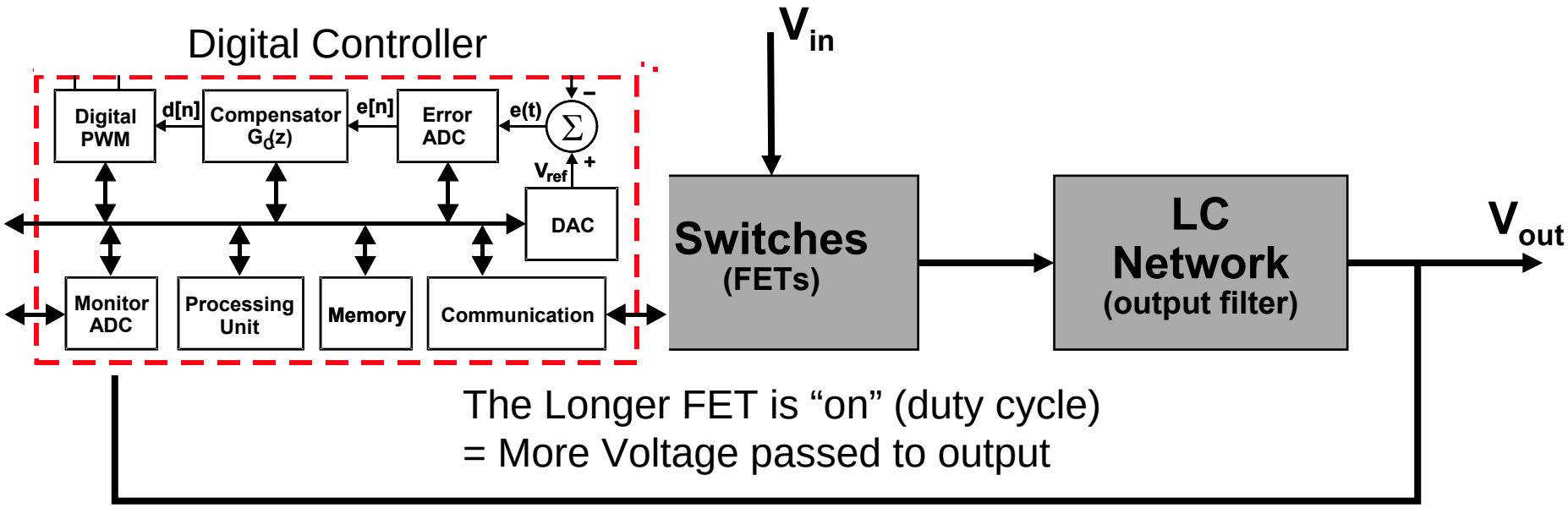
C2000 Digital Power Solutions

Agenda

- Power Systems Overview
- Why Digital Control
- Digital Controller Requirements
- Why C2000 for Digital Power
- Software Development Tools
- Hardware Development Tools

Voltage Regulator Systems



Goal: Maintain constant Vout regardless of change in Vin or load, within spec.

The controller block is what differentiates between a digital power system and a conventional analog power system

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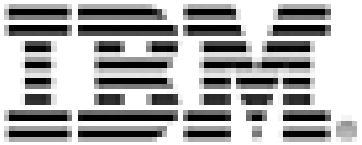
Why Move to Digital?



Powercasts © 2006 Darnell Group, Inc.

Wants their server power suppliers to because it…

- Reduces Costs
  - Development
    - Tunable Platforms Lead to New Products Quicker
  - Qualification
    - Calibration, better noise and temperature immunity
  - Manufacturing
    - Reduced Board Area
    - Reduced Parts Count = Lower Inventory
- Higher Quality
  - Adaptive; efficiency across load range
  - Flexibility Through Programmability
  - Calibration at Final Functional Test
  - Less Sensitive to Environment and Component Drift
  - Better Noise Immunity
  - Parameter Monitoring for Continual Quality Improvement
- Higher Reliability
  - Intelligent Diagnostics, Failure Prediction; Reporting Capability
  - Reduced Parts Count = Fewer Field Failures

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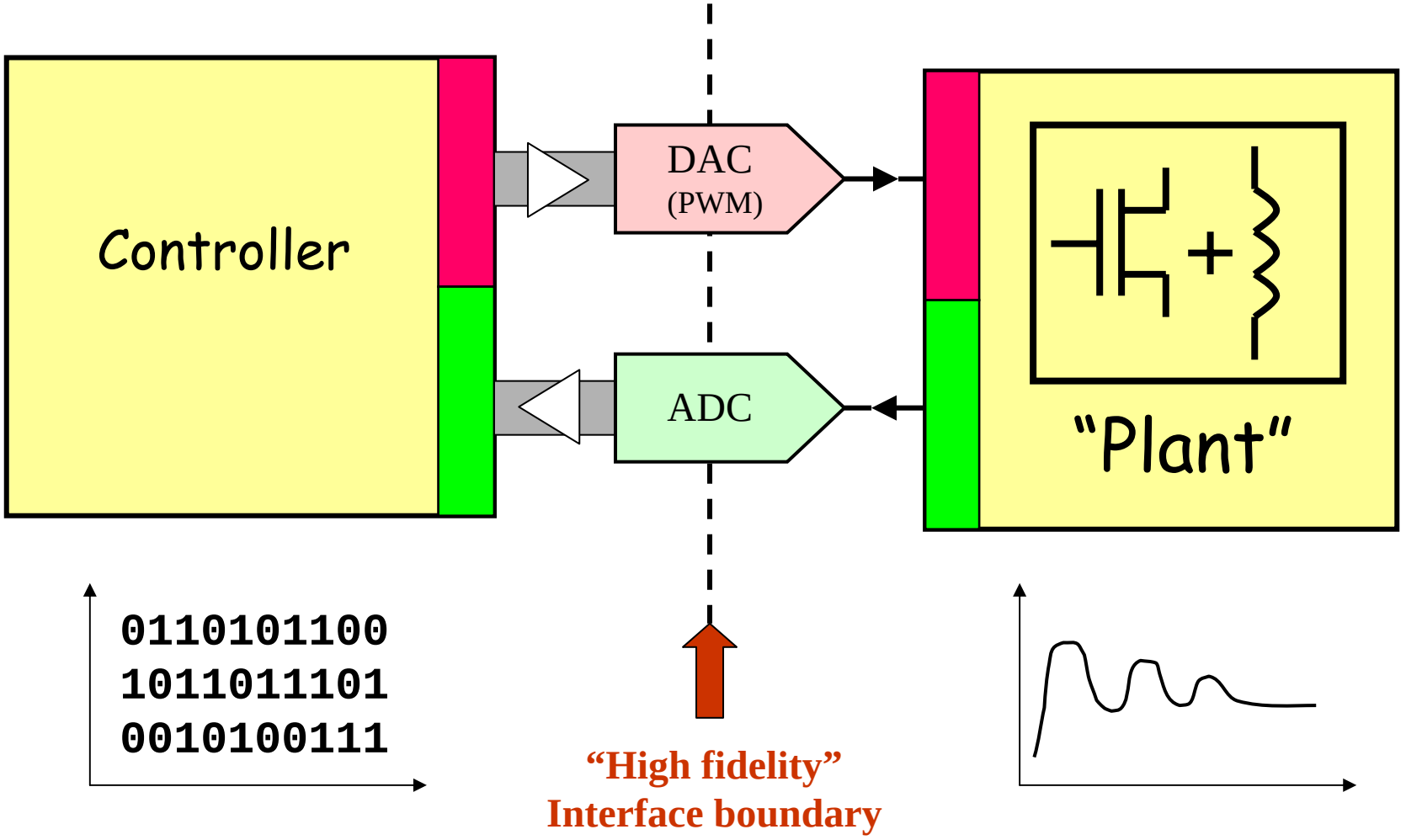
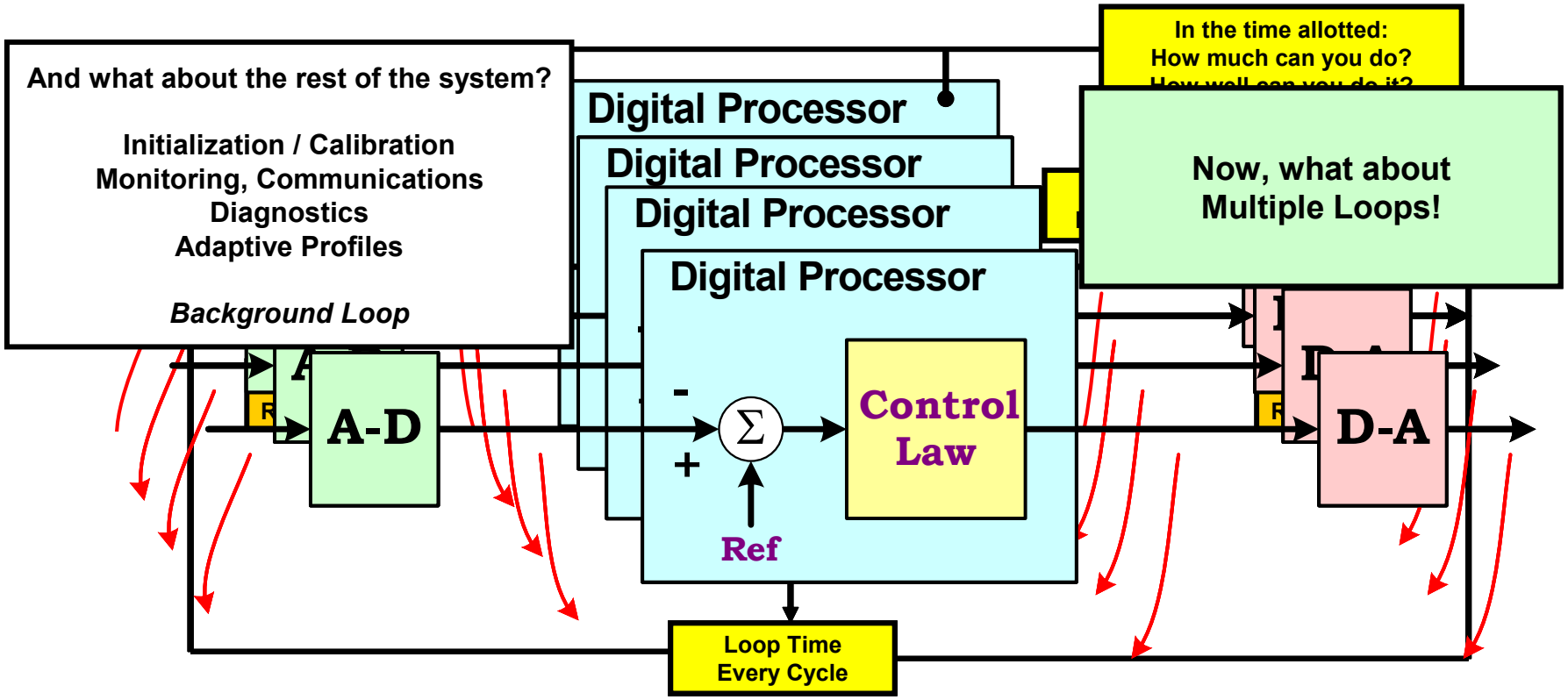
Digitally Controlled System



Time Sampled Systems

What Matters?

