 8-bit uC core
 - Ending with 32-bit RISC CPUs including FPU and MMU, capable of running a desktop Linux distribution
- Enables SoPCs with low-cost FPGAs
 - **S**ystem **o**n a **P**rogrammable **C**hip
 - Single-chip solution, uC and legacy peripheral ICs are replaced by FPGA logic resources

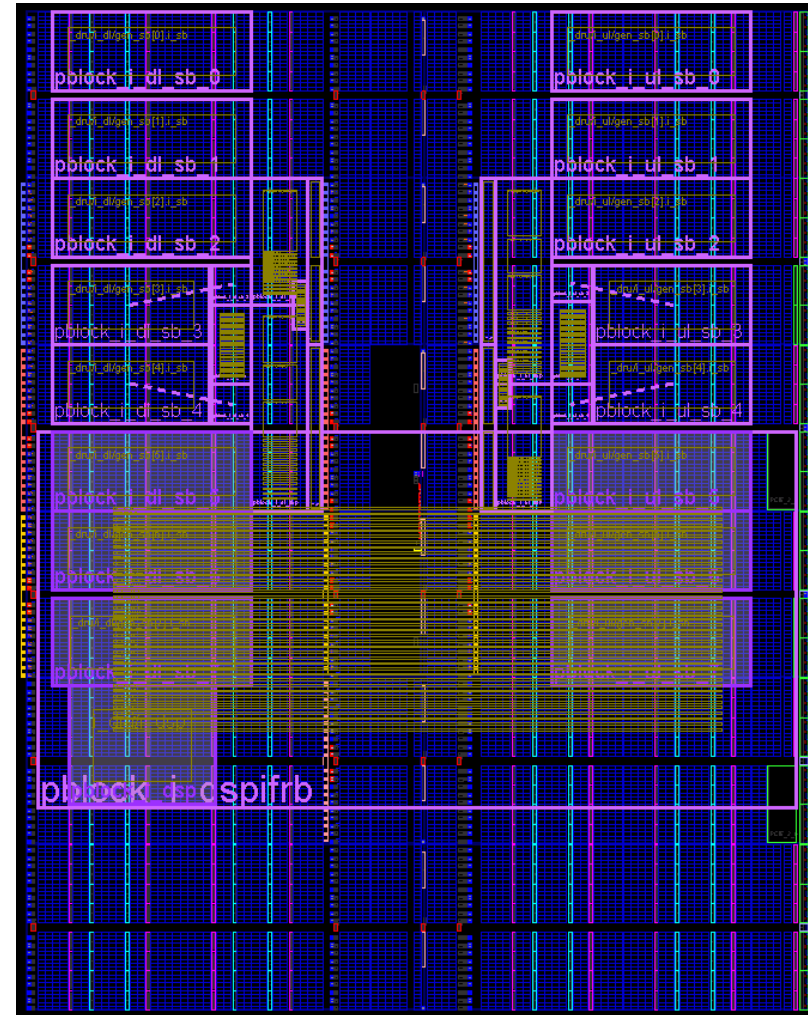


- Architecture design is vital for
 - System performance
 - Resource usage
 - Timing closure
 - Power consumption
- HDL: **Hardware** Description Language
- Only strict synchronous design practices lead to reliable FPGA systems!
- FPGAs allow on-chip debugging with fast iteration times (typically less than one hour)



- **Code Generation vs. HDL Entry**
- Code Generation
 - Allows fast migration of already available code (e.g. written in C or MATLAB) to an FPGA target
 - Not very resource-efficient, lacks performance
 - Tools are very expensive and often complicated to use and maintain
- HDL Entry
 - Allows very resource-efficient and performant implementations
 - Same functionality fits into a smaller, slower and therefore cheaper FPGA
 - Longer development time
 - Simple tools, available for free (text editor...)
- **IP Cores and HDL Libraries**
- IP Cores
 - Device-specific implementation (netlist)
 - Provide complex functions
 - MPEG encoder
 - CAN interface
 - Many vendors
- HDL Libraries
 - Device-independent implementation (HDL)
 - Provide mostly basic functions
 - Asynchronous FIFO
 - SPI Master
 - Company-internal

- **Floorplanning, mapping, place and route**
- Floorplanning
 - Necessary for high-speed designs on large FPGAs
- Map
 - Mapping of the synthesized netlist to available resource elements of the target device
- Place
 - Placing of the mapped elements to the available physical resources of the device
- Route
 - Implementation of the logical connections with physical routing resources



On-Chip Debugging

- Today's FPGA tools allow to easily implement logic analyzer functionality in FPGA logic

