Lecture 15
Nonvolatile Memory & Energy Management

CE346 – Microprocessor System Design

Branden Ghena – Fall 2023

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Administrivia

- Quiz today! Remind me at 4:30

- Office Hours
  - Still available for projects
  - Friday 1-5 we'll be in the Ford classroom for project help

- Projects
  - Get working on them! Likely can't order new things after Thanksgiving

- Hardware
  - I have *the rest* of the hardware on hand to distribute
  - Let's do it right now so I don't have to interrupt the quizzes later

Bonus Topics

- We won’t have time to talk about these, but I have slides, so I included them at the end of this lecture

- SD Card protocol

- PPI and task/event chaining

Today's Goals

- Discuss uses of memory, especially nonvolatile memory, in embedded systems

- Introduce internal flash peripheral

- Discuss matters of energy on embedded systems
    - Where to gain energy?
    - How much does the Microbit use?
    - How do we write software for *very* low energy systems?

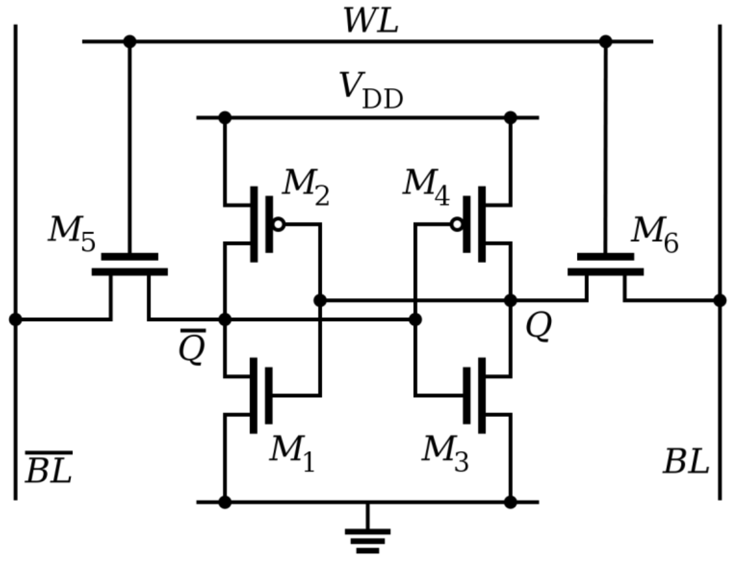
Outline

- **Memory in Computing**
- nRF52 Non-Volatile Memory Controller
- Energy Sources
- Microbit Energy Use
- Intermittent Computing

Memory in computing

- Various different memories serve different purposes in computing
- Needs
  - Fast, infinite-lifetime memory to keep things like stack memory
  - Nonvolatile memory that can be read from
- Desires
  - Fast, infinite-lifetime nonvolatile memory

Register technology: SRAM



- Static RAM (SRAM)
  - Each cell stores a bit in a bi-stable circuit, typically a six-transistor circuit
  - Static – no need for periodic refreshing; keeps data while powered
  - Relatively insensitive to disturbances such as electrical noise
    - Energetic particles (alpha particles, cosmic rays) can flip stored bits

- Fastest memory on computer
  - Also most expensive and takes up most space per bit
  - Typically used for registers and cache memories

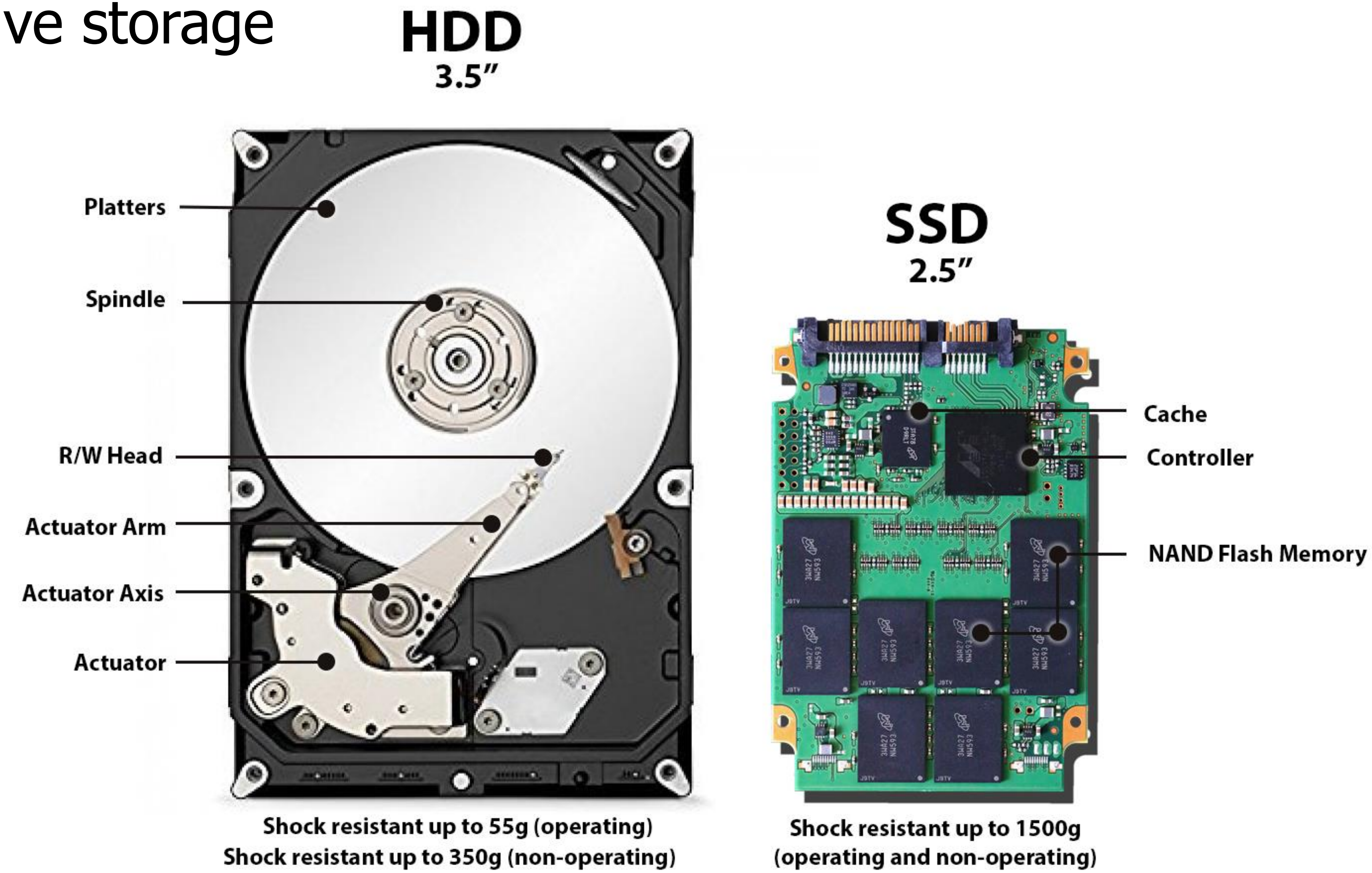
SRAM can be used a permanent memory in a pinch