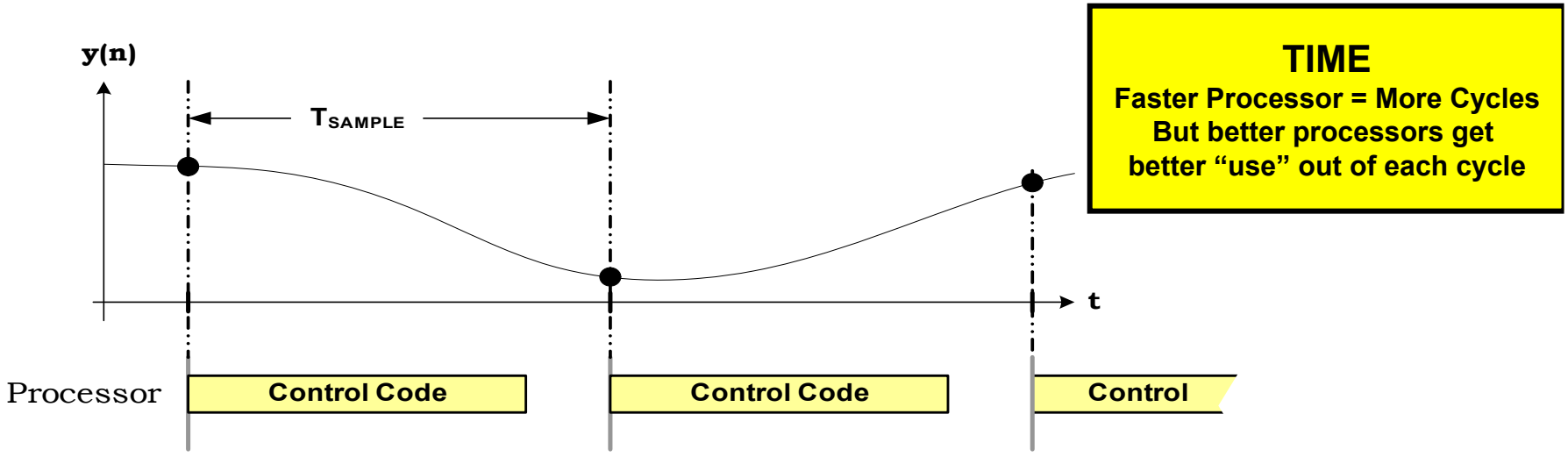


You need to sample-control-output i.e. “close the loop” within the sample period T.

Sample Period = Frequency of System Update

Faster Sampling = Better Control!

Time: How much do you get?



- The system control signals must be updated a specific rate, or sample frequency
- In a digital system the controller must read in a sample, process it, and then send out updated control signals
  - This requires that the controller execute the control code faster than the sample frequency
- *The faster the sample frequency, the less time the processor has to execute the control code.*

Control Loop Execution Times

- Digital power systems typically operate much faster than a motor control system
  - This is because faster sampling frequencies allow higher switching frequencies
  - Higher switching frequencies enable more efficiency and smaller electrical components
- Fast loop speeds make digital power very processor intensive

TIME
Faster Processor = More Cycles
But better processors get better "use" out of each cycle

	Sample F = KHz	Period ns	Cycles @ 40 MHz	Cycles @ 60 MHz	Cycles @ 100 MHz	Cycles @ 300 MHz
Motor Control	10	100,000	4,000	6,000	10,000	30,000
	20	50,000	2,000	3,000	5,000	15,000
PFC AC/DC	50	20,000	800	1,200	2,000	6,000
	100	10,000	400	600	1,000	3,000
DC/DC	250	4,000	160	240	400	1,200
	500	2,000	80	120	200	600
	1,000	1,000	40	60	100	300
	1,500	667	27	40	67	200
	2,000	500	20	30	50	150

What do you spend this time on?

- Sample Frequency = execution time for control loop
  - Interrupts / Latency
  - ADC Sampling / Converting
  - Control / Compensation
    - Ex: 2nd order Look-Up Table, Direct-Form Digital Filter, PI / PID Digital Filter, 2P2Z, 3P3Z
  - PWM Driver (Pattern Generation)
    - Ex: Buck, Phase Shifted Full Bridge, PFC, 2 Phase Interleaved, Multi-phase Interleaved, Half H-Bridge, Full Bridge, DAC, etc
  - *Processor must be able to execute loop faster than the sample frequency*
- Extra cycles are spent running background tasks or other control loops
  - Communications, sequencing, margining, fault detection, “secret sauce”
  - *Control loop execution time directly affects what other tasks the processor can run*

TIME

What can you do?

TIME

How well can you do it?

To be discussed in the software section…

Background Loop

- Cycles not used by the control loop are used in the background task
- Background tasks encompass digital communication to report status, fault, and on-line diagnostics. Other possibilities are:
  - Dynamic configuration
  - Margining
  - Soft start/stop
  - Tracking
  - Sequencing
  - Synchronization
  - Selectable fault response
  - Output voltage set-point
  - Load current monitoring
  - Temperature monitoring
  - OC, OV, and OT protection threshold programming
  - Power Good, Critical Fault Indicators
  - Error data logging to flash or through comms

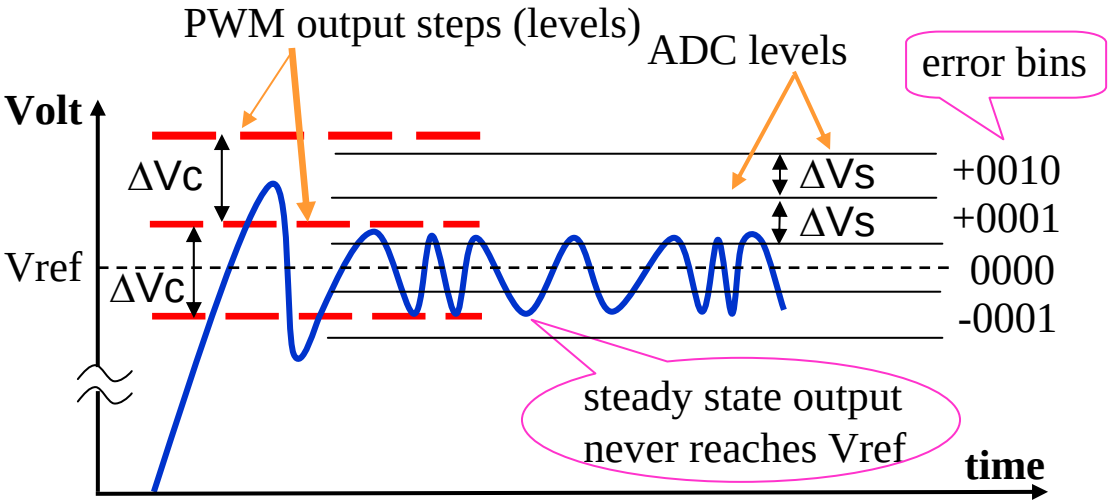
- *Background tasks enable customer's "special sauce" that differentiates from competitors*

Importance of Resolution

- Analog to digital and digital to analog resolutions directly affects how precisely the system can be controlled
  - For digital power systems this corresponds to **PWM resolution and ADC resolution**
- **For most controllers ADC resolution isn't a problem, but PWM resolution is**
- ***With poor PWM resolution the controller can't hit desired output, as the PWM output does have enough resolution***

RESOLUTION

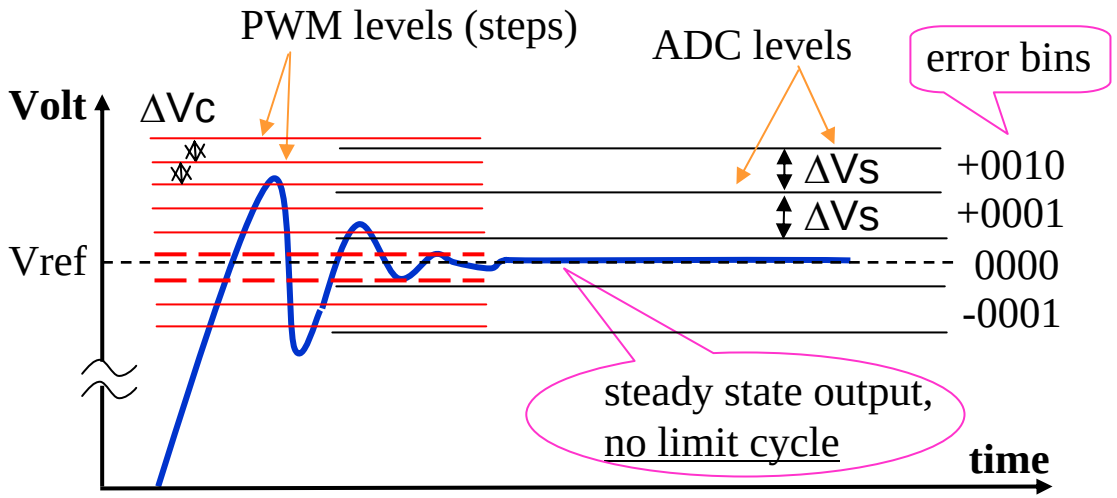
Sample & Output



Good PWM Resolution

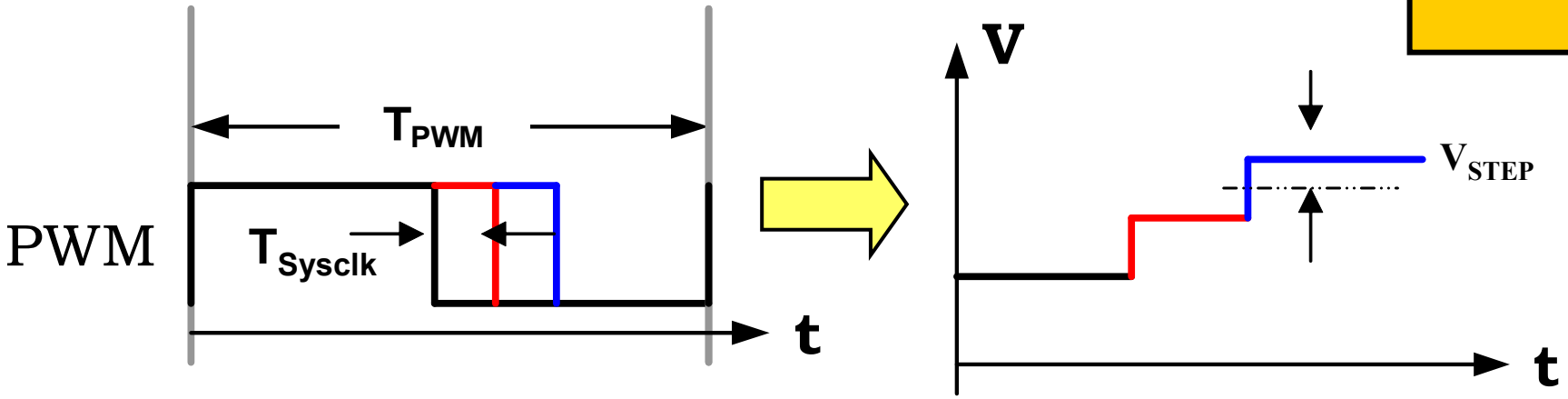
Output Resolution

- High resolution on the PWM output enables more “steps” enabling the controller to hit the desired output
  - *PWM steps typically correspond to duty cycle, other PWM characteristics can also affect the system.*
- **Typically to have enough resolution the system’s DAC resolution must be greater than the ADC resolution**



DAC Resolution: PWM Steps

Output Resolution



DAC Resolution = Log_2 (Period/ Step-Size)

Update Period	PWM Step	
(kHz)	25 ns (bits)	10 ns (bits)
20	11.0	12.3
50	9.6	11.0
100	8.6	10.0
150	8.1	9.4
250	7.3	8.6
500	6.3	7.6
750	5.7	7.1
1000	5.3	6.6
1500	4.7	6.1
2000	4.3	5.6

- PWM step size is based on the PWM clock, which is usually derived from the CPU clock
  - 40 MHz Clock = 25 ns Step
  - 100 MHz Clock = 10 ns Step
- Minimum PWM resolution needs to be >=10 bits
- For high frequency loops standard PWM gives too little resolution

DAC Resolution: High-Res PWM

Output Resolution

- At 20MHz almost any power stage can be controlled
- At a resolution of 150 pico seconds frequencies over 20MHz can be achieved
  - To reach the frequency with a traditional PWM the clock would need to be over 6.6GHz!
- *High resolution PWM technology from TI enables 150ps resolution off of a 40MHz clock*

Update Period	PWM Step		
	25 ns	10 ns	150 ps
(kHz)	(bits)	(bits)	(bits)
20	11.0	12.3	18.3
50	9.6	11.0	17.0
100	8.6	10.0	16.0
150	8.1	9.4	15.4
250	7.3	8.6	14.7
500	6.3	7.6	13.7
750	5.7	7.1	13.1
1000	5.3	6.6	12.7
1500	4.7	6.1	12.1
2000	4.3	5.6	11.7