- Real-time capturing of FPGA-internal signals

- Offline readout of captured signals via JTAG

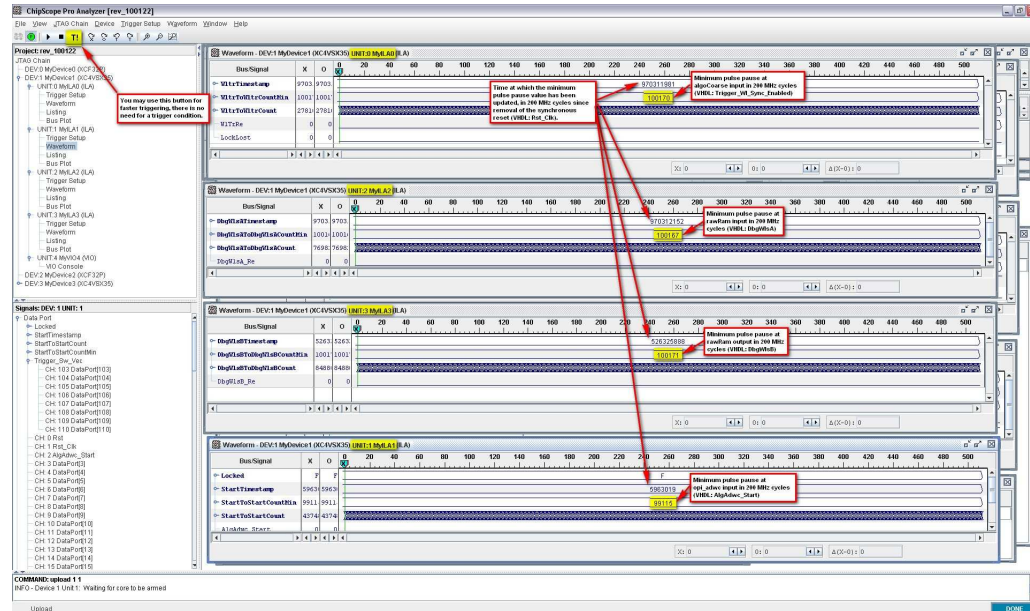
- Logic analyzer GUI on host computer

- Almost unlimited trigger-conditions, configurable on the fly

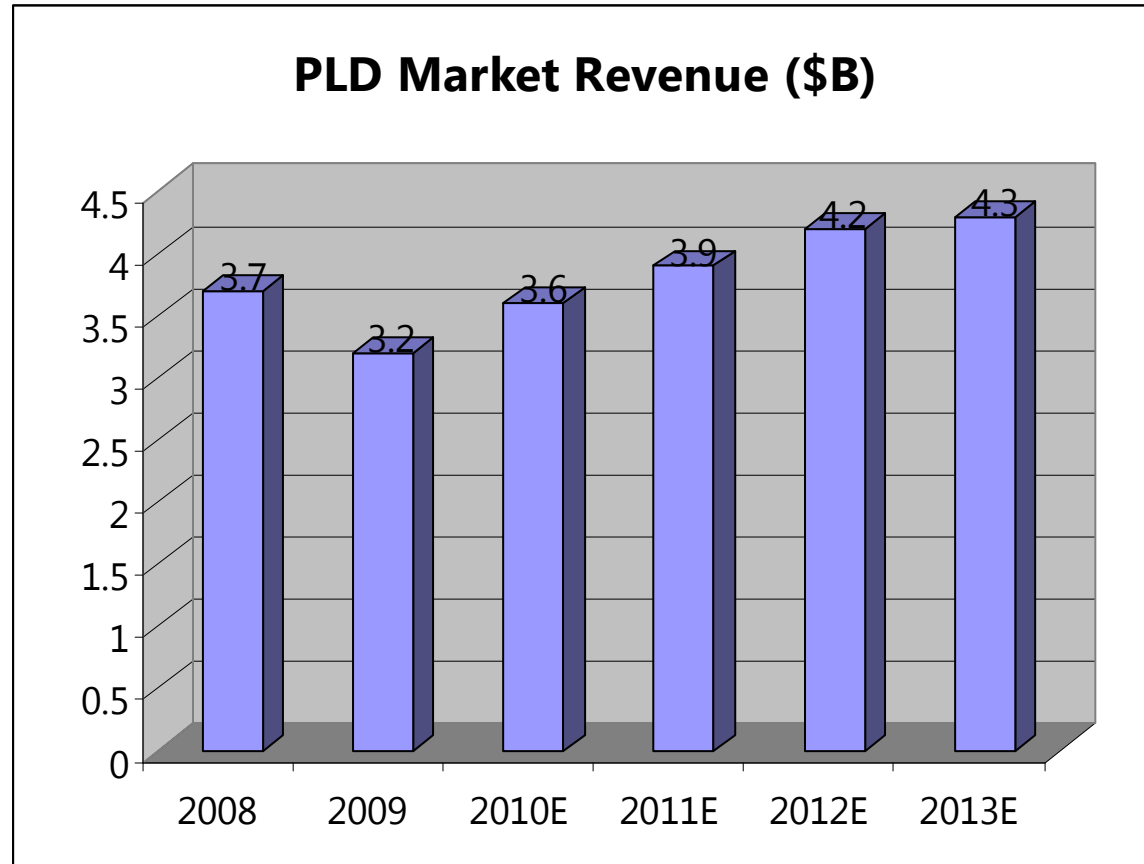
- Possibility to control FPGA-internal signals from the host PC

- Very limited memory depth

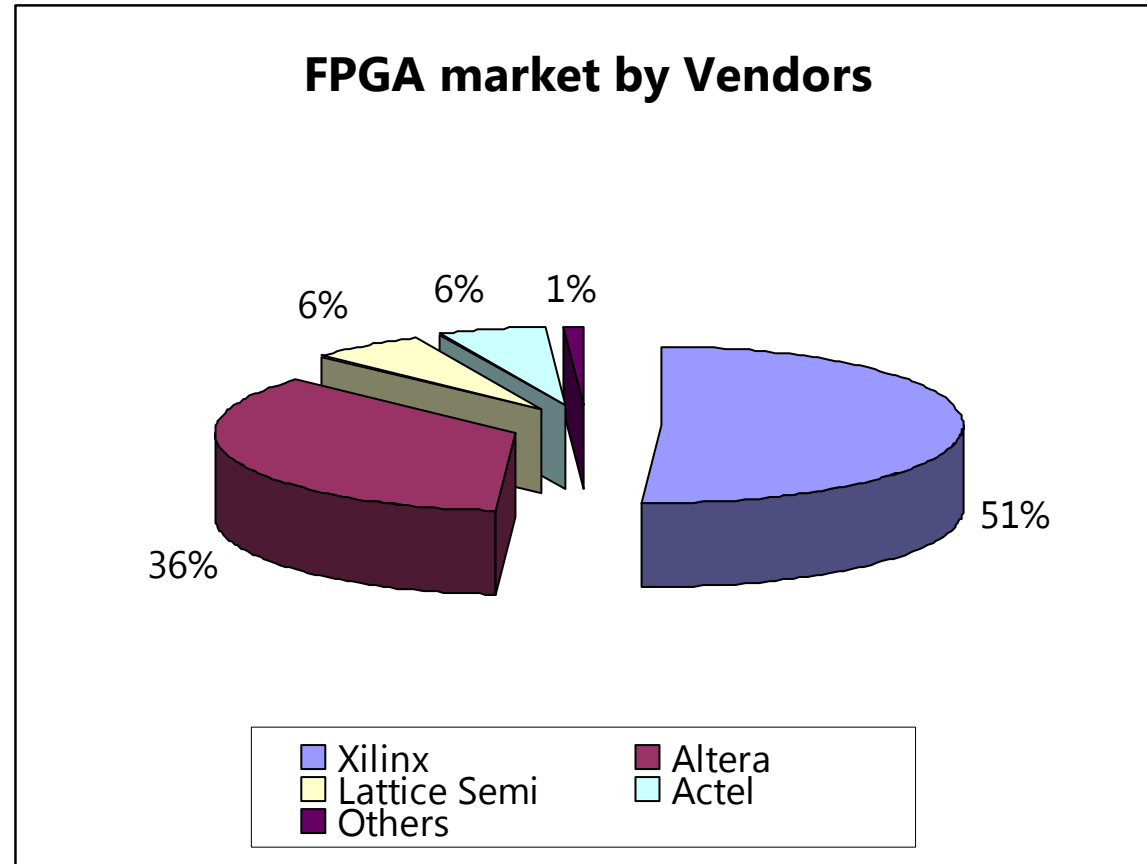
- FPGA has to be re-implemented in order to change the logic analyzer structure



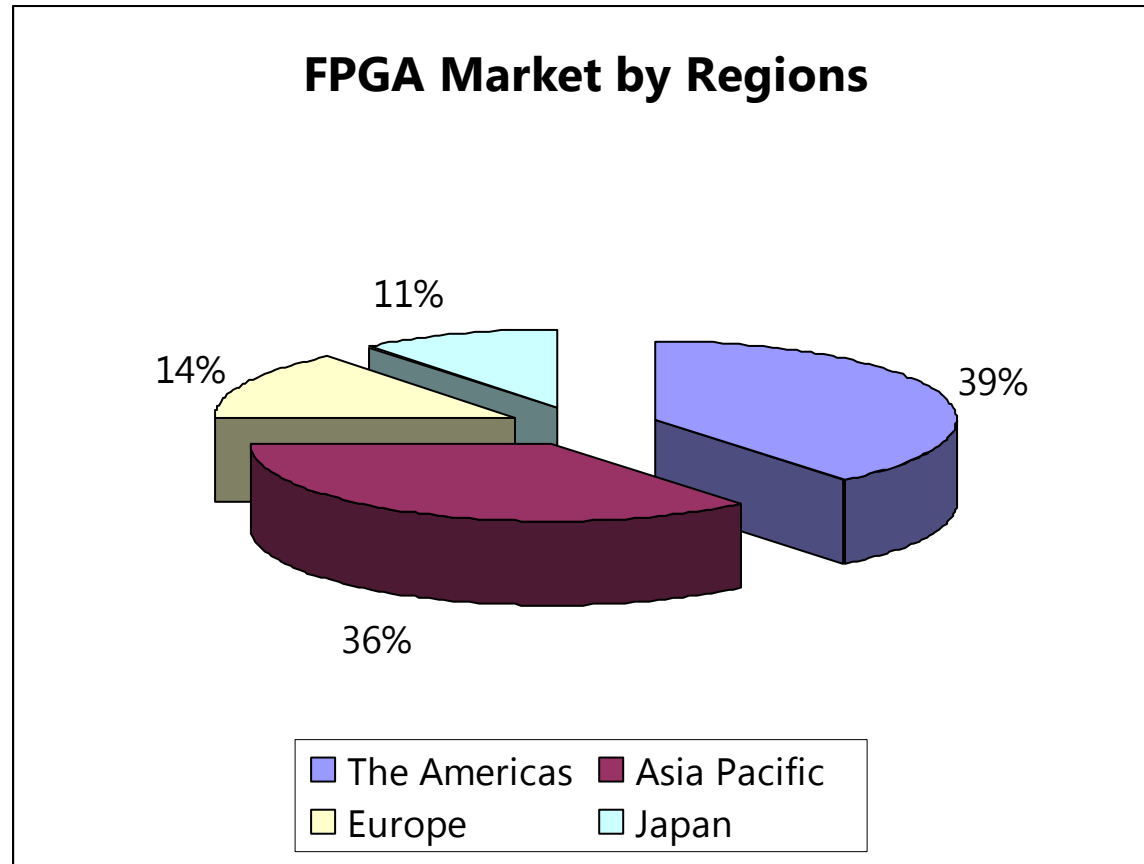
- Roughly 1.3% of total semiconductor market revenue
- PLD market revenue is believed to grow by 35% from 2009 to 2013
- FPGAs make up about 75% of the PLD market revenue