- Gameboy and Gameboy Color used batteries to save state

- Gameboy Advanced games used batteries for an internal clock

- PSA: old Gameboy games have likely lost their save files

Disk drive storage



Necessity breeds creativity

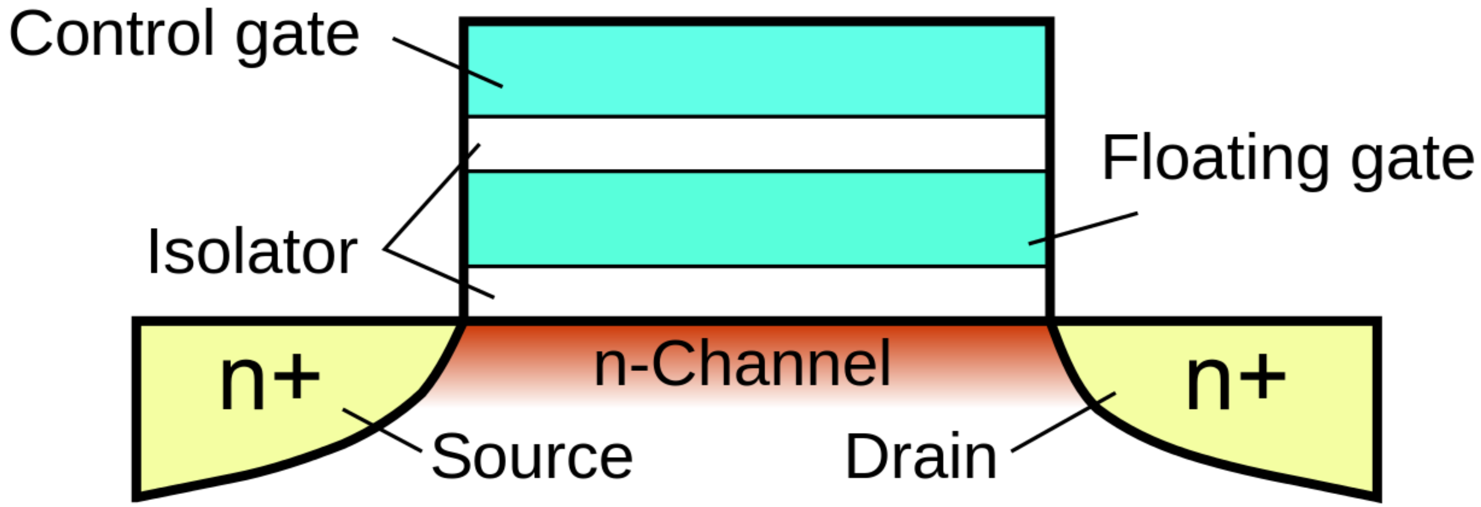
- Original iPod used a small disk drive

Floating-gate transistors

- Concept behind transistor-based non-volatile memory
  - EPROM, EEPROM, and Flash

  - High voltage on control gate creates charge on floating gate
  - Charge on floating gate activates/deactivates transistor

- High voltage degrades the structure, leading it to eventually fail after enough writes



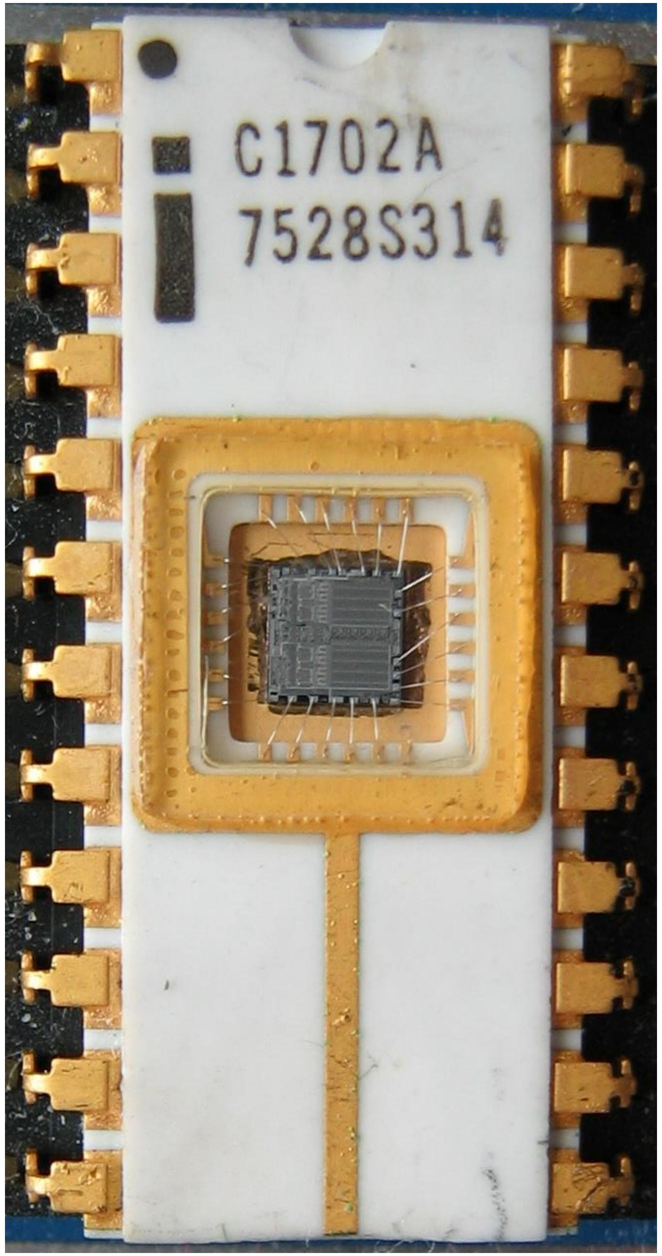
EPROM

- Erasable programmable read-only memory

- Erasable
  - If you shine UV light directly on the IC
  - Needed a window to expose the IC

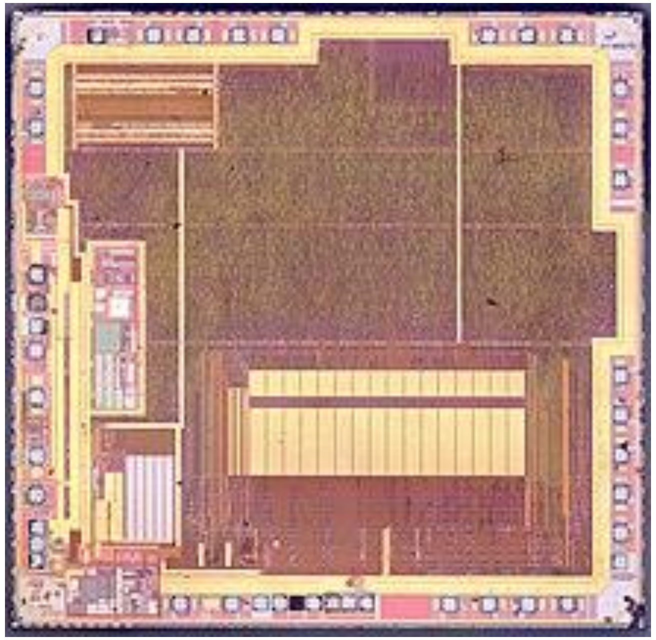
- Programmable
  - With high voltage (25-50 volts)

- Typically acted as read-only memory in circuits



EEPROM

- Electrically-erasable programable read-only memory
- Same concept as EPROM, but includes internal circuitry to allow rewriting under normal conditions
  - Slow and high-power to write
  - Has a longer lifetime compared to flash, ~100k writes
- Can be built into other ICs
  - Example: AT90USB162 microcontroller (512 bytes)



Flash

- Similarly based on floating-gate transistors
  - But with a different design that allows for faster erase of entire blocks
  - More limited lifetime, ~1k-100k writes (10k common for embedded)

- Cannot erase individual bytes, must erase in units of blocks
  - Read can happen in units of bytes though

- Heavily used in commercial devices
  - Flash drives
  - SSDs
  - Smartphone storage
  - Microcontroller non-volatile storage!