What's Important for a Digital Controller

1. High speed control loop execution
   - Processor must be able to execute control loop faster than the system update frequency
   - Processor needs to execute control code fast enough to leave headroom for background tasks
2. High fidelity analog to digital and digital to analog conversion
   - High speed, good resolution ADC
   - High resolution PWM output
3. Software
   - Since the system is being controlled digitally, software to control the system must be written
   - Customers need example code, libraries, and easy to use development tools

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Piccolo MCU

12-bit

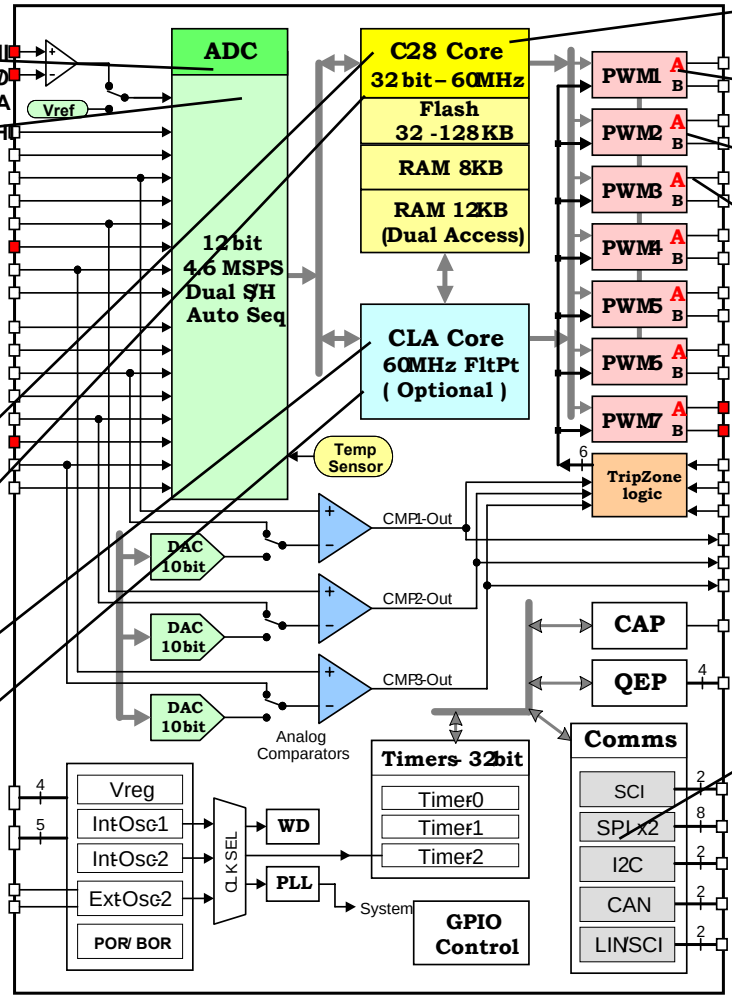
220 ns

16-25 ns

32-bit

16 ns

32-bit
Floating Point



150 ps

11-18 bits

7
Independent
PWM Pairs

Completely programmable MCU for all comms, background tasks, monitor, fault detection, sequencing, etc.

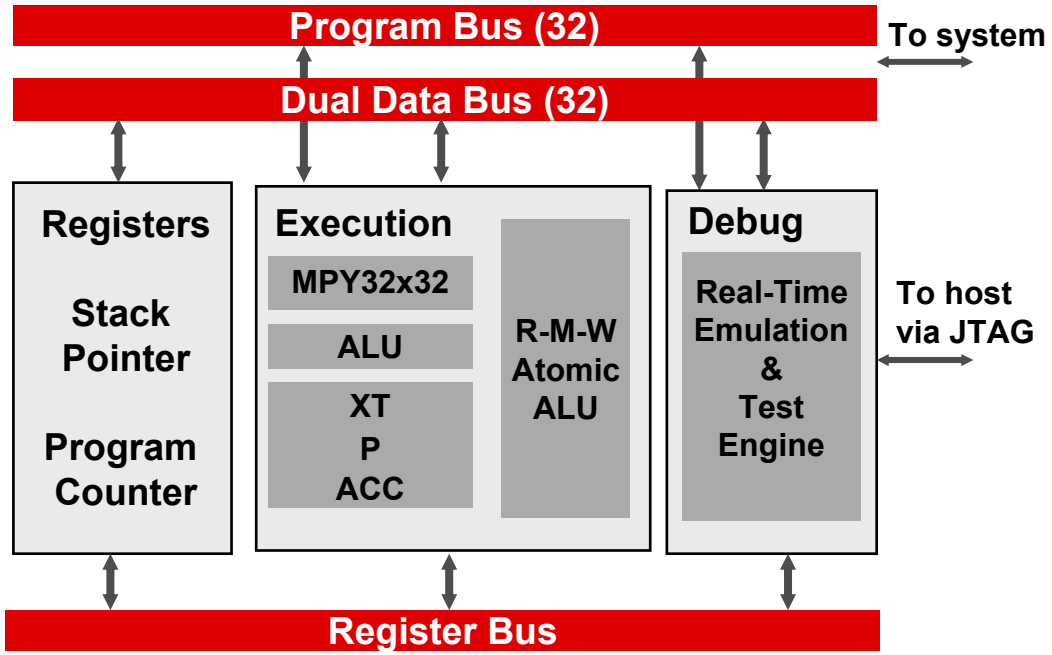
Flexible communication options, including I2C, CAN, and UART

- **Minimized external chip "life support"**
  → Single 3.3V, Dual Oscs, Clock Fail, POR, BOR
- **Analog integration**
  → High-speed ADC, comparators, 10 bit DACs
- **Algorithm Acceleration (with CLA)**
  → Companion 32 bit math engine
- **Reduce Sample to PWM update delay**
  → CLA direct connect to ADC, PWM, Memory,...etc
- **Reduce Sample Latency**
  → ADC sequencer with "On demand" conversion

38 to 80 pins, 105C/125C
$1.85 - $4.60 1ku

C28x Core

The 32-bit C28x core is at the heart of every C2000 28x microcontroller. Based on a DSP architecture, the core is optimized to quickly execute math-based operations, but can also handily process general-purpose code.



C28x CPU

- 32-bit fixed-point DSP
- RISC instruction set
- 8-stage protected pipeline
- 32x32 bit fixed-point MAC for single-cycle 32-bit multiplys
- Dual 16x16 bit fixed-point MACs
- Single-cycle instruction execution

Modified Harvard Bus Architecture

- Separate data and instruction buss
- Two data buses – one for read, one for write
- Enables fetch, read, and write in a single cycle

Emulation Logic

- Real-time emulation allows interrupt servicing even when main program is halted
- Debug host has direct access to registers and memory
- Enables data logging to the debug host
- Multiple hardware debug events and breakpoints

Control Law Accelerator (CLA)

Independent 32-bit floating-point math accelerator

Operates independently of the C28x CPU

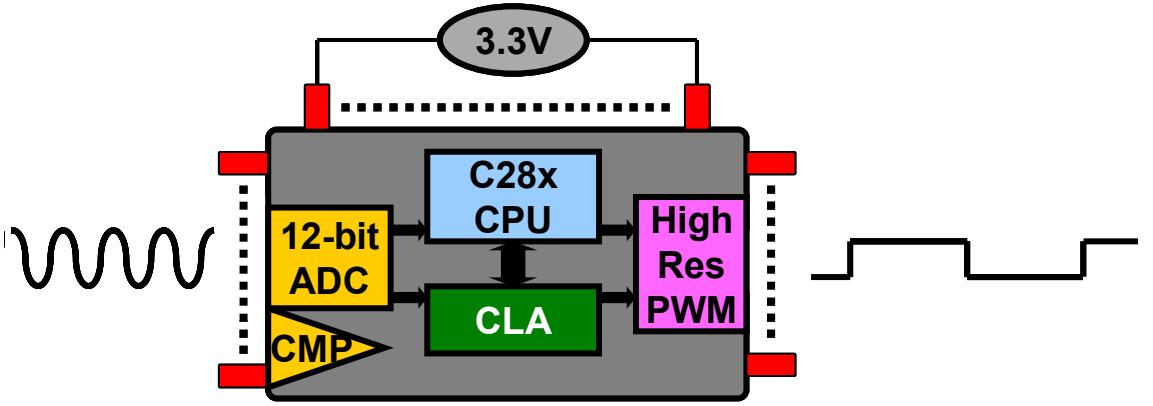
- Independent register set, memory bus structure & processing unit
- Low interrupt response time

Direct access to on-chip peripherals

- Execution of algorithms in parallel with the C28x CPU

Fully programmable: IEEE 32-bit floating

- Removes scaling and saturation burden



Reduced **Sample-To-Output** Delay

Faster System Response & Higher MHz Control Loops

Improved Support For Multi-Channel (Phase/Freq) Loops

Digital Power Applications

Improved System Robustness

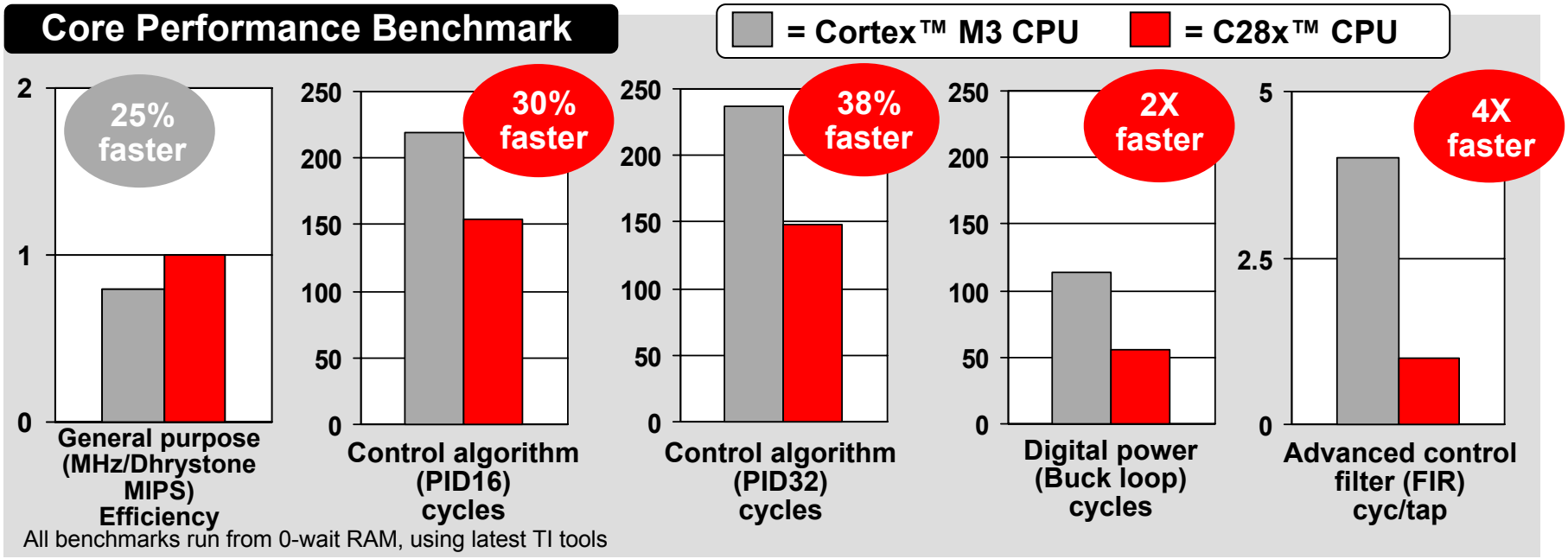
Automotive, White-goods

Free-Up C28x CPU For Other Tasks (communication, diagnostics)

General Purpose MCU Applications

Piccolo™ is the right solution for Real-Time Control

Core Performance Benchmark



All benchmarks run from 0-wait RAM, using latest TI tools

Operation	Cortex-M3 (72 MHz)	C28 (60MHz)	C28/CLA (60MHz)
Feedforward control cycles	786	482	482 / 0
Feedback control cycles	1762	1081	0 / 550
Total Control Law cycles	2548	1563	482 / 550
MHz used (20 kHz loop)	**~51MHz**	**~32MHz**	**~10/11MHz**