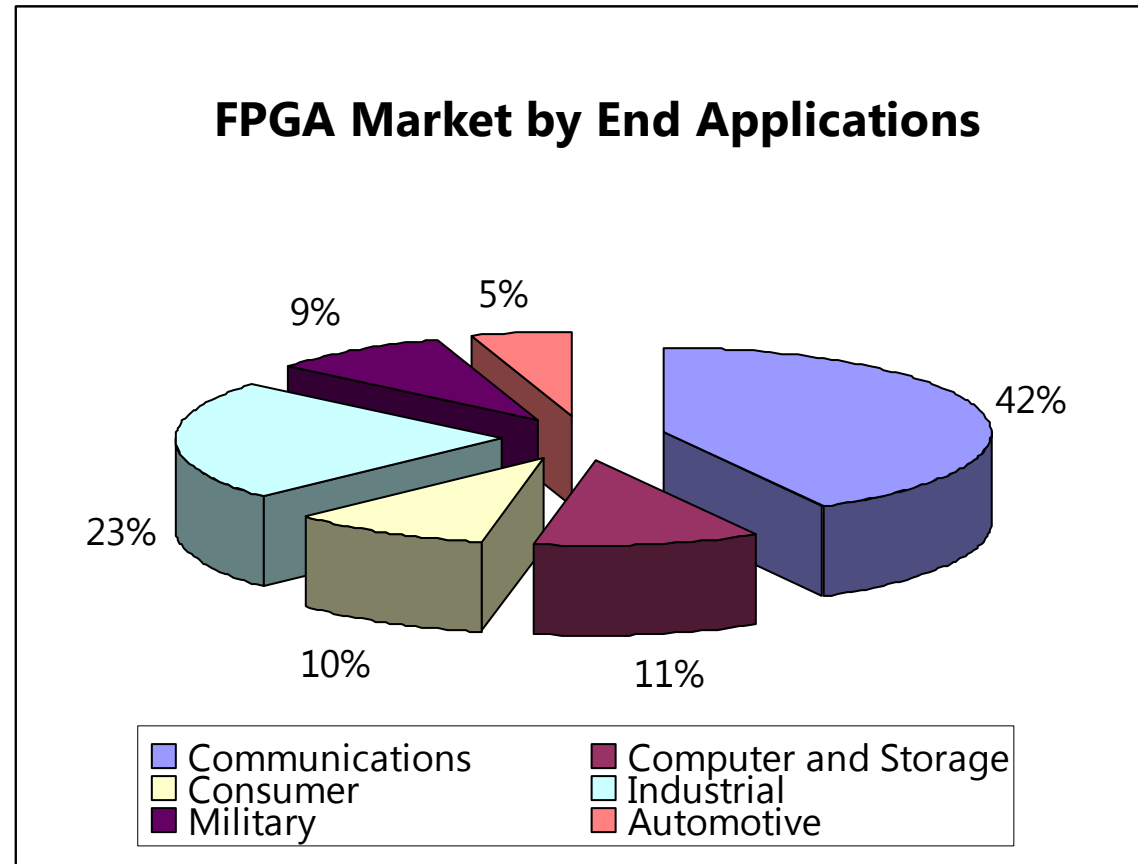
- Xilinx and Altera share the high-performance FPGA market as well as the major part of the low-cost FPGA market
- Lattice Semi is a traditional player in the low-cost FPGA and CPLD market
- Actel provides Flash-based, low-power, mixed-signal and space-qualified FPGAs



- Japan actually belongs to APAC
- Europe is the smallest market
- The Americas are not the biggest market



- Industrial applications are dominant in Switzerland
- There is also some significant activity in the communications sector in Switzerland



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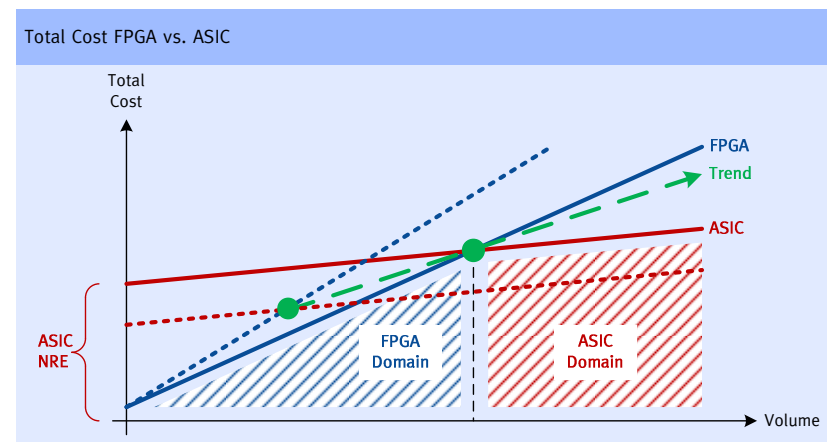
The Case for FPGAs – Unique Selling Points (1)

- Real parallel processing
 - Vast parallel processing power for DSP applications
 - No conflicts in accessing shared resources (because there aren't any...)
- Hard real-time capabilities
 - No operating system, no scheduler, no IRQ latency, only pure hardware
 - Nanosecond time resolution (e.g. 200 MHz FPGA clock frequency -> 4 ns cycle time)
- High integration and customization potential
 - Single-chip systems with standard and custom parts

- Reconfiguration / remote update capability
 - Configuration can be changed over and over again
 - Allows early system tests on hardware instead of time-consuming simulations
 - Deployed systems can be updated in the field, e.g. over the internet
 - Therefore often used as configurable external I/O
- Long-term availability
 - Devices are usually available for > 10 years
 - System functionality is defined by HDL code rather than by hardware schematics
 - HDL code is easily ported to a new FPGA generation (no change to embedded processor code)