More exotic memories

- FRAM and MRAM are both rising protentional Flash replacements
  - Non-volatile
  - Writable at the byte level
  - Very high to infinite write/erase cycles
  - Lower energy costs for writing and reading

- They use unrelated magnetic techniques for data storage

- Starting to appear in microcontrollers
  - TI MSP430s have used 16 kB FRAM
  - Apollo4 (ARM Cortex-M4F) has 2 MB of MRAM

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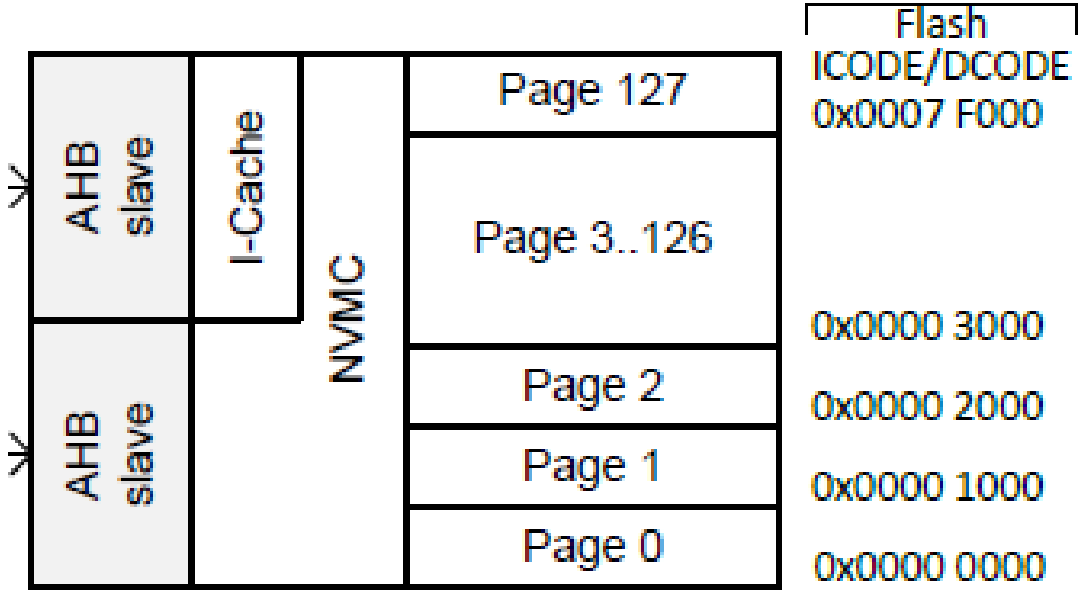
Flash memory on the nRF52833

- 512 kB total Flash memory
  - 128 pages each 4 kB in size

- Non-Volatile Memory Controller (NVMC) controls access
  - Enables writing to flash
  - Enables erasing flash
  - Manages status of flash



Writing to Flash

- Configurable, disabled by default
  - Enable with configuration register

- Rules for writing to Flash
  - Must write word-aligned 32-bit values
  - Can only write 0 values, not ones
  - Can only write 2 times before erasing (even if there are still 1 bits)

- Takes 42.5 μs to write a 32-bit word
  - 64 MHz clock ⇨ 2720 cycles per 32-bit write

Erasing Flash

- Lifetime: 10000 erase cycles per page

- Options
  - Erase a single page (4 kB): 87.5 ms
  - Erase all of flash (512 kB): 173 ms

- CPU is halted if executing code from Flash during the erase
  - That's 5.6 million cycles…
  - Code can execute from SRAM instead
  - Can also be split into a series of partial erases
    - Which must add up to a complete erase time before writing

Factory Information Configuration Registers

- Read-only memory

- Chip-specific information and configuration
  - Code size
  - Unique device ID
  - Production IDs
  - Temperature conversion functions

User Information Configuration Registers

- Additional Flash memory for non-volatile user configurations
  - Writable and erasable through NVMC processes described earlier

- 32 words of customer information (128 bytes total)

- Special configurations
  - Reset pin
  - NFC pin enable/disable
  - Debug configuration

Break + Question

- Could you run a system entirely within Flash?

- Could you run a system entirely within RAM?

Break + Question

- Could you run a system entirely within Flash?
  - Yes, but it would go _very_ slowly
  - Local variables would be pretty hard to manage
    - 87.5 ms of code pause every time you write to a variable…

- Could you run a system entirely within RAM?
  - Yes, but code would need to be loaded from somewhere else
    - Need initial state that is nonvolatile

  - Would run just as fast and be lower energy, actually

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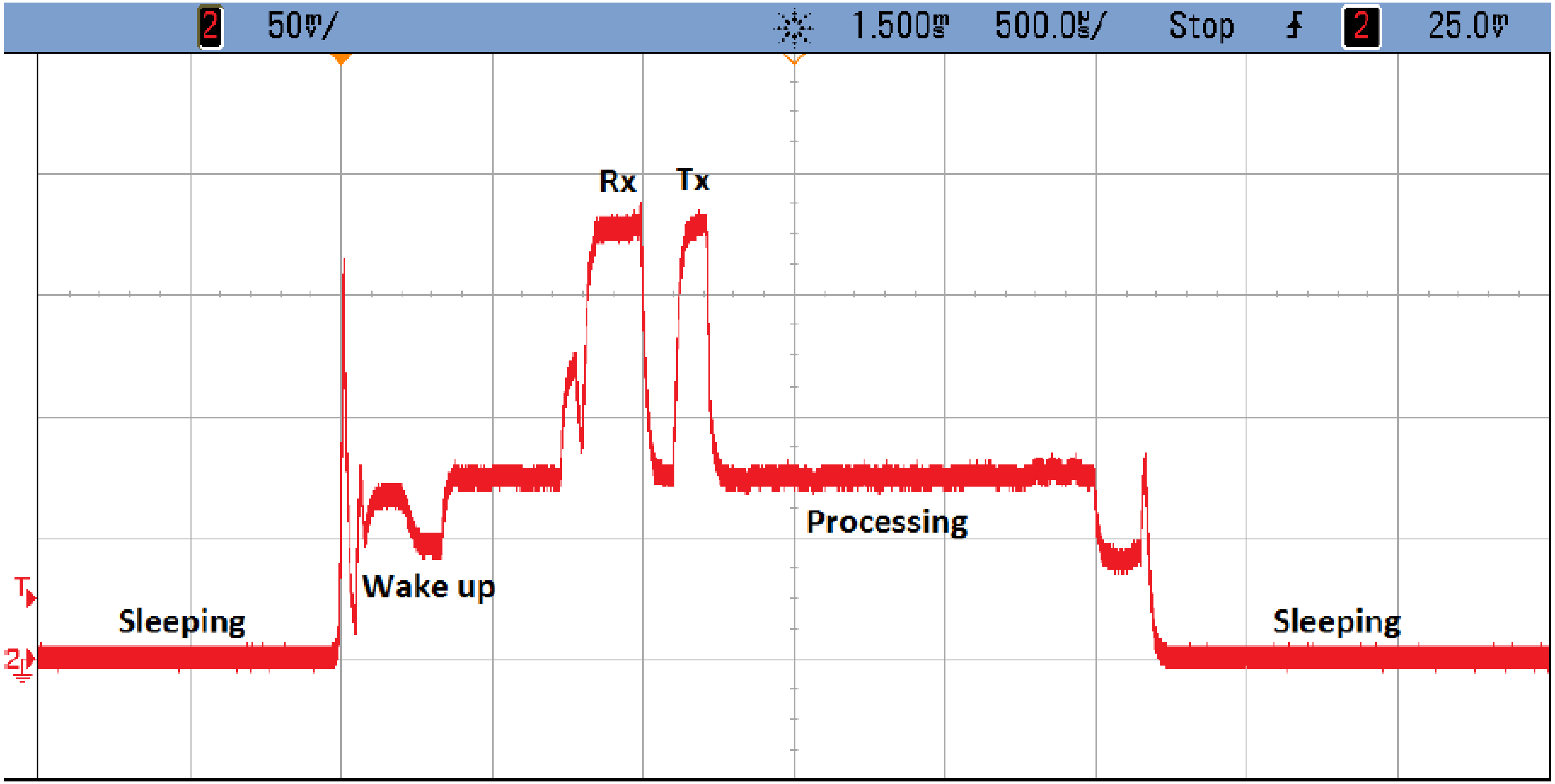
Measuring energy use

- Base equations
    - Power = Current * Voltage (Watts)
    - Energy = Power * Time (Joules)

- Energy = volts * amps * seconds
    - Voltage is *usually* constant for a system
    - Time is how long you are running for / measurement period

    - Current changes based on activities being done
        - Often energy is presented as a current draw
        - Maybe an average current draw
        - With Voltage and Time implicit

Example current trace during wireless communication



Current Consumption versus Time during a single Connection Event

Wired power through USB

- Provides 5v at up to 500 mA (USB 2.0) or 900 mA (USB 3.0)
  - Or power delivery specifications, which can do far more power

- Must be converted to different voltage to use
  - Voltage regulator takes in 5v and spits out 3.3v
  - Has its own maximum current!