Dhrystone benchmark is industry standard, does not benchmark the math performance of a processor

< 1/3 headroom

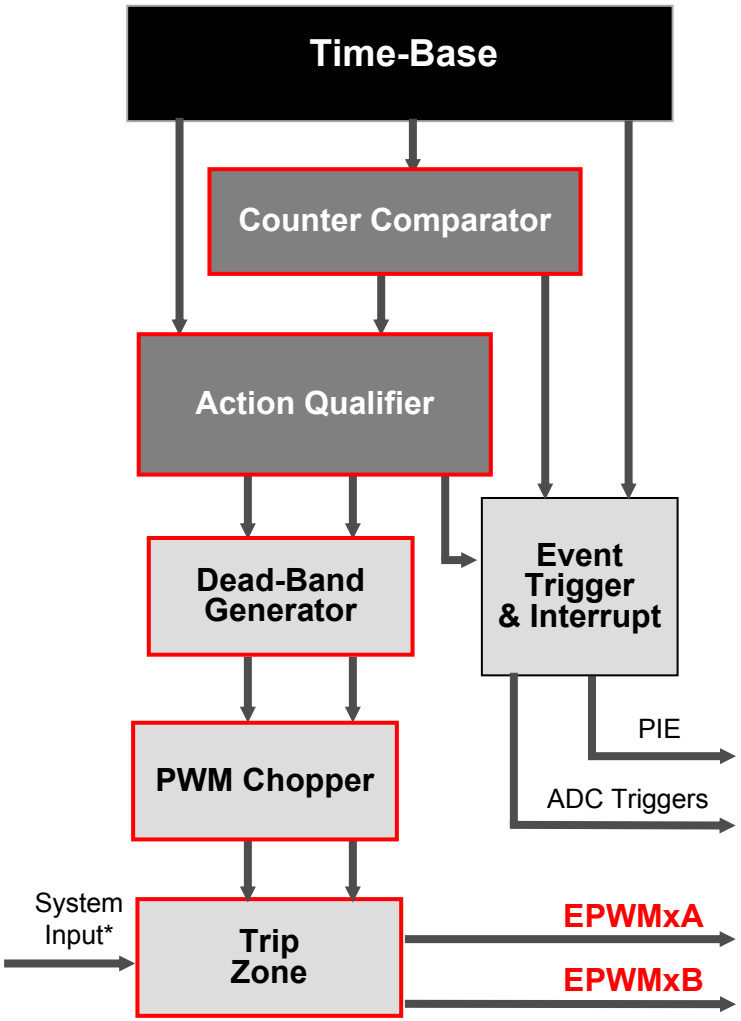
20% faster, lower frequency, 50% headroom

5X faster, lower frequency 80% headroom

Texas Instruments

Enhanced PWM (ePWM)

Each ePWM module has two independently configurable outputs, EPWMxA and EPWMxB, as illustrated below:



Dedicated 16-bit Time Base

- Uses prescaled CPU system clock.
- Synchronizes with other ePWM Modules in phase shift and frequency

Counter Comparator (CC)

- Registers and comparators eliminate the need to interrupt the CPU in PWM generation
- Can function as a 16-bit input capture (rising edge only)

Action Qualifier

- Generates actual PWM signal with information from CC and timer.

Programmable Dead-Band Generator

- Programmable rising-edge and falling-edge delay

PWM Chopper

- Allows a high-frequency carrier signal to modulate PWM waveforms
- Programmable chopping frequency, duty cycle, and first pulse width

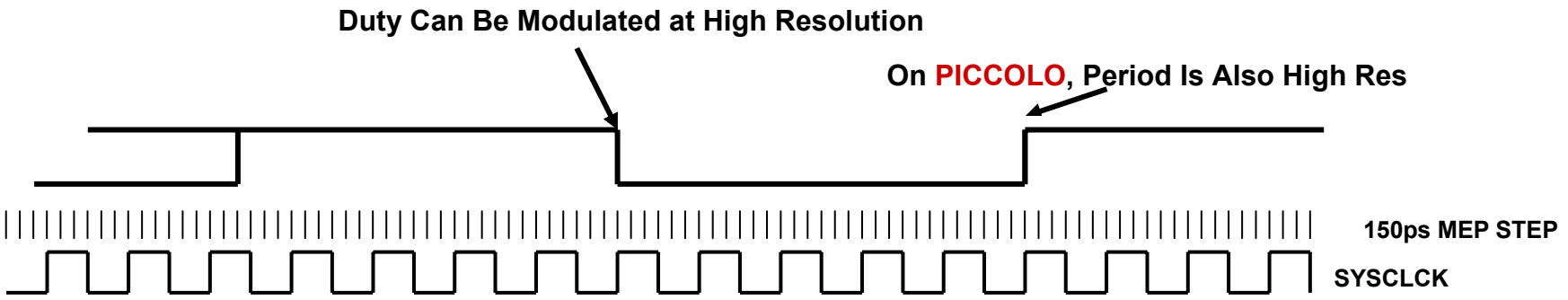
Programmable Trip Zone Generator

- Quickly overrides PWM signals to a pre-programmed state.
- One-shot or cycle-by-cycle operation
- Can generate events, filtered events, or trip conditions

Event Trigger and Interrupt

- Two ADC start-of-conversion signals and a PIE interrupt request line

High Resolution PWM



EX:
Target PWM f = 189.753KHz
50% Duty Cycle
40MHz SYSCLK

Hi-Res
189.755KHz, error = 2Hz = 0.001%

No Hi-Res
190.476KHz, error = 721Hz = 0.38%

Update Period	PWM Step		
(kHz)	25 ns (bits)	10 ns (bits)	150 ps (bits)
20	11.0	12.3	18.3
50	9.6	11.0	17.0
100	8.6	10.0	16.0
150	8.1	9.4	15.4
250	7.3	8.6	14.7
500	6.3	7.6	13.7
750	5.7	7.1	13.1
1000	5.3	6.6	12.7
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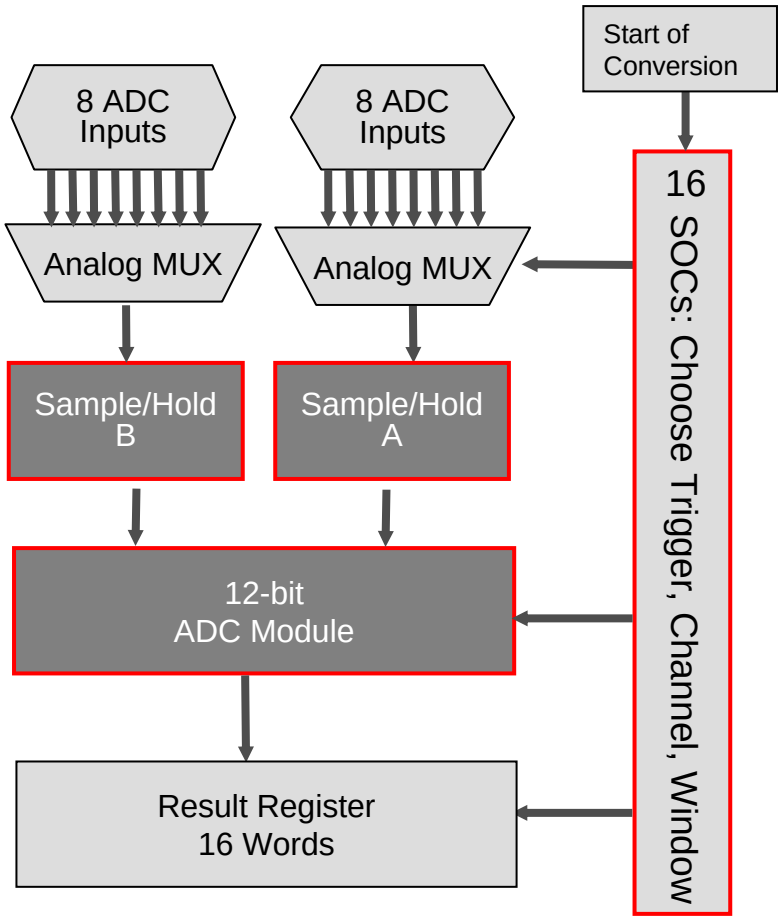
12-bit Pipeline/SAR Hybrid ADC

Piccolo's hybrid ADC allows flexible creation of conversion sequences.



Start of Conversion (SOC) Configuration and Logic Block

- 16 SOC triggers from Software, CPU timers, ePWMs, and GPIOs
- Allows easy creation of conversion sequences
- Multiple conversions can be processed in Round Robin or Priority Modes
- 9 flexible interrupts

Up to 16 Analog Inputs

- 16 channel, multiplexed analog inputs.
- Supports both 0-3.3V fixed range and ratio-metric input range

Analog Mux

- Uses SOC input to select which channels will be processed

Dual Sample and Hold

- Dual sample/hold enable simultaneous sampling or sequencing sampling modes
- Adjustable acquisition window ensures proper sampling

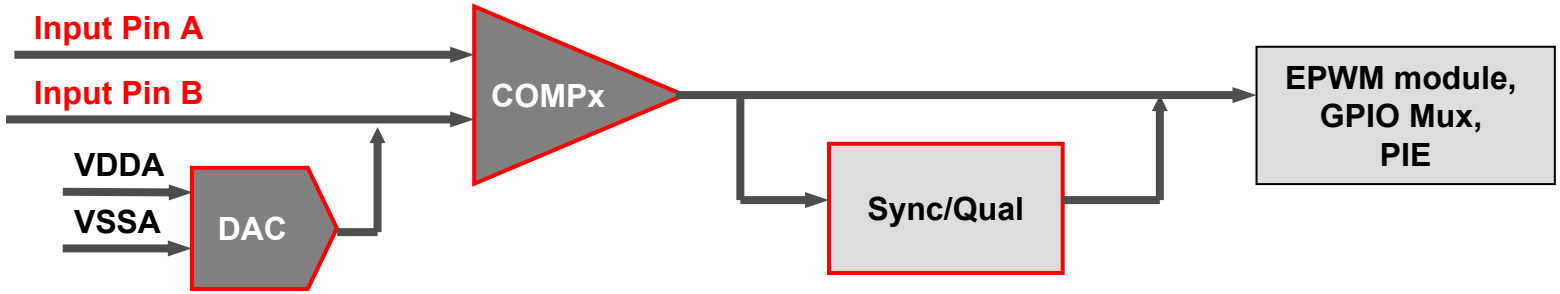
12-bit Analog-Digital Converter

- Fast conversion rate: Up to 5MSPS
- Just-in-time interrupts (early interrupts) eliminates context switch latency by calling interrupts before conversion finishes

Result Registers

- Sixteen result registers (individually addressable) to store conversion values

Comparators



- Comparators enable instant protection in the case of a fault condition
  - Example: Output is shorted, system starts to draw too much current. Current measurement fed directly to the comparator. Once too much current is drawn comparator instantly shuts off PWMs shutting down the system
- 30ns response time to PWM modules
- Comparator can also be used for Peak Current Control
- For more information see “C2000 Architecture and Peripherals” presentation