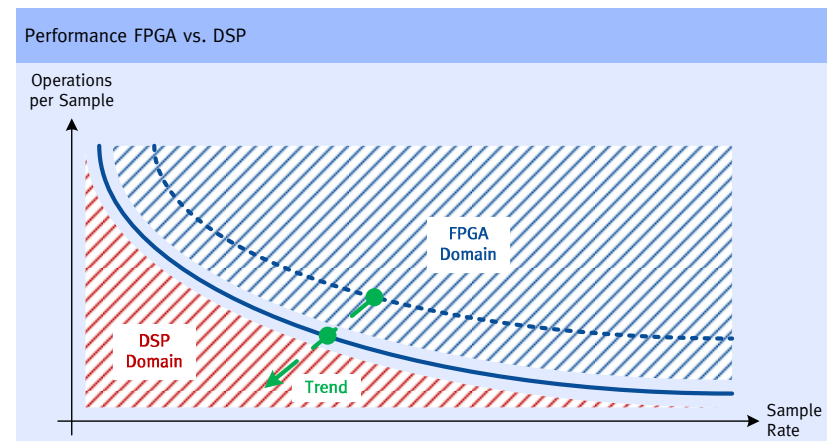
- FPGAs can't beat ASICs when it comes to
 - Low power
 - Ultra small form factor
 - Ultra high design security
 - Ultra high volume
- ASICs need volume to overcome the NRE penalty
 - NRE increase with each process shrink
 - FPGA logic gets cheaper with each process shrink
 - The break-even is moving towards higher volumes with each process shrink
- Remote update and faster time to market become more and more important
 - FPGAs gain ground in the ASIC domain
- FPGAs are often used for ASIC prototyping

Parameter	FPGA	ASIC
Clock frequency		✓
Power consumption		✓
Form factor		✓
Design security		✓
Reconfiguration	✓	
Redesign risk (weighted)	✓	
NRE	✓	
Time to market	✓	

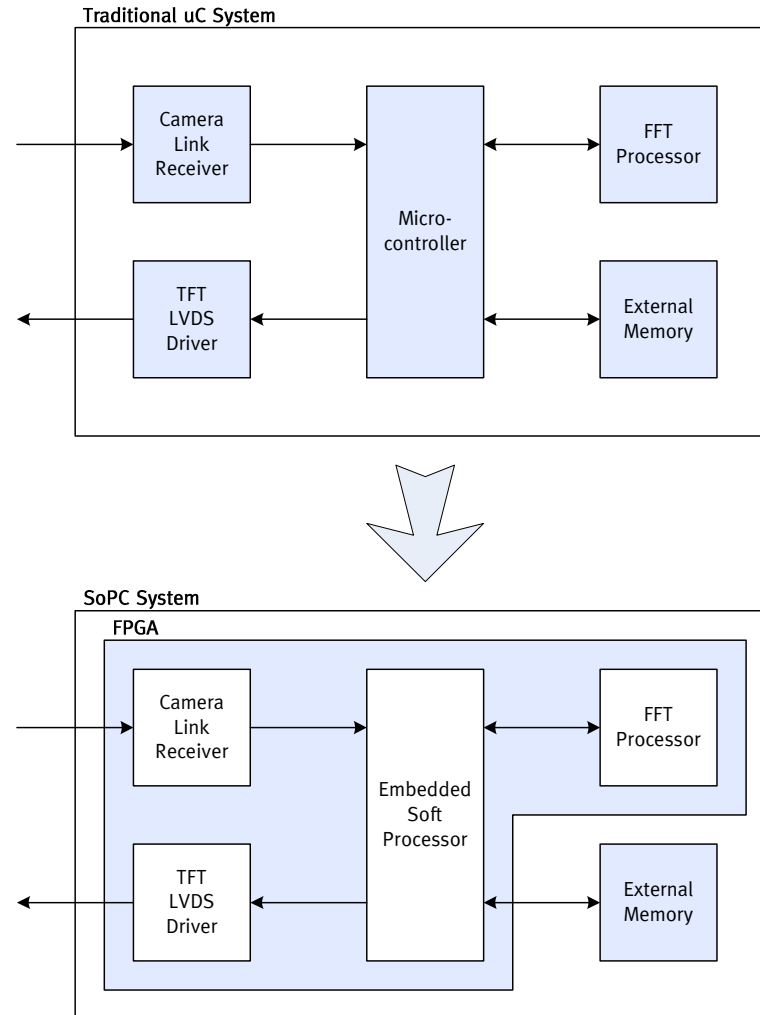


- DSPs are widely used in low-cost, low-power and low- to mid- performance systems
- DSPs suffer from their serial instruction stream when it comes to more complex systems running at high sample rates
- FPGAs can provide a performance boost of 10..1000 compared to DSPs for such applications (e.g. software defined radio).
- FPGAs even excel when compared in MAC/\$ and MAC/W.
- Hard-macro CPU cores in the FPGAs take over traditional DSP tasks (e.g. complex protocol stacks), enabling single-chip high-performance signal processing systems

Parameter	FPGA	DSP
System performance	✓	
Multi-channel architecture	✓	
Many operations per sample	✓	
Many conditional operations		✓
Floating point		✓
Absolute power consumption		✓

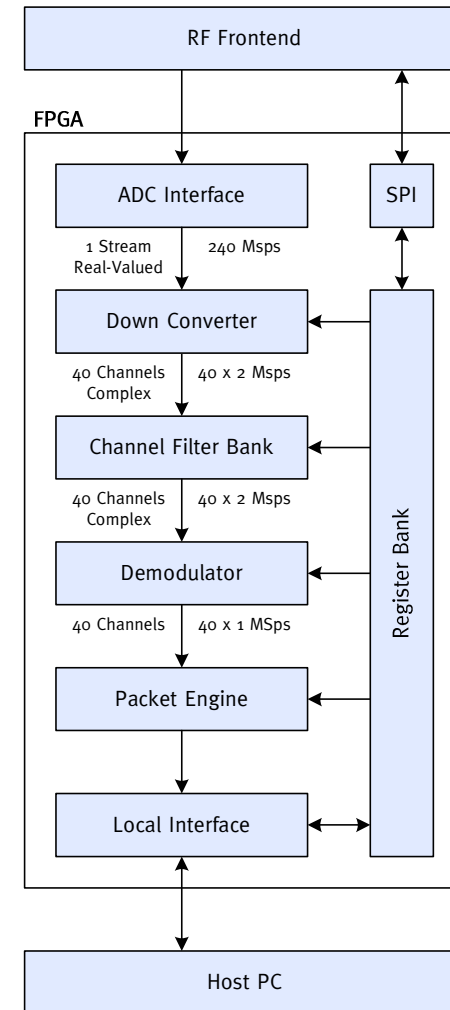


- „Microcontrollers are cheap and energy-efficient, FPGAs are expensive and power-consuming“
 - If a microcontroller can do it, there is usually no need for a FPGA
- SoPC designs with FPGA-internal soft processors are beneficial if
 - The system requires a FPGA anyway
 - Many external ICs would be needed along with a microcontroller
 - PCB space is a major concern
 - High design flexibility is required
 - Long-term availability is a major concern
 - Reduced part count
 - BSP defined through VHDL-code