- System is limited by the minimum of USB or regulator power
  - Microbit: regulator gives 3.3v at up to 600 mA
    - USB 2.5 Watts, Regulator 1.98 Watts ⇨ System 1.98 Watts
    - This is a max! Stay 15-30% below regulator limit

Thinking about energy

- Batteries often list energy in mA*h (milliamp – hours)
  - Coin cell battery: 3v at 220 mAh
  - 2x AA battery: 3v at 2000 mAh
  - iPhone 11 battery: 3.7v at 3000 mAh

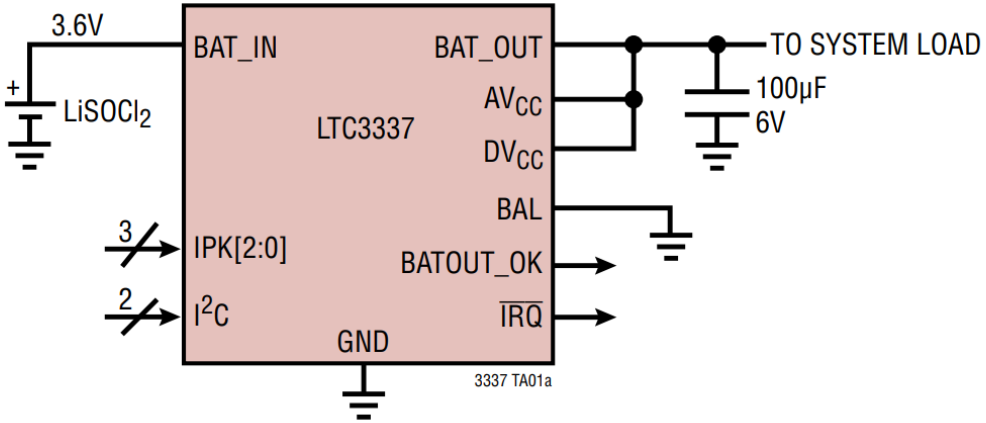
- Also usually limited by regulator
  - Sometimes just directly connected to system
  - We can run at 3v just fine! (3.7v is no good though)

- Voltage can vary with charge
  - But only a little, right before battery is depleted
  - Example: coin cell goes down to ~2.7 volts

How are batteries measured?

- Measuring energy remaining is a difficult problem
  - Many questions to be handled
    - How much did it start with?
    - How much energy has been used?
    - What type of battery is it?
  - Energy is not as constant a quantity as one would hope
    - Pulling out lots at once has an overhead penalty

- Coulomb Counter (aka Battery Fuel Gauge)
  - Designed for a specific battery “chemistry”
  - Monitors charge flowing in each direction
  - I2C interface for reading battery state



- Accuracy is not exact, more of an educated guess

How are batteries managed?

- Usually a dedicated IC for charging and managing battery packs
  - Recharges battery with appropriate amount of current

  - Monitors issues of battery health
    - Various status monitoring
      - Overcharge, undercharge
      - Overcurrent
      - Overtemperature, undertemperature
    - Will go so far as to cut off the system to protect the battery

- Takeaway: complicated problem, approach with caution!
  - Best to reuse an existing design, if possible

Microbit only uses battery energy in a simple way

- Battery input connects directly to regulator
  - No protection for battery health
  - No battery charging capabilities

- Usually this is fine for simple, low-power systems
  - It means that the input voltage can vary though
  - Makes the reference voltages for the ADC/Comparator more important

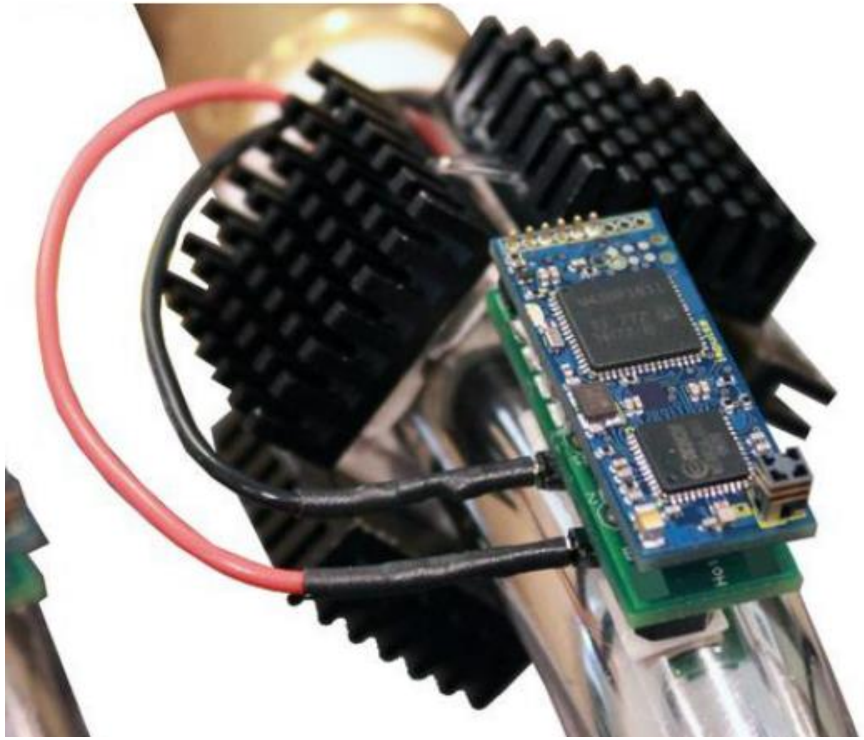
Energy harvesting

- Grab energy from the environment and use that!
  - Could augment with a battery and use energy to recharge
  - Could go entirely batteryless and live on harvested energy alone

- Sources
  - Light (outdoor or indoor. most successful)
  - Airflow (outdoor or air vents)
  - Motion (on human body)
  - Temperature differential (difficult in practice)
  - RF (very low energy source)

Temperature harvesting from hot pipes

- Peltier junctions create a voltage from temperature differential
  - Challenge: needs a large differential for more energy

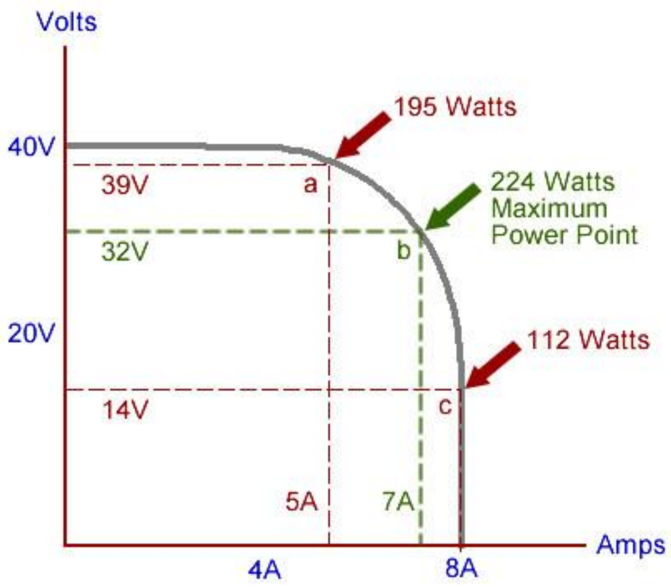


Managing harvested energy

- Often uses an IC to pull in energy and provide to system

- Harvested voltage/current are often very small
  - Signal in millivolts is pretty common
  - Need to accumulate over time to power system
    - Fill up a capacitor