Comparator Reference Guide

Piccolo: F2802x, F2803x – spruge5

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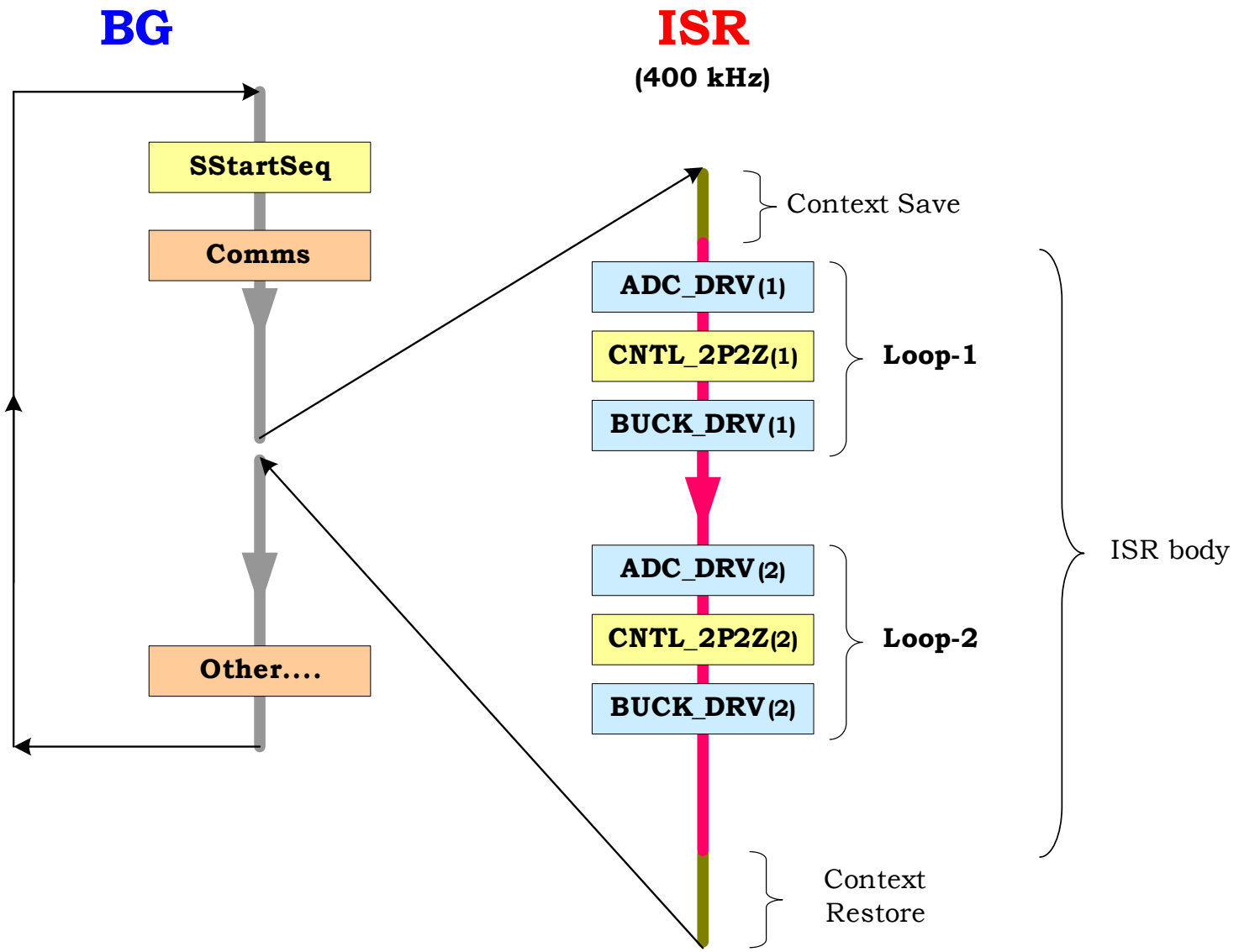
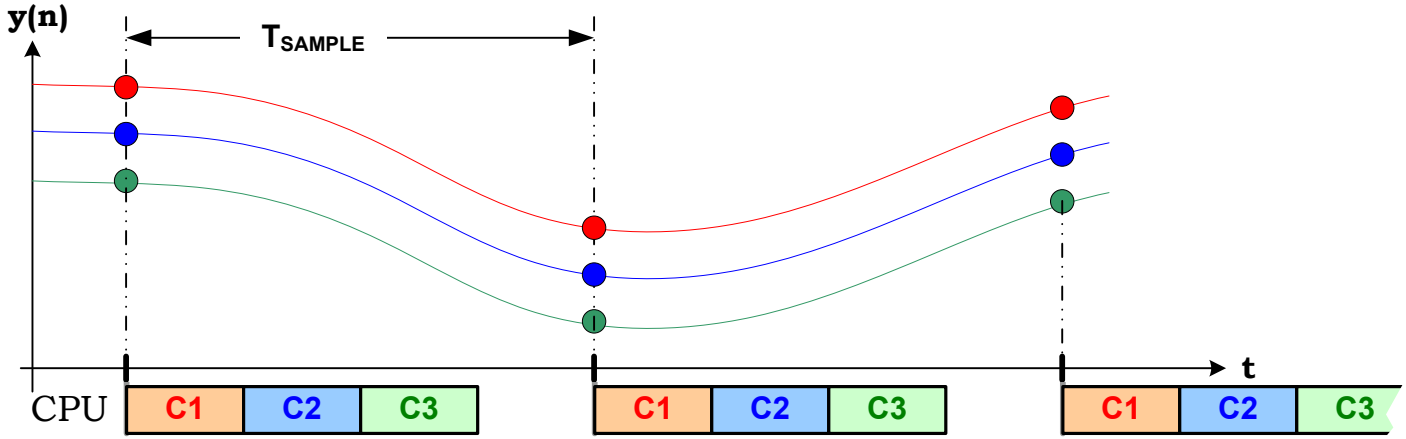
Control Software Basics

- Typically want to have one control loop interrupt and multiple background tasks
  - Single control loop interrupt runs all control loops
  - Enables software to be simple and loop execution time to be very deterministic
- For multiple control loop, the control loop interrupt runs at the speed of the fastest loop and the other loops are divided into sections
- Background loop runs all other tasks and services non-control (lower priority) interrupts
- This is TI's method for control software, some customers use and RTOS or other control schemes. The key is that the control loops must execute at a precise rate.

Software Structure

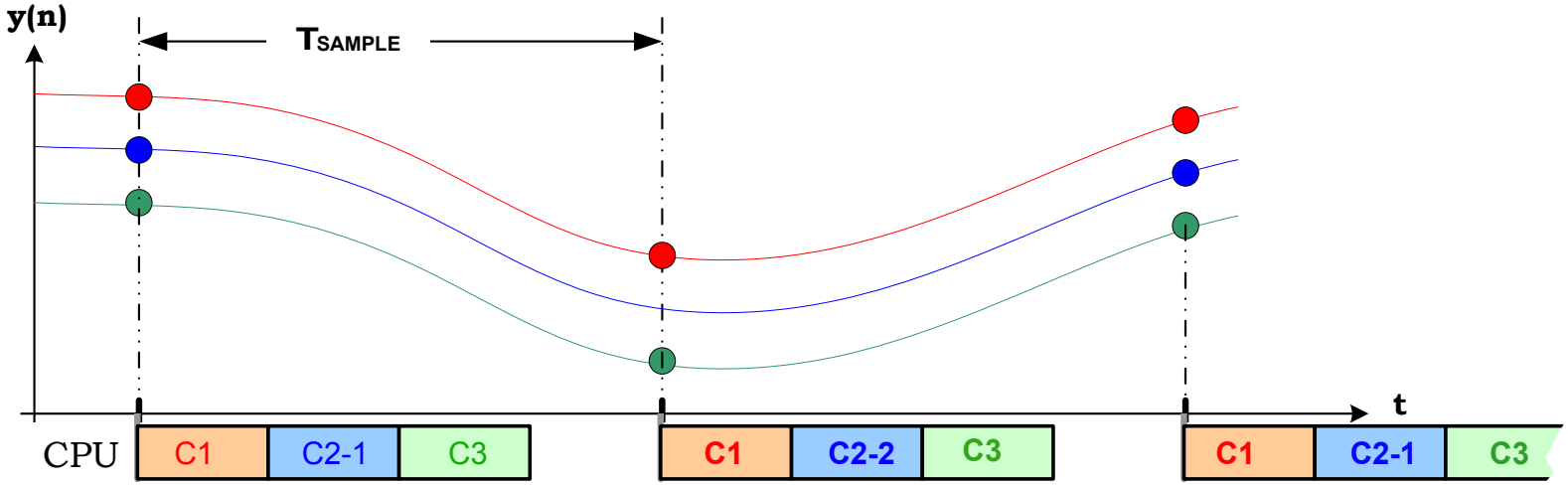


Ru nning Multiple Loops



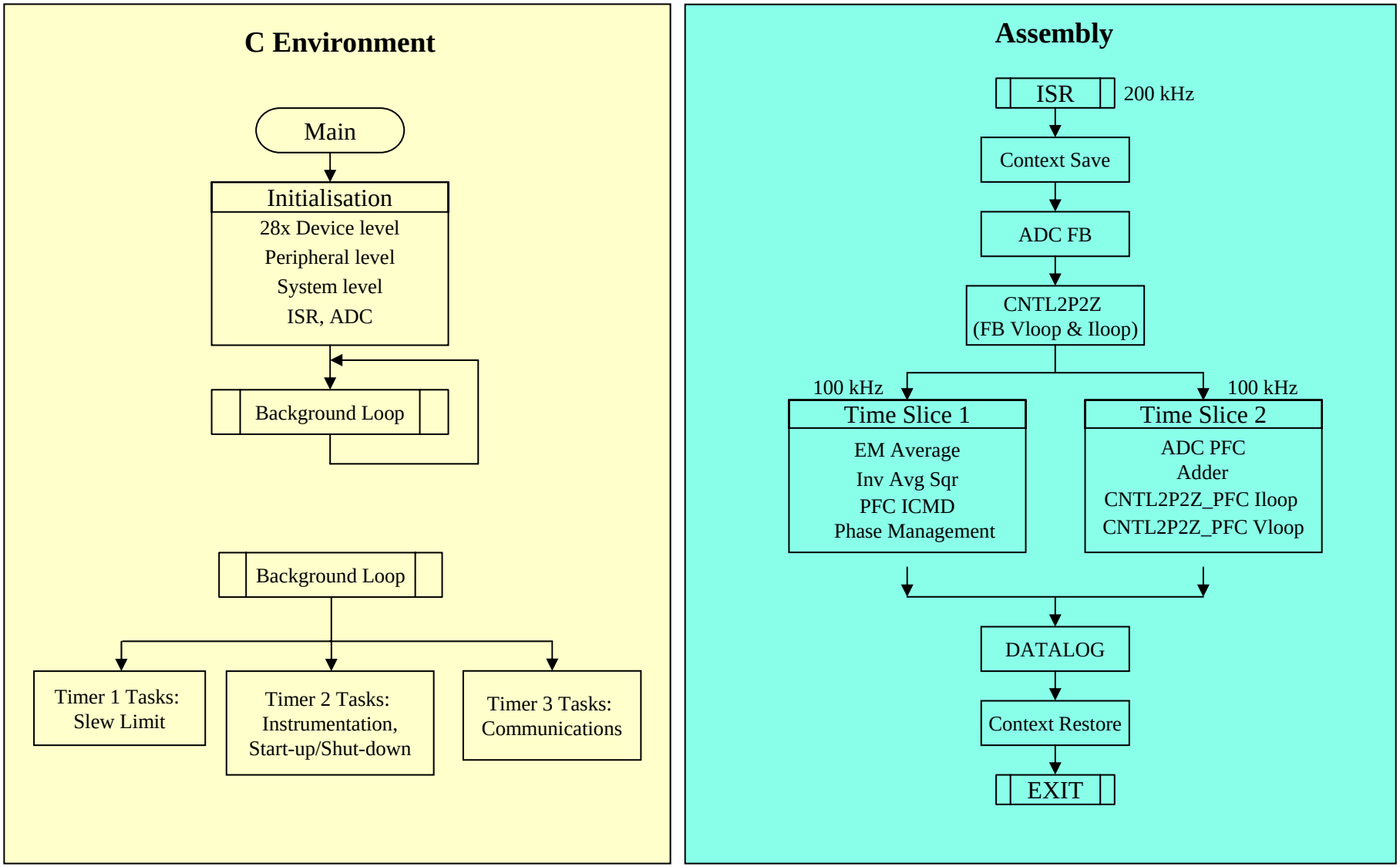
If you can close all the loops in a single Sample Time, GREAT!