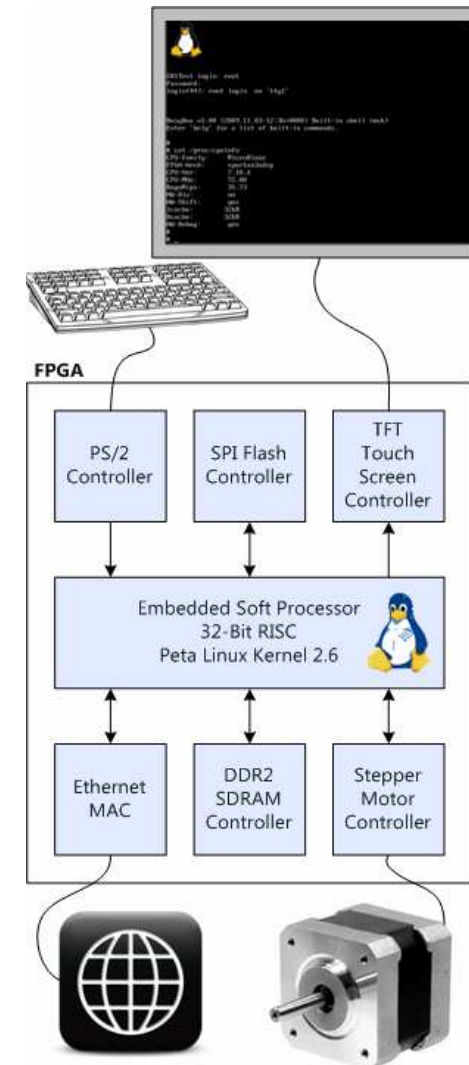


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- Software defined radio
 - Most of the signal processing of a RF receiver/transmitter is done in „software“
- Real-world application
 - 2.4 GHz RF receiver
 - 240 Msps sampling rate
 - Down conversion to 40 channels at 2 Msps each
 - Parallel baseband-processing of all 40 channels with a time division multiplexed datapath architecture
 - Channel filters
 - Demodulators (FSK, PSK)
 - Spartan-3A DSP low-cost FPGA
 - 126 multipliers running at 240 MHz clock frequency



- FPGA SoPC demonstrator
 - TFT display with touch function
 - PS/2 keyboard
 - Gigabit Ethernet (TCP/IP)
 - Stepper motor controller
 - 32-bit RISC CPU running Linux 2.6
 - GUI based on Nano-X
 - Everything in a single low-cost FPGA (Xilinx Spartan-3A DSP on a Enclustra Saturn SX1 FPGA module)
- Linux provides user I/O, networking and a well-known application development platform
- FPGA logic provides custom functions



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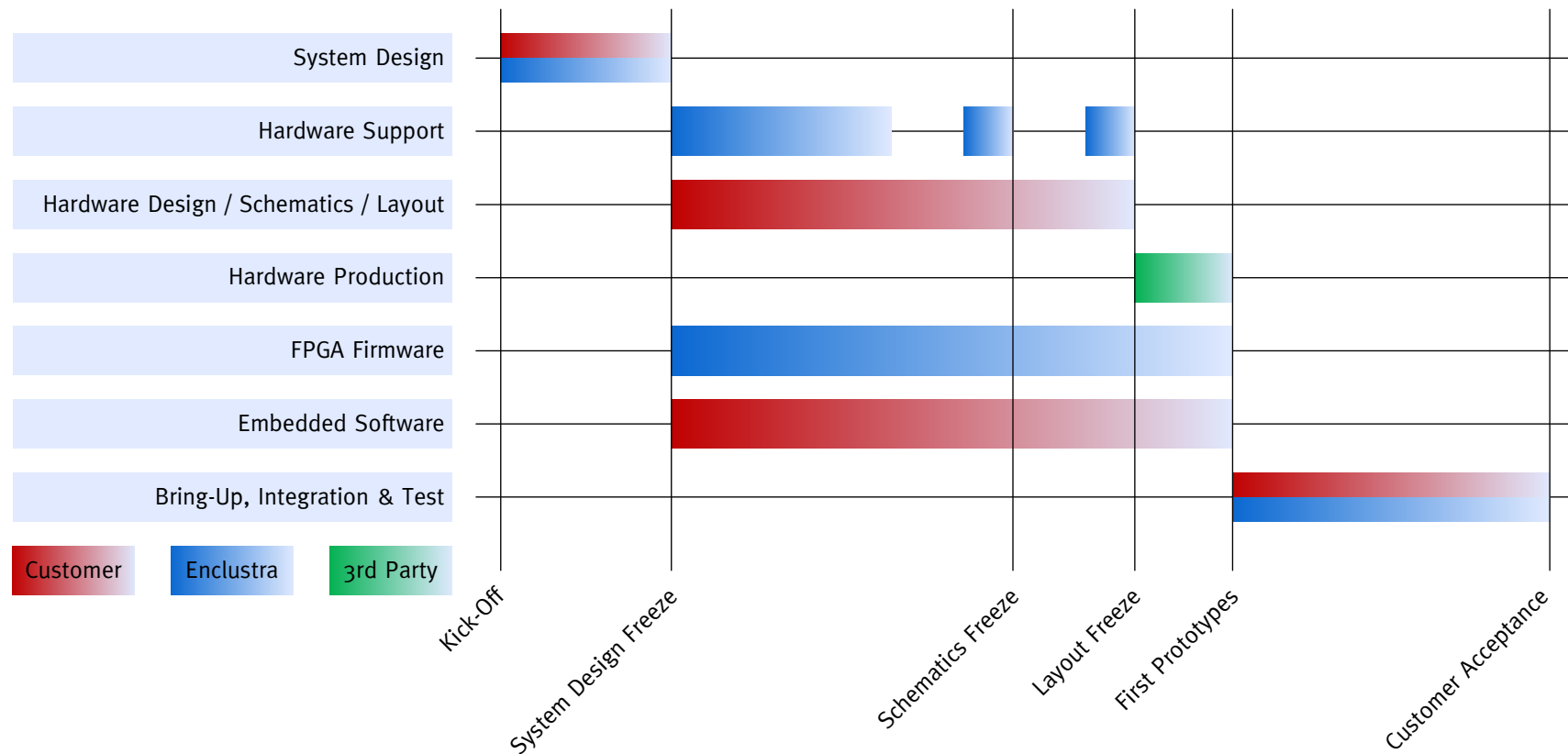
Example Project – Motion Control Specification

- Technical requirements:
 - Motion control module
 - Up to 4 DC or 2 stepper motors
 - Up to 2 BLDC motors in a later stage
 - CAN interface
 - Trajectory planner/integrator
 - All calculations in SI units
 - 1..5 KHz position/velocity control
 - 10..100 KHz current control
 - 4 integrated FET H-bridges
 - Credit-card size
- General information:
 - Motion control platform for next-generation products
 - High-volume (> 10'000 units/year)
 - Must comply with various engineering standards
- Commercial requirements:
 - Manufacturing costs < X \$
 - Available no later than day Y
 - Engineering costs are secondary