- Need particular load for maximum power
  - ICs often implement
    Maximum Power Point Tracking (MPPT)
  - Varies load automatically to always
    harvest the most possible energy



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- Energy Sources
- **Microbit Energy Use**
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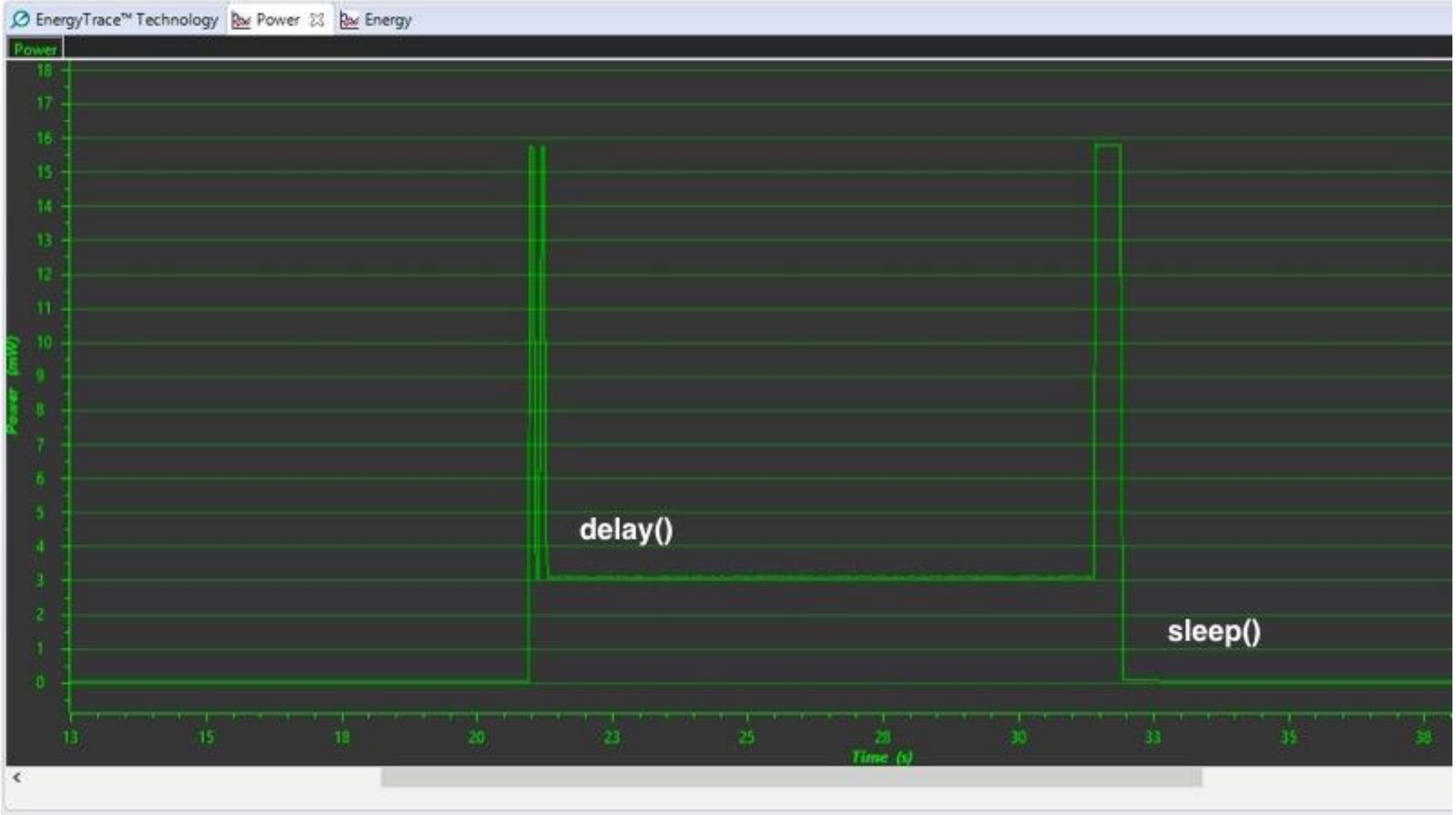
Thinking about energy

- Battery energy
  - Coin cell battery: 3v at 220 mAh
  - 2x AA battery: 3v at 2000 mAh
  - iPhone 11 battery: 3.7v at 3000 mAh

- nRF52833 active current: 5.6 mA (at 3v)
  - Coin cell: 40 hours -> ~2 days
  - 2x AA: 360 hours -> ~15 days
  - iPhone 11: 535 hours -> ~22 days

- So how does any of this work???

Sleep mode power draw



Microcontroller sleep modes

- Sleep mode
  - Processor stops running but memory values are preserved
  - Most peripherals are disabled
  - Continues until an interrupt occurs and wakes the microcontroller
    - Usually a timer or GPIO input

- nRF52833 sleep mode current: 1.8 μA (GPIO port event only)
  - Coin cell: 122222 hours -> ~5000 days -> ~14 years

- Low-power systems shoot for less than 1% duty cycle
  - Average current of ~100 μA or less
  - Warning: other stuff on the board counts!!
    - LEDs are 1-10 mA each… Power is not a concern of the Microbit

Microbit current draw (microcontroller)

- Active CPU
  - 5.6 mA (executing from Flash)
  - 1.8 μA (sleep mode with RAM retention)

- Transmitting RF packet
  - 15.5 mA (+8 dBm)

- Other peripherals
  - SAADC: 1.37 mA
  - Timer: 729 μA (for any Timer peripheral)
  - I2C: 6.6 mA (pull-down resistors when transmitting 0 bit)
  - Everything else is handfuls of μA

Microbit current draw (non-microcontroller)

- KL27 (JTAG interface microcontroller)
  - 2 μA sleep, 8 mA active
- Speaker
  - 0-27.5 mA (changes with input signal)
- Microphone
  - 0-120 μA (activated with GPIO pin)
- Accelerometer/Magnetometer
  - 2-212 μA (depends on sensing rates, 200 is magnetometer)
- LEDs
  - 0-230 mA (can be activated individually)
- Everything else
  - 0-1 mA (mostly due to pull-up resistors)

Max and min current for Microbit

- Maximum current: 280 mA at 3.3 volts (~1 W)
  - With *everything* active
  - Well within limits of regulator

- Minimum current
  - ~15 mA (always-on power LED)

  - If you removed the power LED:
  - <100 µA (with everything off)

nRF52 sleep mode

- Triggered with assembly instruction
  - WFI (Wait For Interrupt) or WFE (Wait For Event)

- Stops processor until woken by interrupt, exception, or event

- On nRF52 automatically disables high frequency clock if unneeded

```
__attribute__((always_inline)) __STATIC_INLINE void __WFI(void)
{
  __ASM volatile ("wfi");
}
```