If you can't, consider multiple Sample/Update Rates. Slower loops as a divisor of your fastest loop.
Time Division Multiplexing



Texas Instruments

Example: Rectifier Software

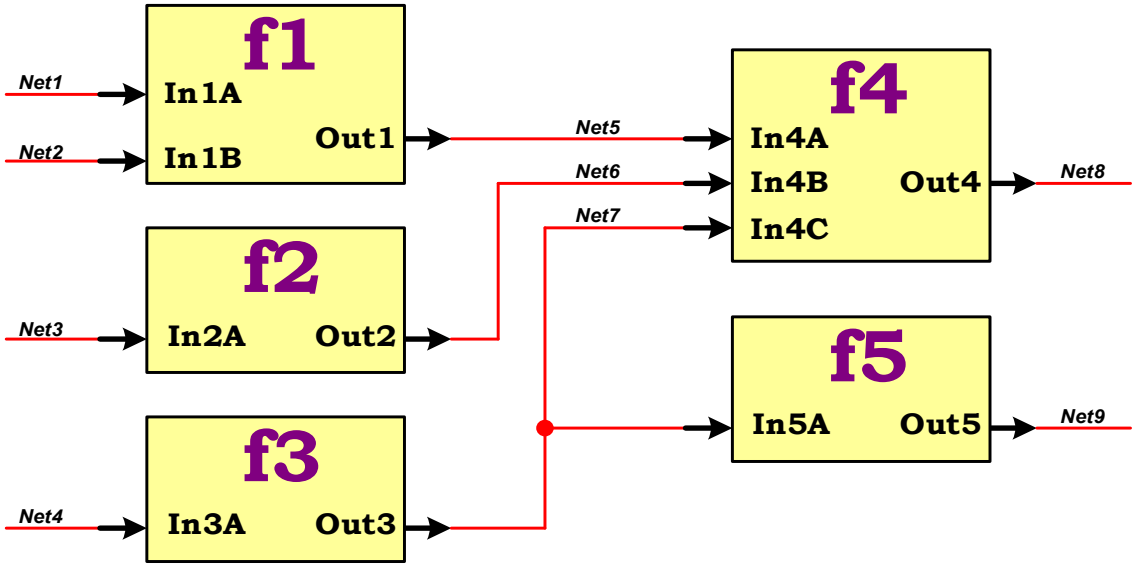


Software Examples and Libraries

- TI's controlSUITE software platform includes examples and modular software libraries
  - With one download controlSUITE provides all digital power software and libraries for C2000 MCUs
- Digital power library uses a modular software approach, with each part of the system being an easy to use software block
  - Over 20 blocks for the C2000 CPU and the CLA
  - Digital power library includes detailed documentation for each block
  - Modular approach enables easy software development

Modular SW Architecture

"Signal Net" based module connectivity



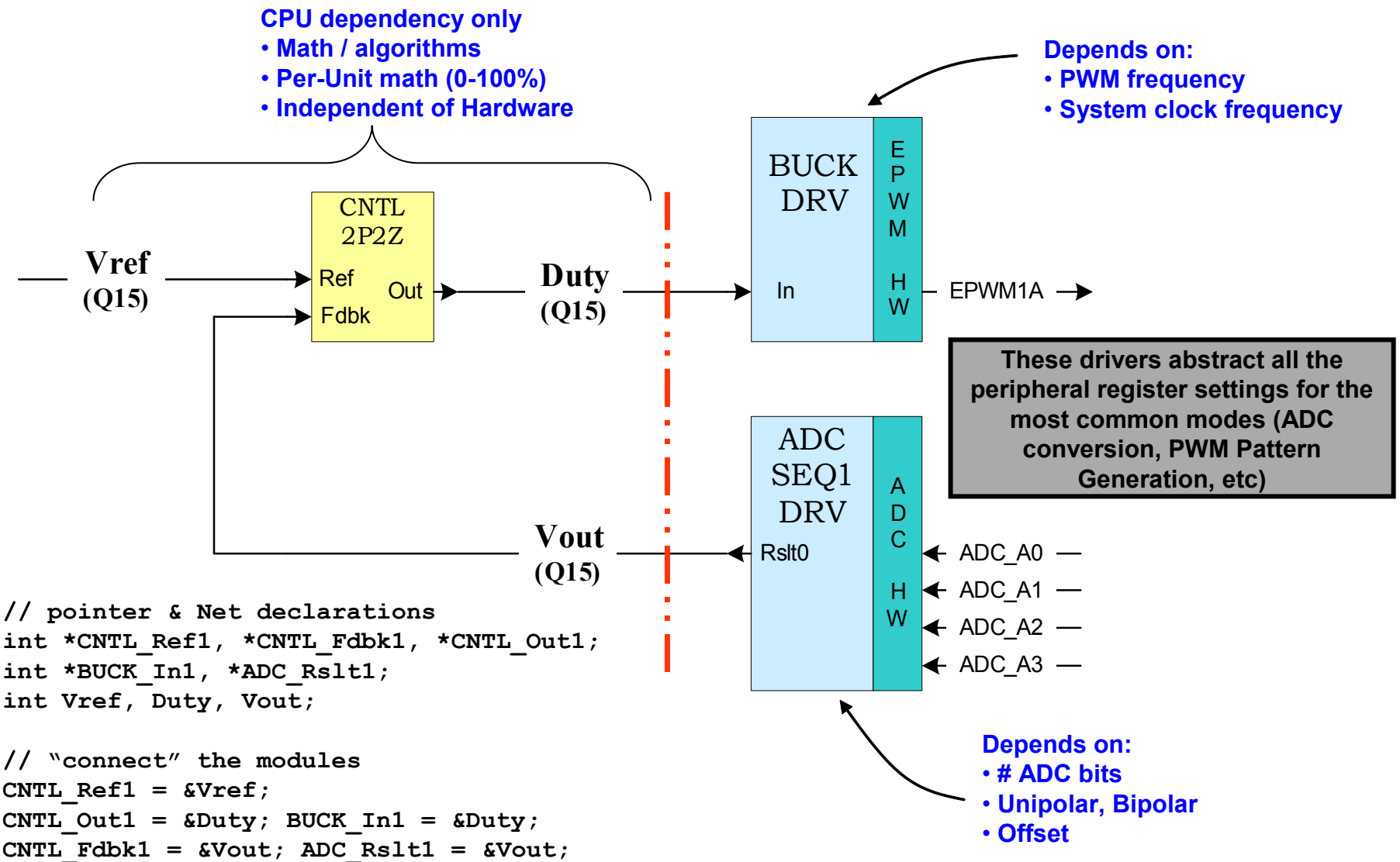
Initialization time

```
// pointer & Net declarations
Int *In1A, *In1B, *Out1, *In2A,...
Int Net1, Net2, Net3, Net4,...

// "connect" the modules
In1A=&Net1; In1B=&Net2; In2A=&Net3; In3A=&Net4; // inputs
Out4=&Net8; Out5=&Net9;                          // outputs
Out1=&Net5; In4A=&Net5;                          // Net5
Out2=&Net6; In4B=&Net6;                          // Net6
Out3=&Net7; In4C=&Net7; In5A=&Net7;              // Net7
```

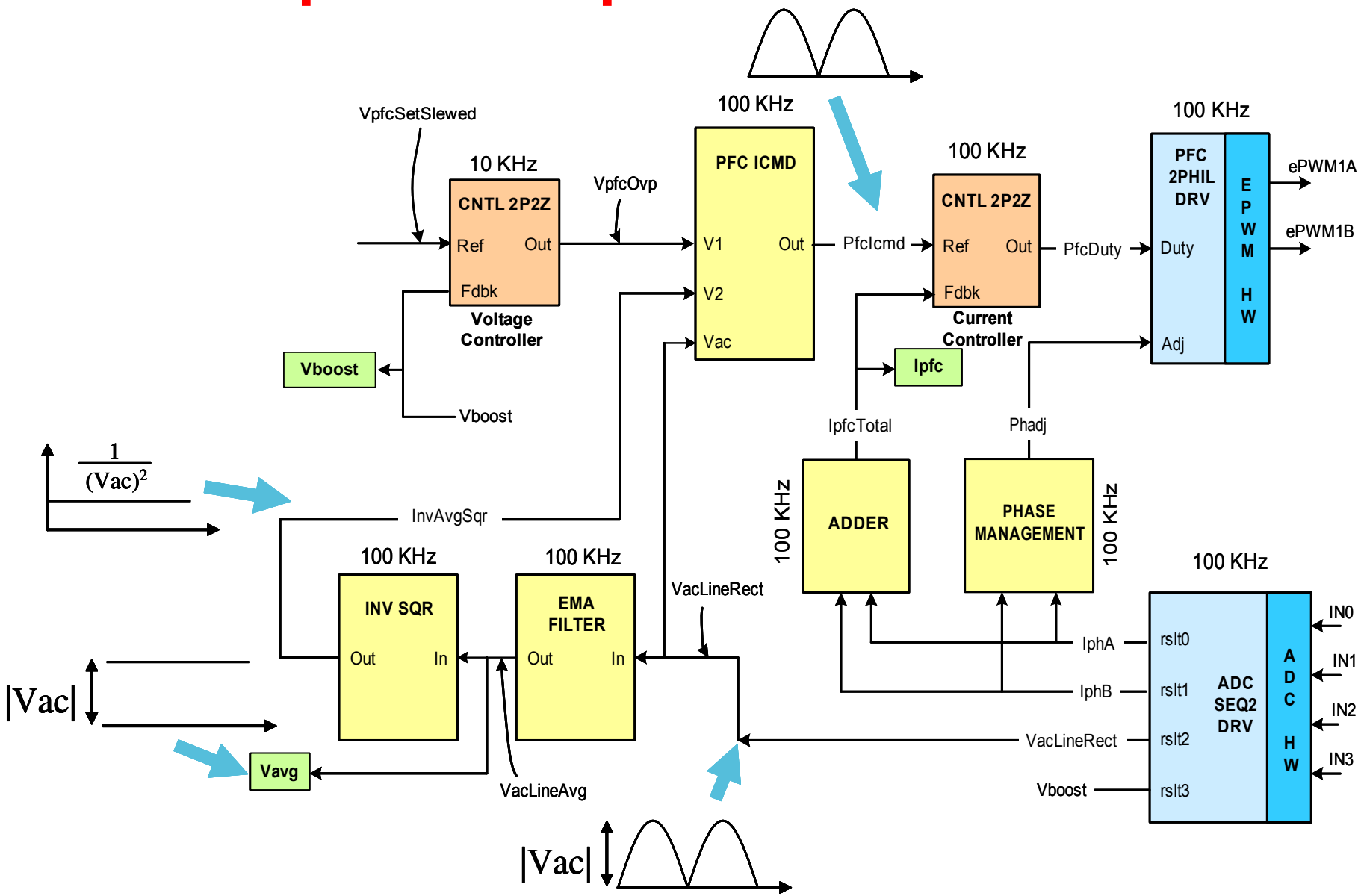
Run time - ISR

```
; Execute the code

    f1
    f2
    f3
    f4
    f5
```

Peripheral Drivers



Example: Example PFC + PSFB



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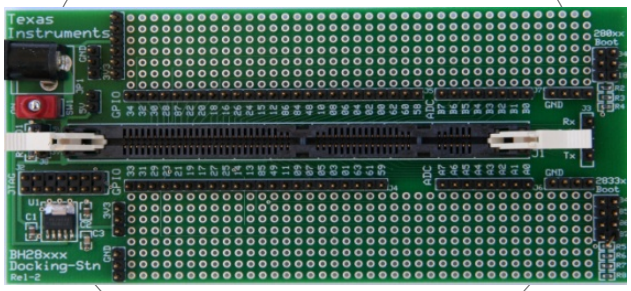
Piccolo controlCARD
Modular, Robust, Standard

controlCARD

- **Low cost, small form factor**
- **Standard DIMM interface**
  - Includes analog I/O, digital I/O, and JTAG signals available at DIMM interface
- **Robust design**
  - Noise filter at ADC input pins
  - Ground plane
  - Isolated UART communication
  - Supply pin decoupling
- **All life support circuitry**
  - Clock, Power Supply, LDO, etc
- **Multiple versions available**
  - Piccolo F28027
  - Piccolo F28035
  - Delfino F28335
  - Delfino C28436
  - F2808
  - F28044
  - $49-69

Pin compatible across the C2000 family!