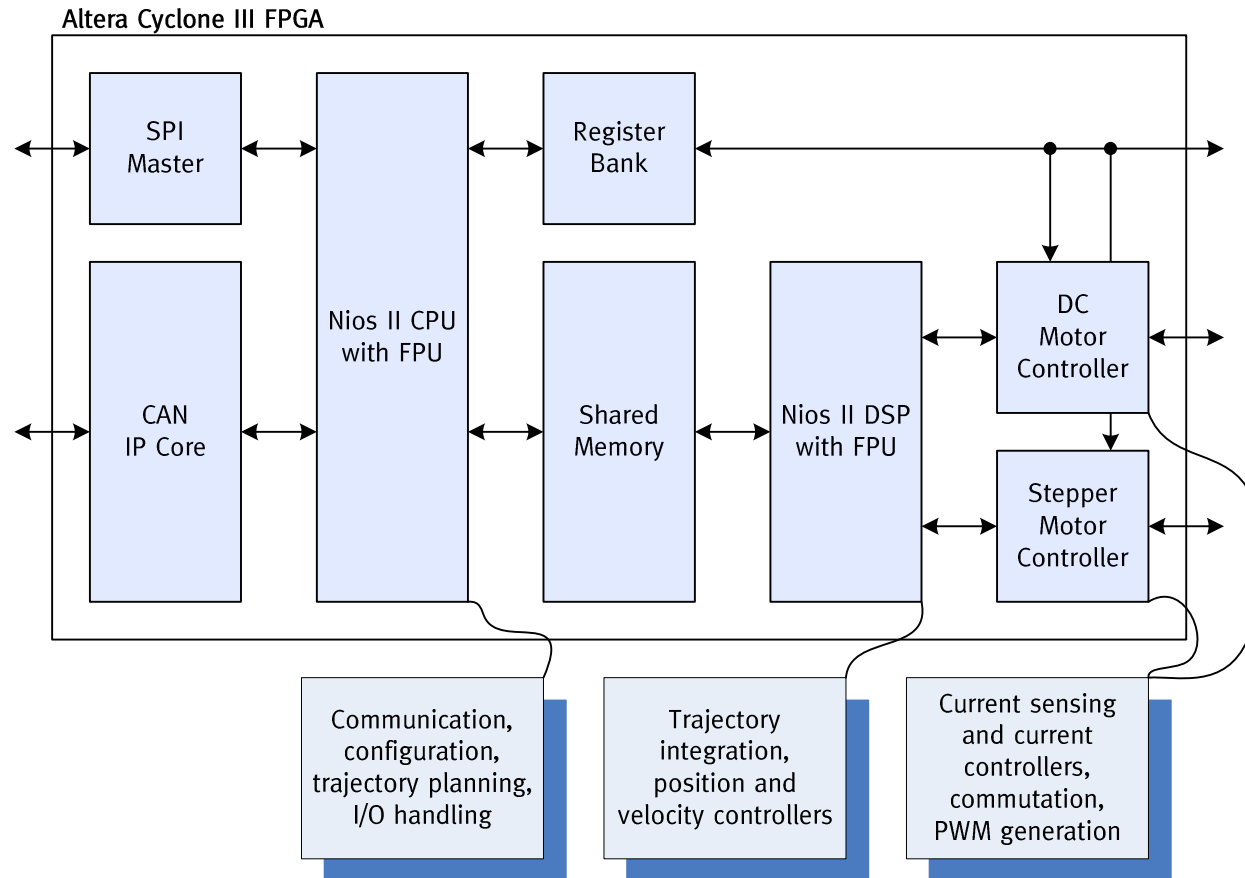
Example Project – Motion Control Project Setup

- General project setup:
 - The customer is responsible for hardware design, production and embedded software
 - Enclustra is responsible for FPGA firmware and FPGA-related system design issues
- Team setup at Enclustra:
 - 1 project manager
 - 1 FPGA firmware engineer
 - 1 hardware consultant
- Team setup at the customer:
 - 1 project manager
 - 2 embedded software engineers
 - 2 hardware engineers
 - and
 - The strategic procurement department
 - and
 - The upper management
 - and
 - Many potential users of the motion control module

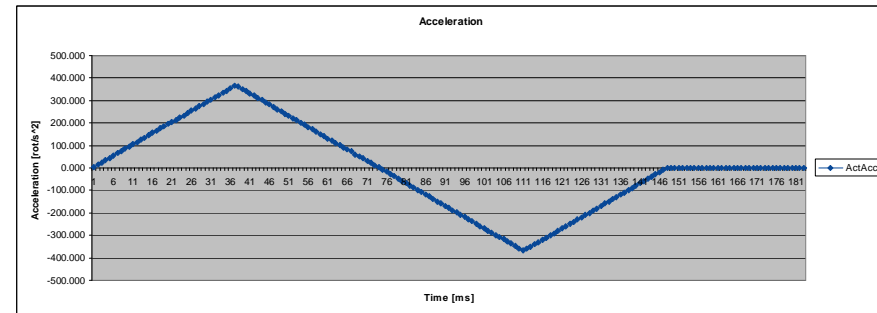
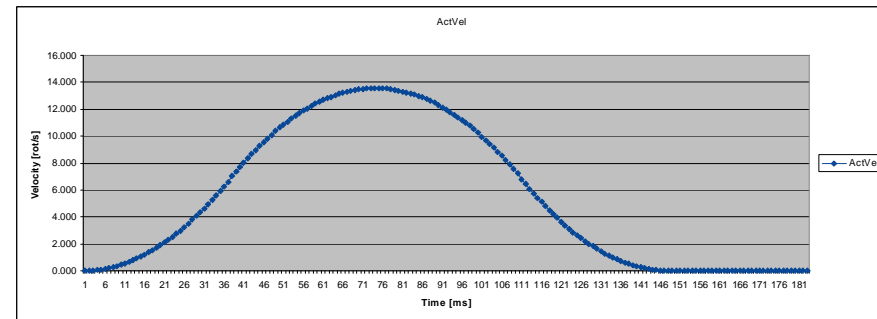
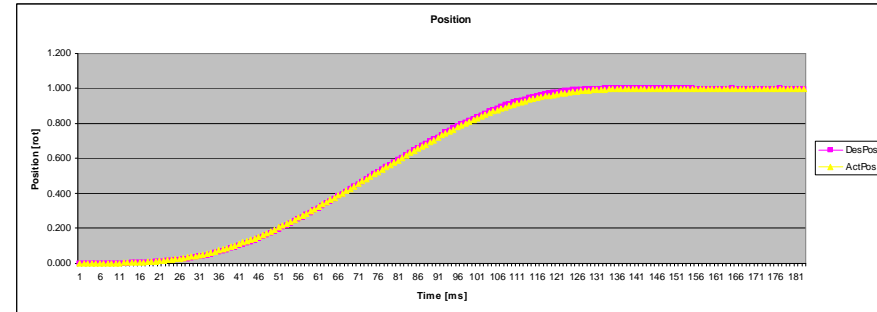
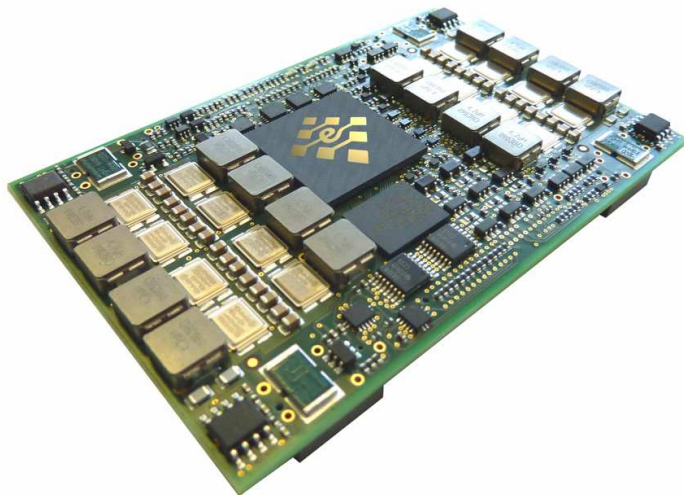
Example Project – Motion Control Project Schedule (Basic Functions)



Example Project – Motion Control System Design (1)