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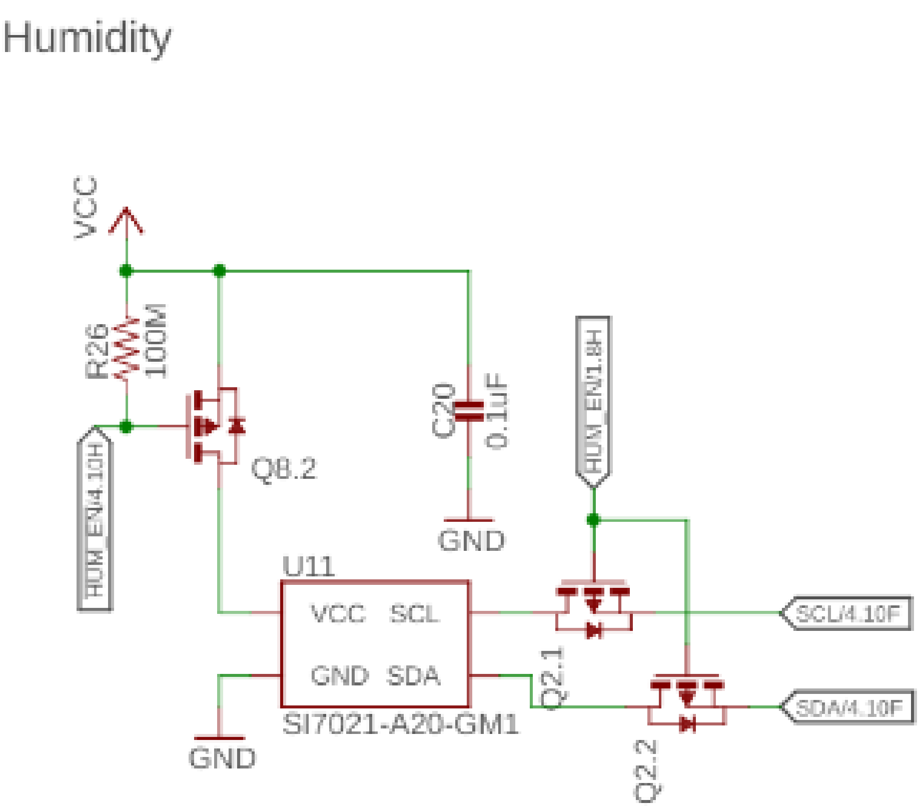
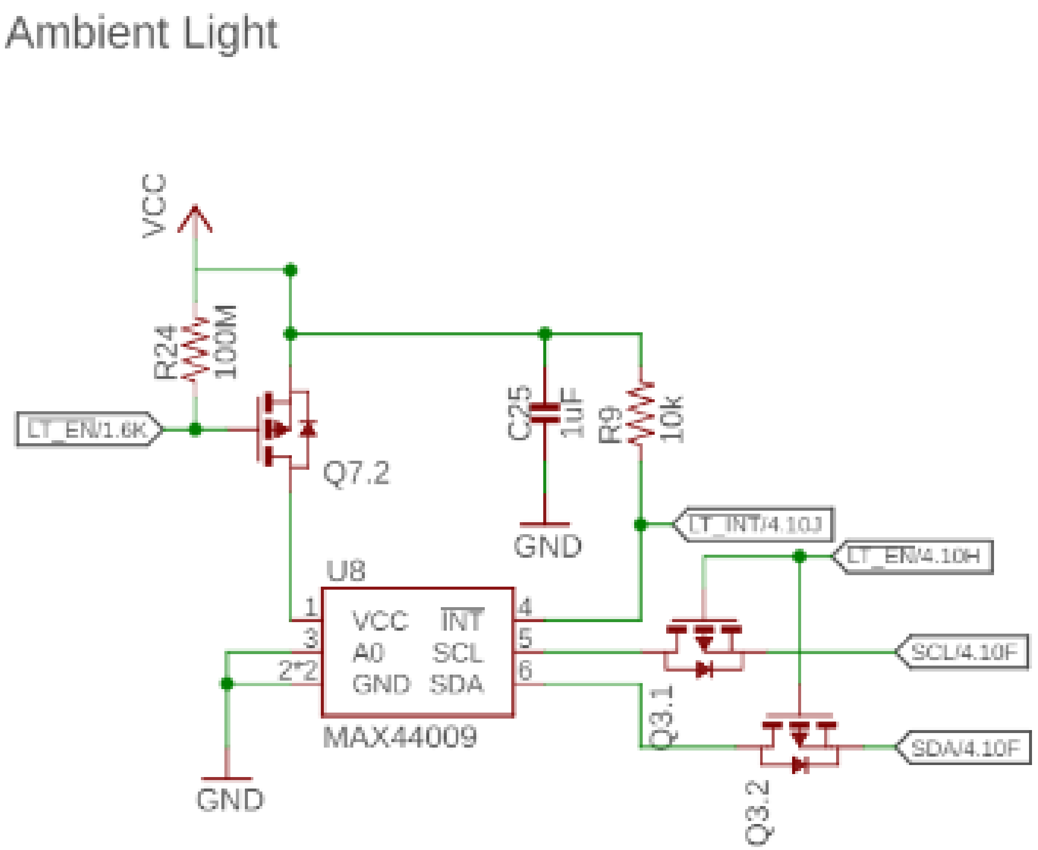
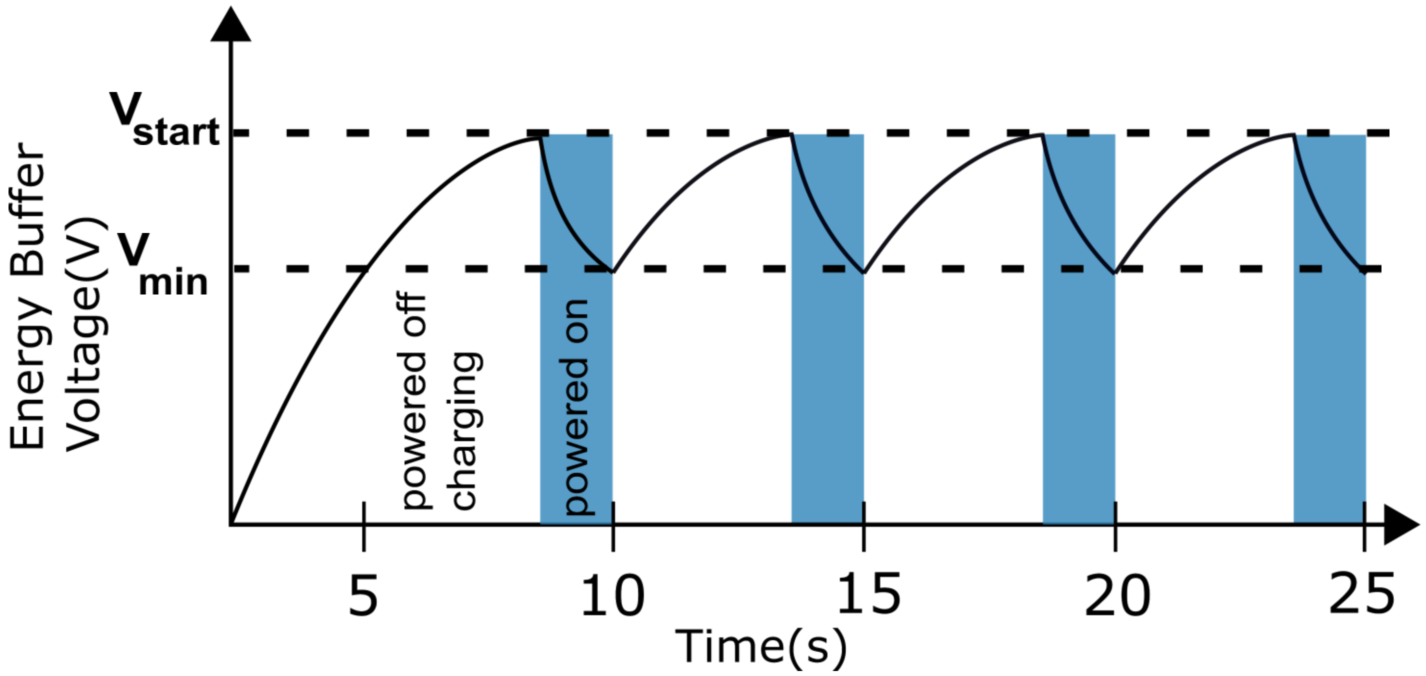
Reducing energy consumption even further