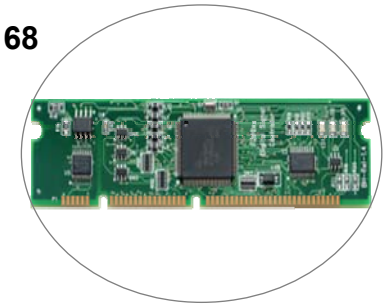
Piccolo DPS Tools Offerings

Device Evaluation

Experimenter's Kit
TMDXDOCK28027
TMDXDOCK28035
TMDSDOCK2808
TMDSDOCK28335
TMDXDOCK28343
$79-$159

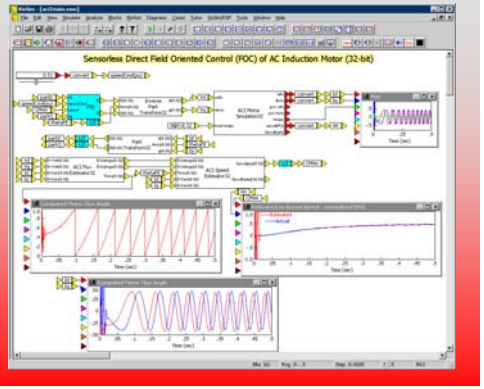
Experimenter's Kit - 168
TMDXDOCK28346-168
$189

Peripheral Explorer
TMDSPREX28335
$179



Graphical Modeling & Code Development
VisSim and The Mathworks

-DPS and Peripheral Blocks
-Simulation and Modeling
-Auto-Tuning
-Code Generation
-Interface to CCStudio IDE
-Integration with Resonant and Renewable Energy Kits



Application Development

Digital Power Experimenter's Kit
TMDSDCDC2KIT
$229

Digital Power Developer's Kit
TMDSDCDC8KIT
$325

AC/DC Developer's Kit
Interleaved 2ph PFC w/ current balancing, PSFB, Peak current mode control
TMDSACDCKIT
$695

Resonant DC/DC Developer's Kit
LLC Resonant DC-DC
TMDSRESDCKIT
$229

Renewable Energy Developer's Kit
TMDSENRGYKIT
$349

DPS Lib
Complete Library of core power control algorithms and peripheral drivers www.ti.com/controlsuite

Piccolo DPS Links

- www.ti.com/dpslib or www.ti.com/controlsuite (7/6/10)
- www.ti.com/c2000getstarted
- Using Multi-Phase DC/DC Power Supply Control

  http://training.ti.com/courses/CourseDescription.asp?iCSID=53935
- Enabling High-Freq Power Conversion Applications

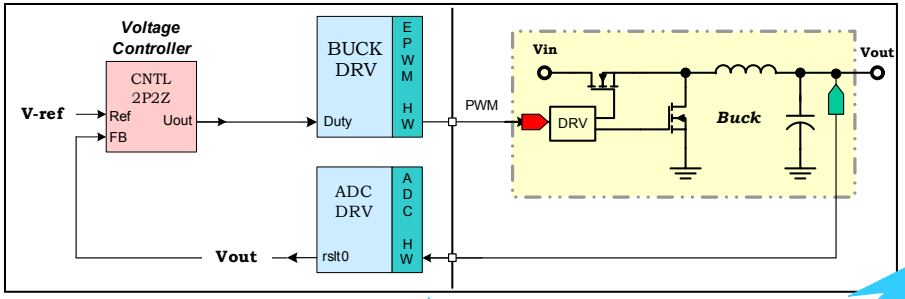
  http://training.ti.com/courses/CourseDescription.asp?iCSID=54032
- Implementing High-BW, Low-Cycle Count Controllers

  http://training.ti.com/courses/CourseDescription.asp?iCSID=54259
- New 4-day Workshop with new power stages and GUI configuration tool!
  - www.ti.com/biricha