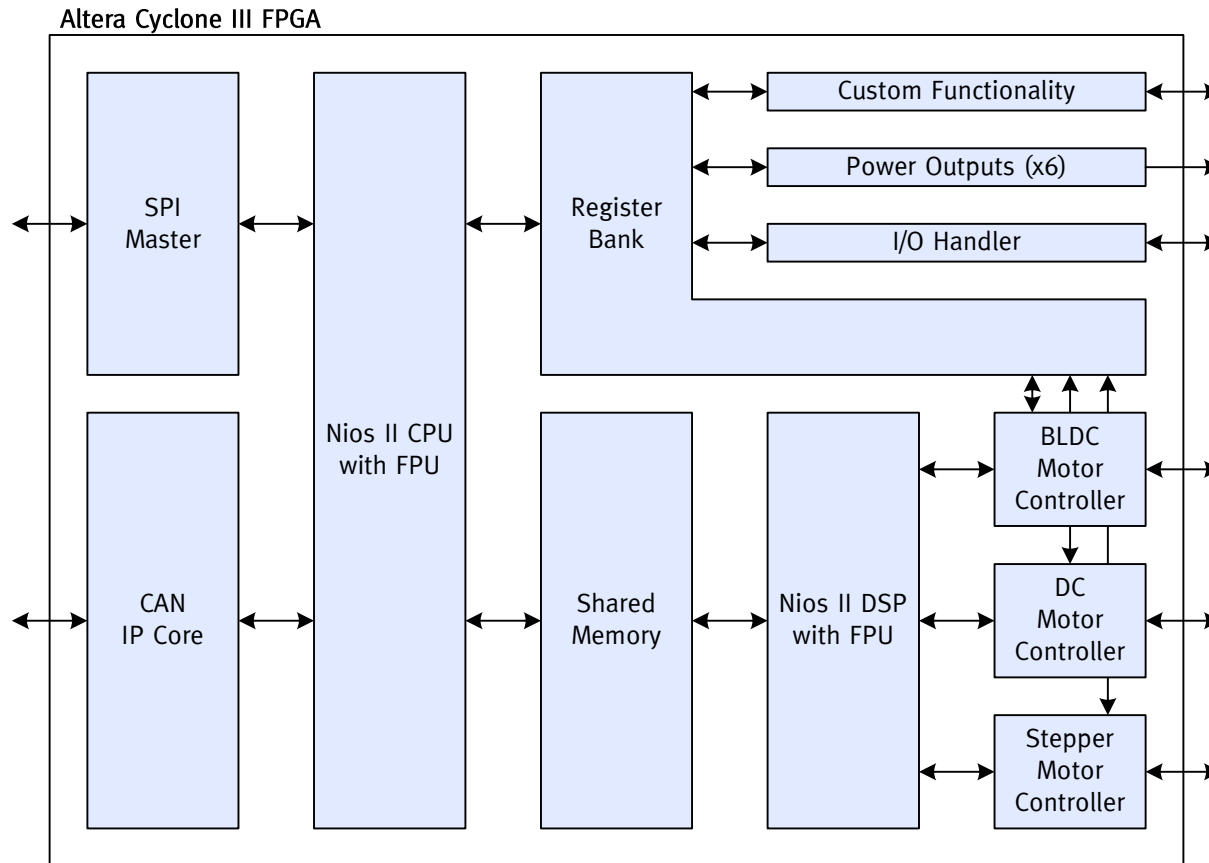
- Bring-Up
 - Power, clocks, FPGA configuration
 - Nios II booting and JTAG communication
- First tests on hardware
 - The first logged move!



Example Project – Motion Control Next Steps

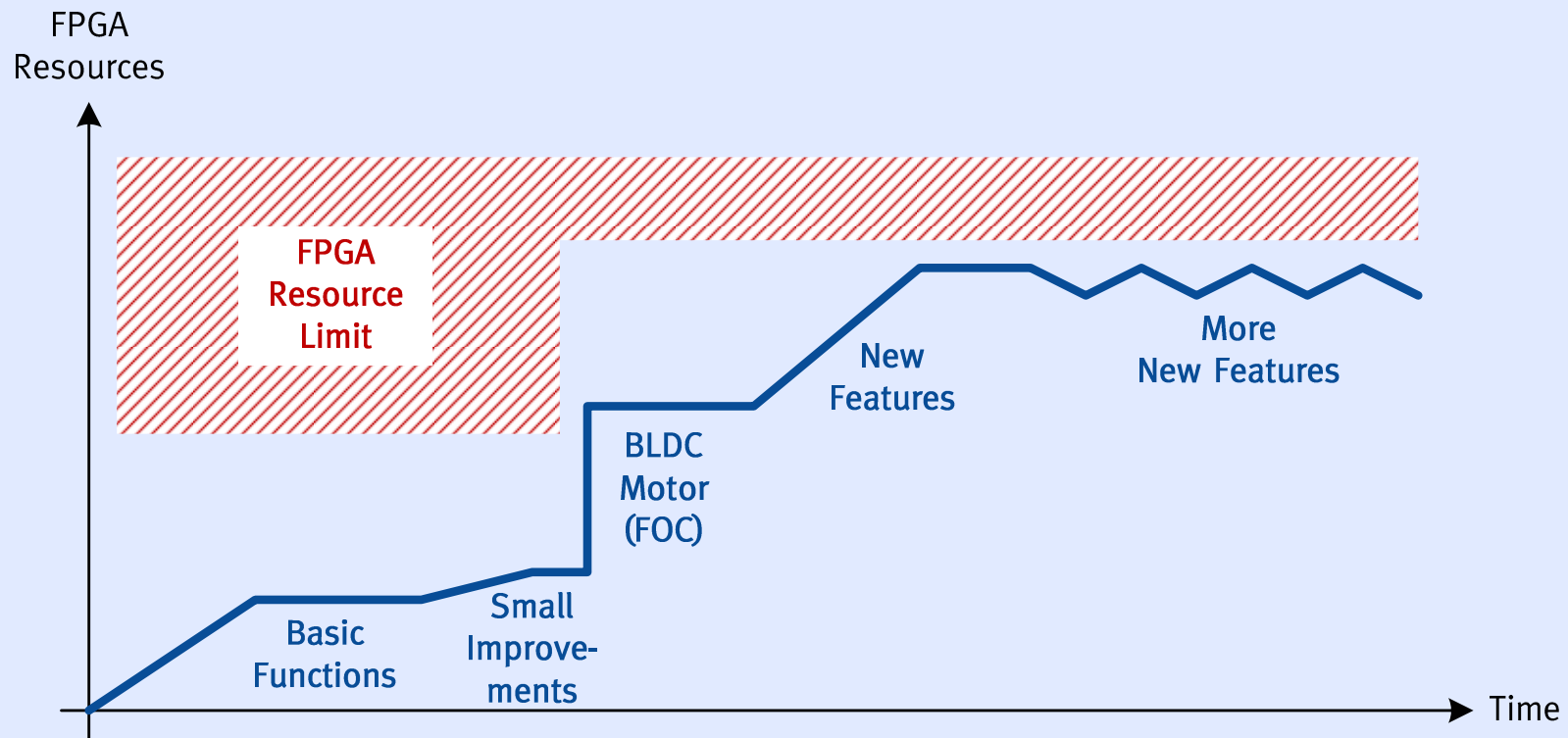
- In-System testing at the customer's site
 - Bugfixes
 - Small improvements
 - First ideas for new features
- First release to internal users
 - More bugfixes
 - More small improvements
 - More ideas for new features
- Customer acceptance for basic functionality on schedule
- New feature wishlist
 - BLDC motor: Field oriented control (FOC) instead of block commutation
 - BLDC motor behaves like a DC motor
 - Resource-consuming
 - Versatile I/O handler with interrupt support
 - Big muxes -> resource consuming
 - Power outputs with custom waveforms generated in FPGA logic
 - 6 times -> resource-consuming
 - Additional custom functionality
 - Much more configurable parameters
 - Growing register bank