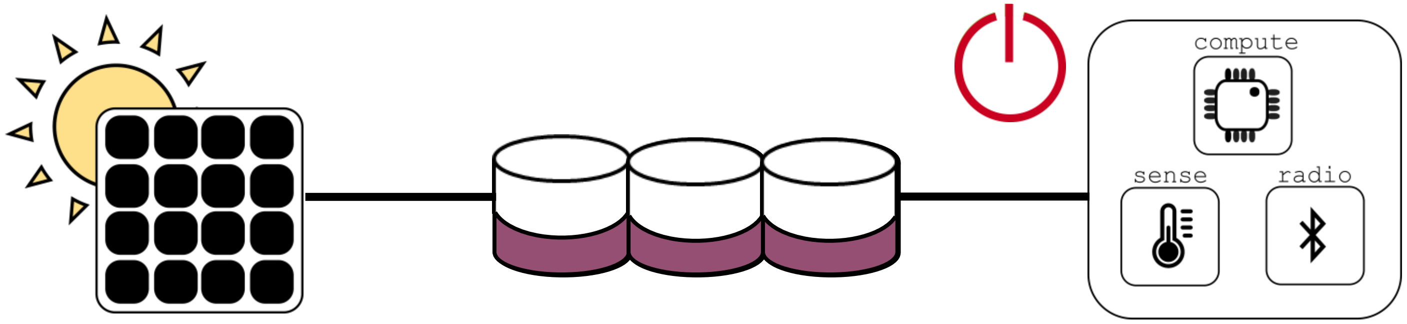
- If sleep isn't enough, you can power things off completely
  - Transistor can be used to turn off the sensor





Energy harvesting can lead to intermittent computing





Disabling the microcontroller

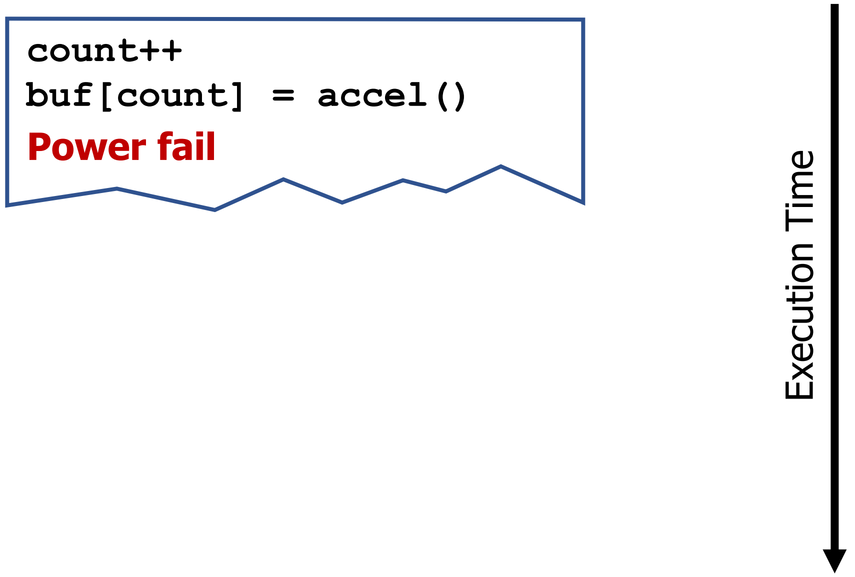
- Even 2 μA sleep current might be too much for energy harvesting
  - Can turn off microcontroller periodically
  - Enable it again once VCC returns

- Problem: how do you write software to deal with intermittency?
  - Run-to-completion with relatively quick code
    - Initialize, sample sensor, send packet, turn off again

  - Code checkpointing
    - Save state from code and restore when power resumes
    - Might be as little as which state the system is in, plus some samples
    - Might be as much as saving entire stack state
    - Needs low-energy, nonvolatile storage (FRAM or MRAM help!)

Programs may not finish

```
int process() {
   count++;
   buf[count] = accel();
   avg = sum(buf)/count;
   transmit(avg);
}
```



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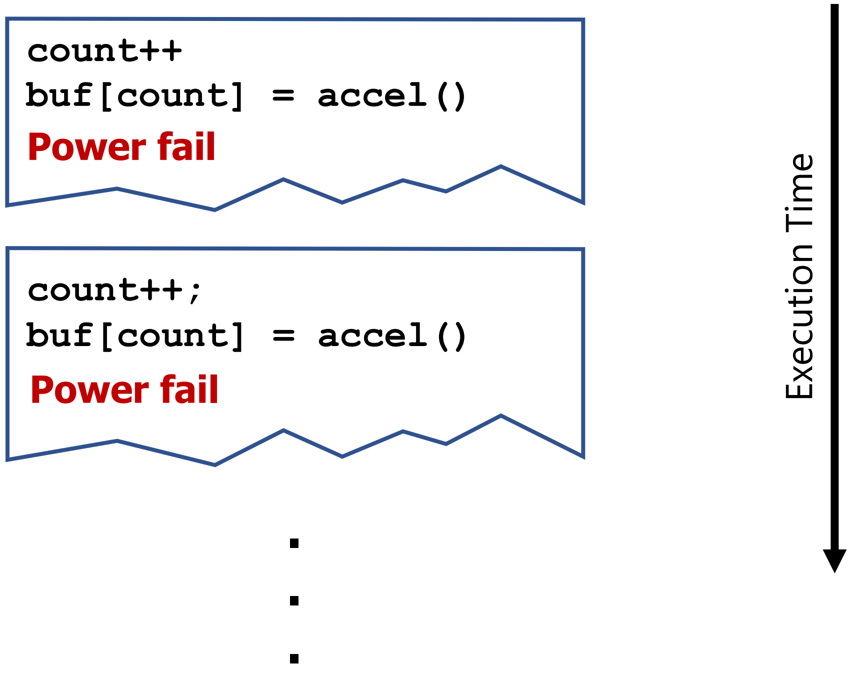

Programs may not finish

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int process() {
   count++;
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}
```

```
count++
buf[count] = accel()
```

Power fail

```
count++;
buf[count] = accel()
```

Power fail

.
.
.

Execution Time

Need to latch execution state periodically!

Checkpointing enables progress

```
int process() {
   count++;
   buf[count] = accel();
   avg = sum(buf)/count;
   transmit(avg);
}
```

Execute with checkpoints

```
count++
buf[count] = accel()
```
Power fail

```
count++;
buf[count] = accel()
```
Power fail

.
.
.

Need to latch execution state periodically!

Execution Time

```
count++
```
Checkpoint
```
buf[count] = accel()
```
Power fail

Checkpointing enables progress

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int process() {
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Execute with checkpoints

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count++
buf[count] = accel()
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Power fail

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count++;
buf[count] = accel()
```
Power fail

.
.
.

Need to latch execution state periodically!