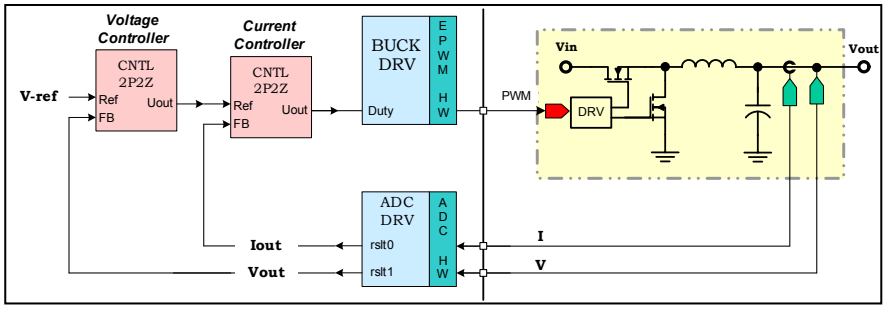
Backup

Flexible Control Methods

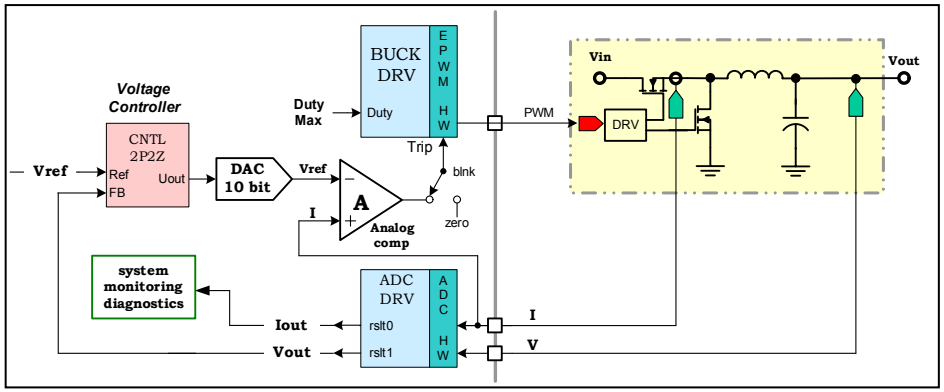
Voltage Mode



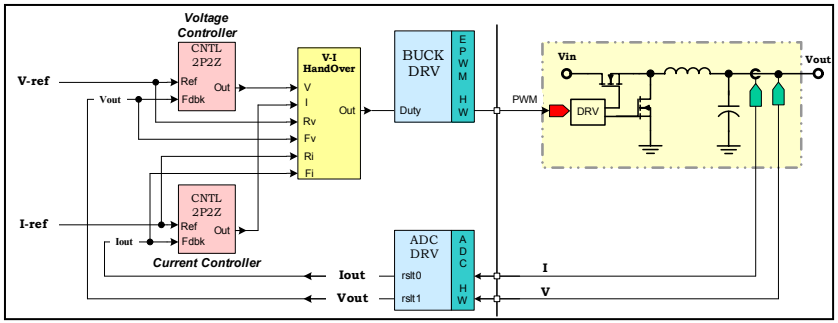
Avg Current Mode

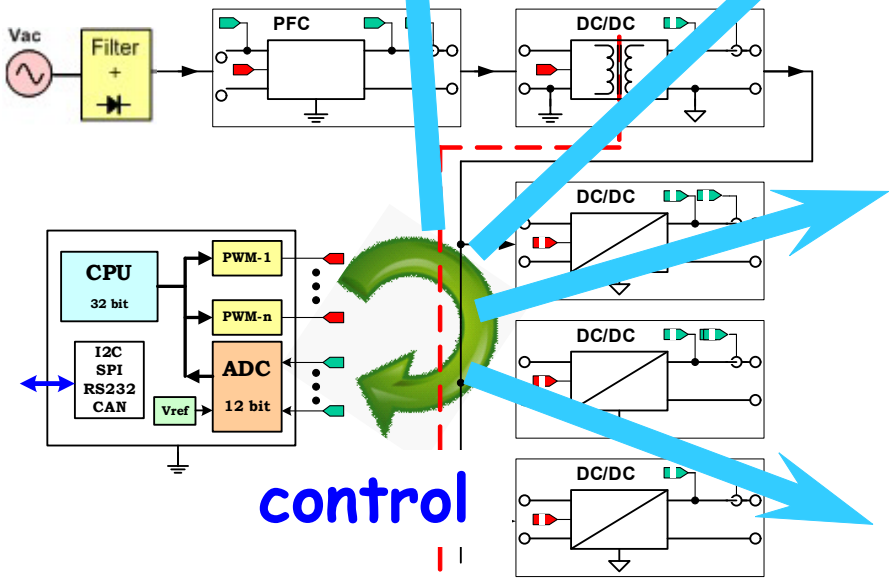


Peak / Over / CbC Current Mode

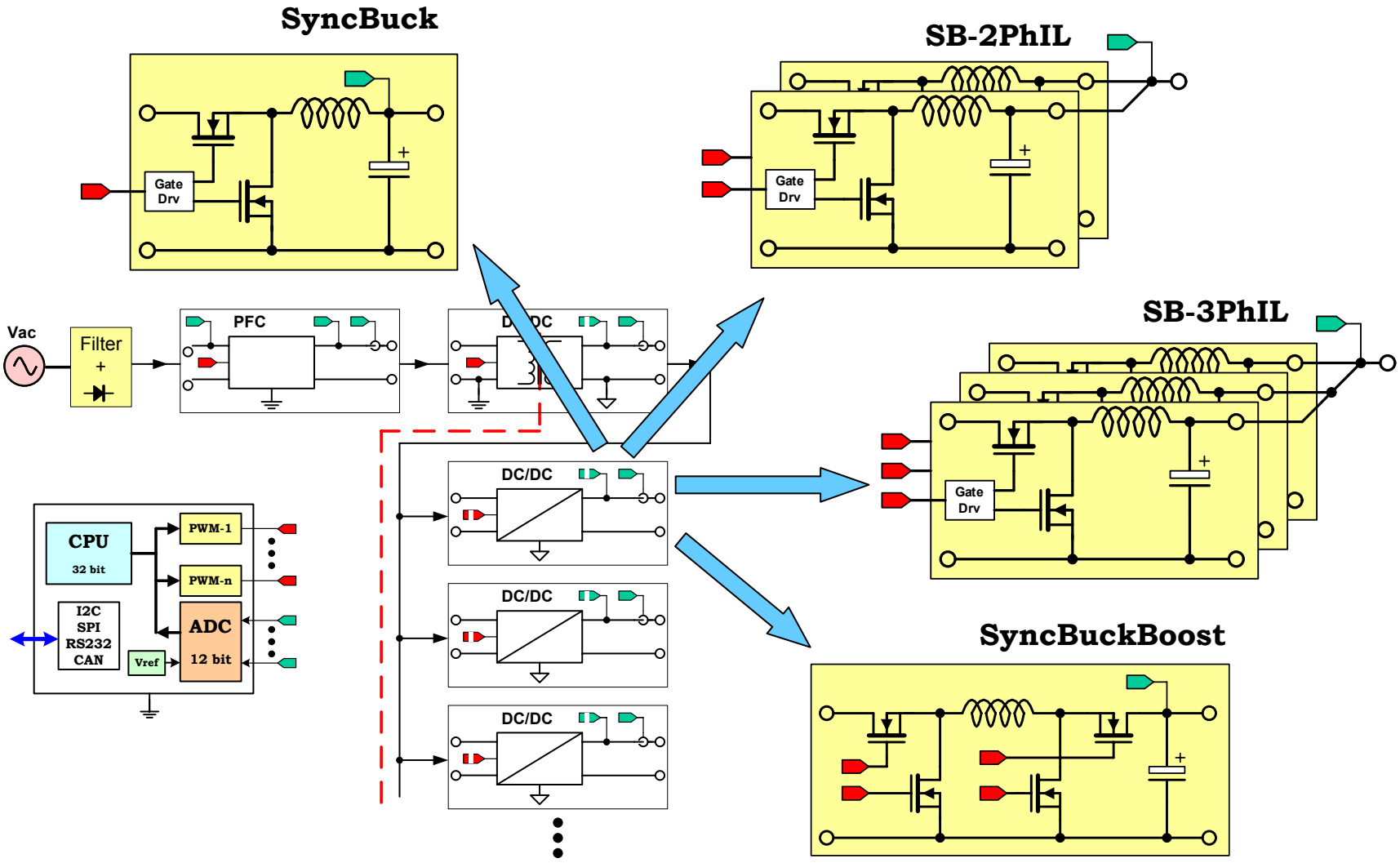


Constant Power

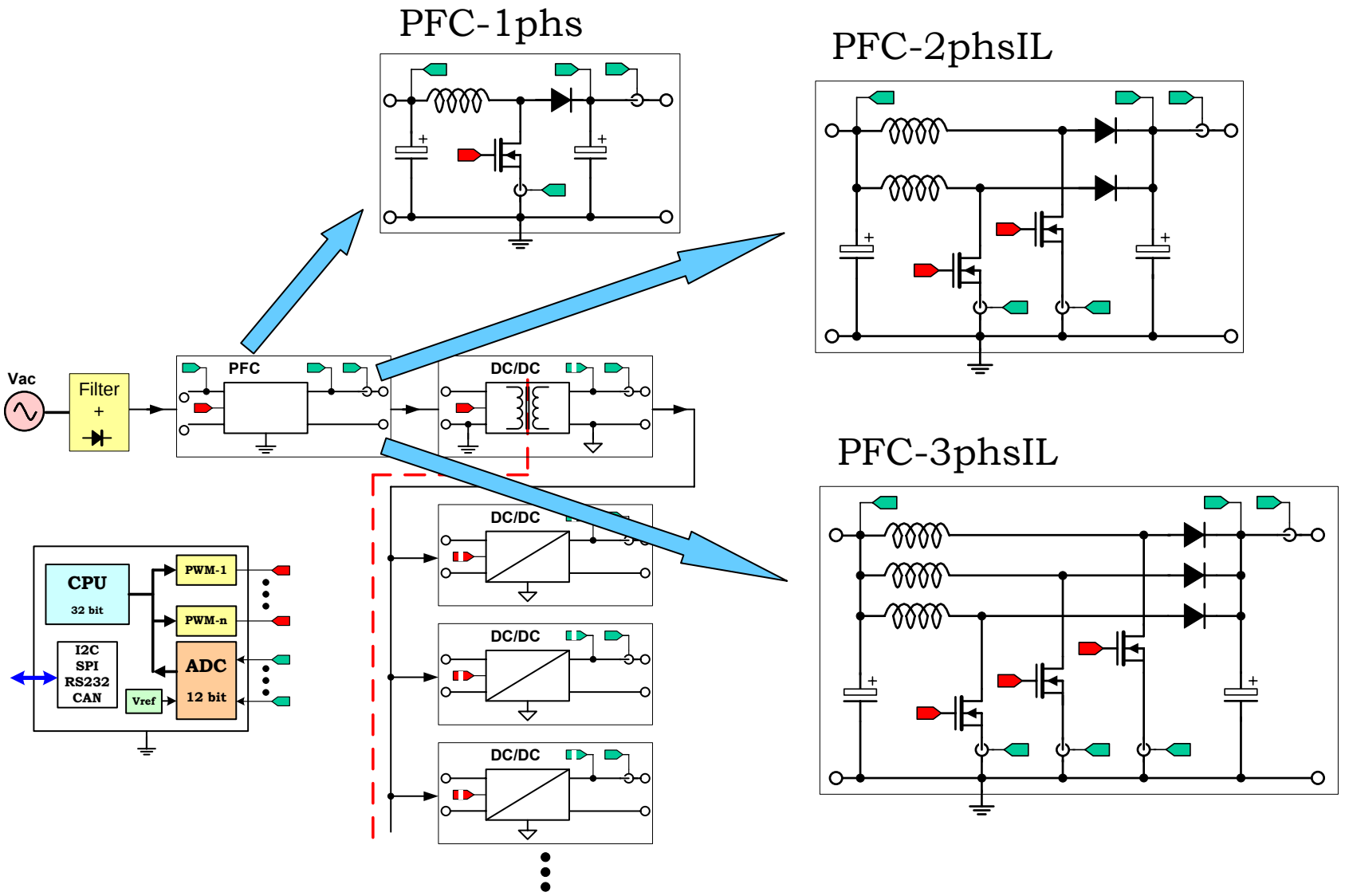




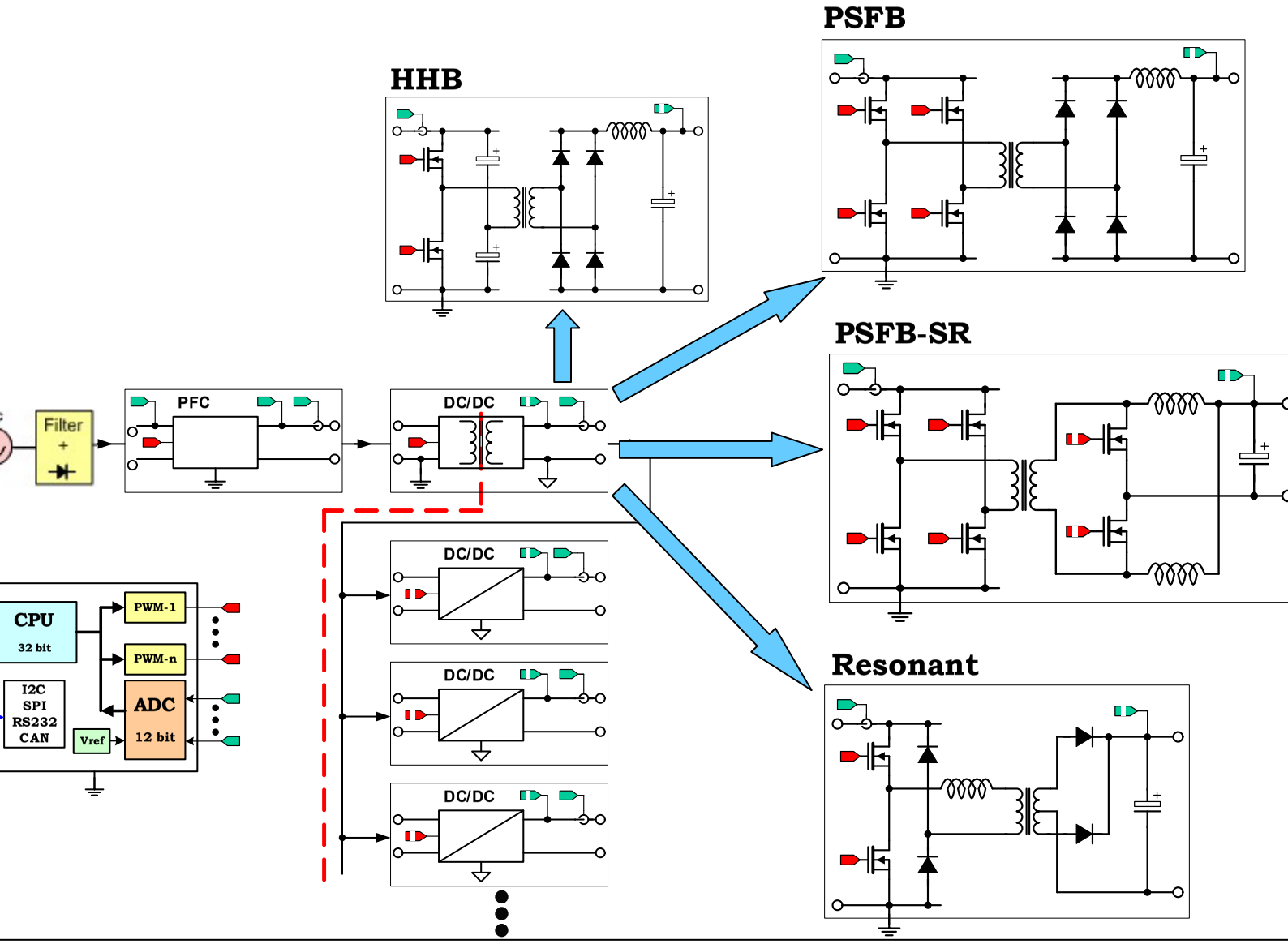
Non Isolated DC/DC Topologies



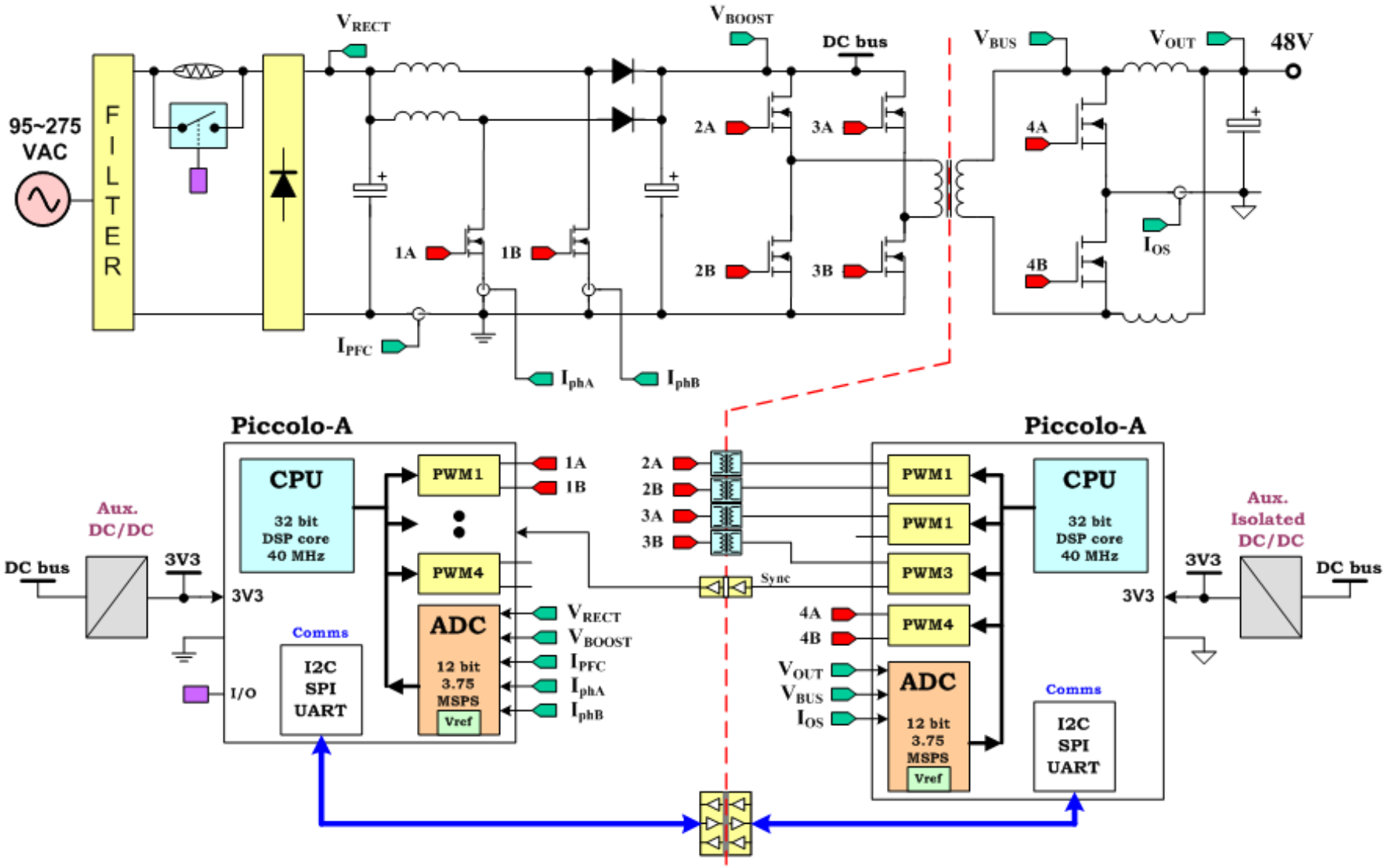
Boost/Power Factor Correction



Isolated Power Supply Topologi



Rectifier: Dual MCUs



Rectifier: Single MCU on Primary