Example Project – Motion Control System Design (2)



Example Project – Motion Control FPGA Resources over Time

FPGA Resources over Time



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- **FPGAs allow fast market entry thanks to their field update capability**
- This often leads to the fallacy that FPGA development does not require thorough verification („we can fix an error after it occurs“)
 - This might be partly true for non security relevant applications running in static ambient conditions
 - FPGA development actually IS done like this a lot more than one might think
 - This often wrongs FPGA technology in the user’s minds, because there WILL be errors in this case
- The development of a reliable FPGA system does not get by without thorough verification!
 - Verification may include behavioral simulation and tests running on the hardware

- **FPGA-based systems allow step-by-step introduction of new features**
- FPGA projects require a thorough change management
 - Request, classification, design, approval, implementation, verification, release
- FPGA projects require a strict release management
 - Define specific feature sets for planned releases and stick to it
 - Build number, build date and time, release number, accurate release history
- Resource usage and power consumption must always be monitored
 - Device migration over different densities (assembly option) is possible, but complicates the initial hardware design
 - Power consumption is highly dependent on the FPGA design (resource usage, clock frequencies, etc.) and the system operating conditions (data toggle rates, etc.)

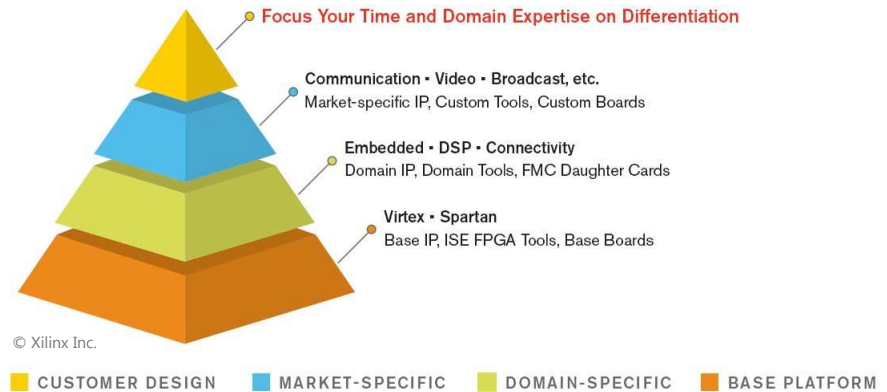
- **Make or buy – the case for outsourcing FPGA development**
- Successful and efficient FPGA design requires in-depth knowledge of
 - Basic digital and analog circuit design, chip design, VLSI
 - HDL (VHDL/Verilog/etc.), FPGA architecture and tools
 - High-speed hardware design
 - Deployed algorithms, I/O standards, protocols, etc.
- Many companies have extensive knowledge in their application area, but do not have the required expertise for successfully employing FPGA technology
- Building up FPGA know-how is a lengthy and expensive process
- Collaboration between application specialists and FPGA technology experts shows great promise for successful product development

- **FPGA jobs in engineering services - what skills do we expect?**
- Technical skills
 - Basic digital and analog circuit design, chip design, VLSI (very important)
 - HDL (VHDL, Verilog, etc.)
 - Basic understanding of FPGA architecture and tools
 - Basic understanding of DSP and SoPC
- Soft skills
 - Keen perception also for complex structures
 - Good communication with customers and colleagues
 - Ability to work in a team
 - Flexibility for changing tasks quickly

- **How can a FPGA engineering company stand out from the crowd?**
- Focus on
 - FPGA technology (don't be a „general merchandise store“)
 - Key application domains (e.g. DSP, SoPC, etc.)
- Provide solutions, not only engineering resources
 - FPGA modules as HW platform
 - IP cores for complex building blocks
 - Custom design for custom functionality
 - System integration
- Not only make the customer happy, but also make him successful
 - What the customer initially wants is most often not what he really needs

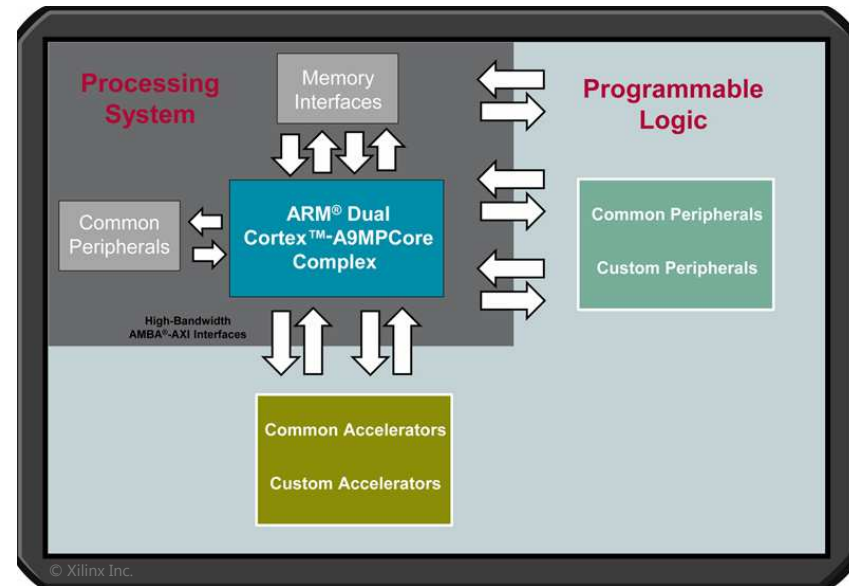
- Enclustra GmbH
 - Company Profile
- FPGA Basics
 - Programmable Logic History
 - FPGA Architecture
 - FPGA Design Flow
 - Market Overview
- The Case for FPGAs
 - Unique Selling Points
 - FPGA vs. ASIC
 - FPGA vs. DSP
 - FPGA vs. uC
- Real-World FPGA Applications
 - Software Defined Radio
 - Linux on FPGA
- Example Project
 - Motion Control
- Conclusions
 - Field Update
 - „Featuritis“
 - Outsourcing
 - Skills
 - How to Stand Out
- **Outlook & Trends**

- Enable designers to focus on innovation rather than on infrastructure by the help of
 - Advanced FPGA silicon
 - Socketable IP cores
 - Development boards
 - Reference designs
- Base IP and tools provided by silicon vendor for free (e.g. SPI)
- Domain-specific IP and tools provided by silicon vendor and design partners (e.g. FFT)



- Market-specific IP and tools provided by design partners and 3rd parties (e.g. video deinterlacer)
- Application-specific boards and FPGA designs done by the end customer

- CPU goes FPGA (not FPGA goes CPU)
- Xilinx Extensible Processing Platform
 - ARM Dual Cortex-A9 @ 800 MHz
 - Memory interfaces and common peripherals as hard macros
 - Programmable logic custom peripherals and accelerators
 - High-bandwidth interconnect between CPU, peripherals and accelerators
 - Partial reconfiguration of programmable logic via CPU



- Fixed processing system
- Scalable programmable logic
- Broad range of available IP
- Software-centric development flow

- PMC, XMC & Co. allow flexible I/O interfaces for traditional single-board computers
- Providing flexible I/O interfaces for FPGA-based processing boards is a different story
- The **FPGA Mezzanine Card (FMC)** standard is addressing this issue
 - 160 (LPC) or 400 (HPC) pin connector, up to 10 Gb/s
 - Standardized connector pin assignments optimized for FPGAs



- Possible applications
 - Different RF frontends for FPGA-based software defined radio systems
 - Various I/O engines for a single FPGA-based processing board



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<http://www.enclustra.com/de/company/publications/>