Execution Time

```
count++
```
Checkpoint
```
buf[count] = accel()
```
Power fail

```
buf[count] = accel()
avg = sum(buf)/count
```
Checkpoint
```
transmit-
```
Power fail

Checkpointing enables progress

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int process() {
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}
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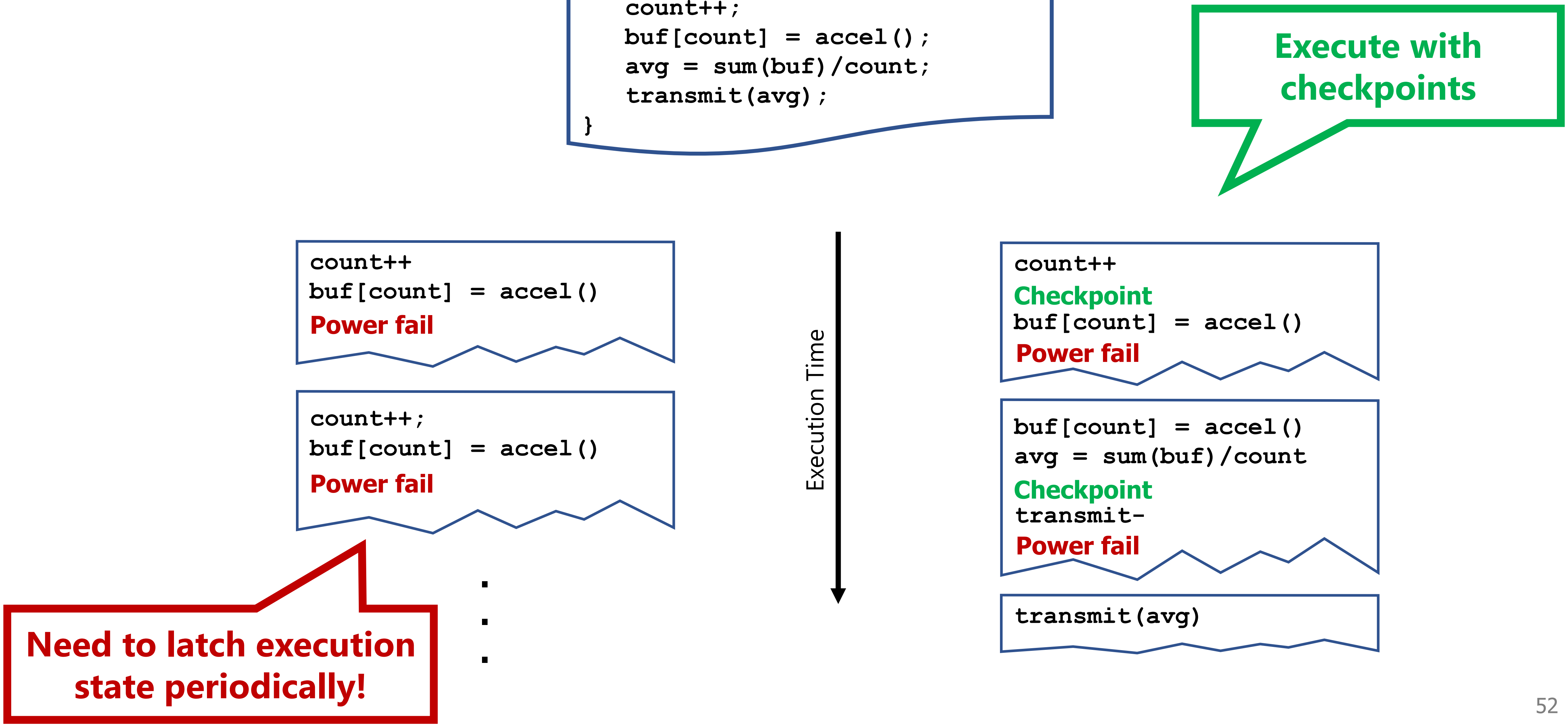

Checkpointing goals

- Have the compiler automatically insert checkpoints as needed
  - Human doesn't have to think about them when programming
- Limit checkpointing overhead while maximizing forward progress
  - Checkpointing will take time to perform, so want to do it rarely
  - Rarer checkpoints mean more progress is lost in average outage
  - Need to compromise on the two based on available energy

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Outline

- **Bonus: SD Cards**

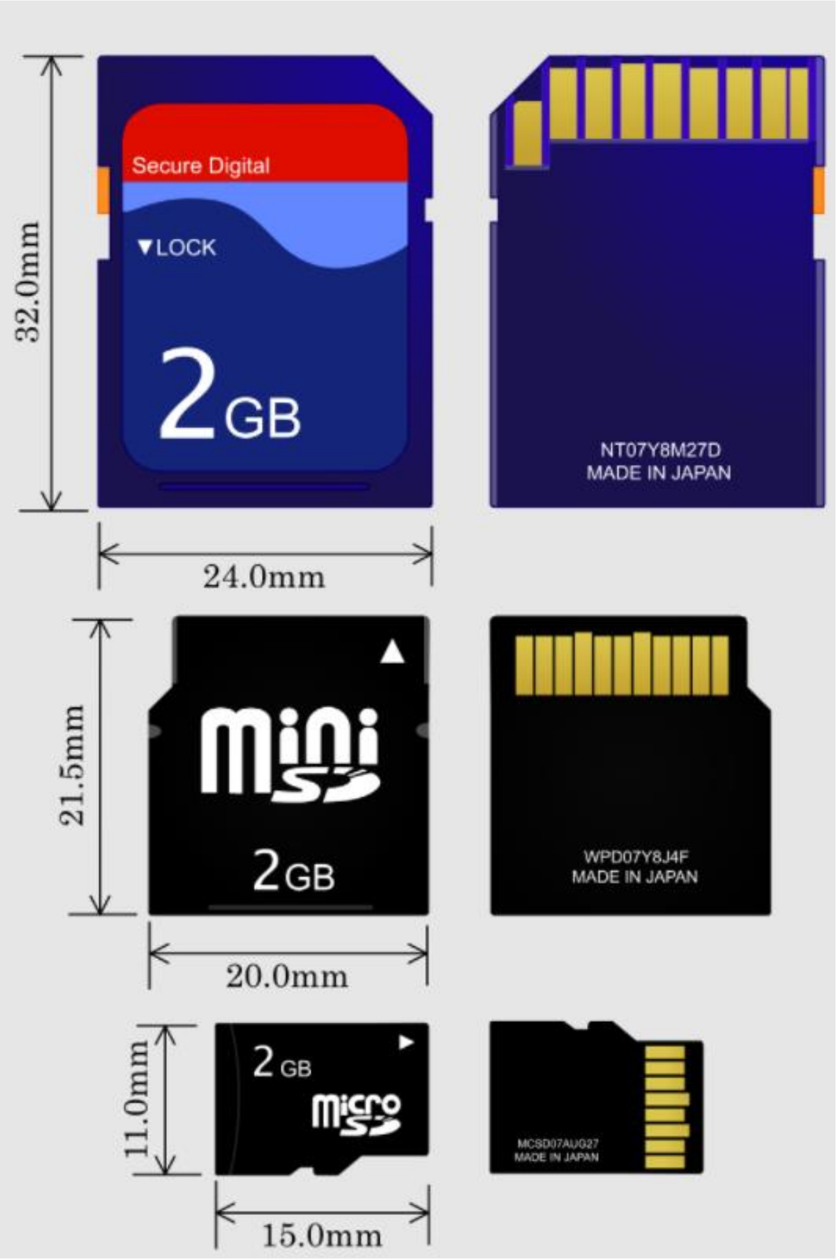
SD card references

- ChaN
  - Embedded systems engineer in Japan (and is amazing)
  - http://elm-chan.org/docs/mmc/mmc_e.html
  - http://elm-chan.org/fsw/ff/00index_e.html

- Various others
  - http://users.ece.utexas.edu/~gerstl/ee445m_s15/lectures/Lec08.pdf
  - http://alumni.cs.ucr.edu/~amitra/sdcard/Additional/sdcard_appnote_foust.pdf
  - https://luckyresistor.me/cat-protector/software/sdcard-2/
  - http://users.ece.utexas.edu/~valvano/EE345M/SD_Physical_Layer_Spec.pdf
  - https://github.com/tock/tock/blob/master/capsules/src/sdcard.rs

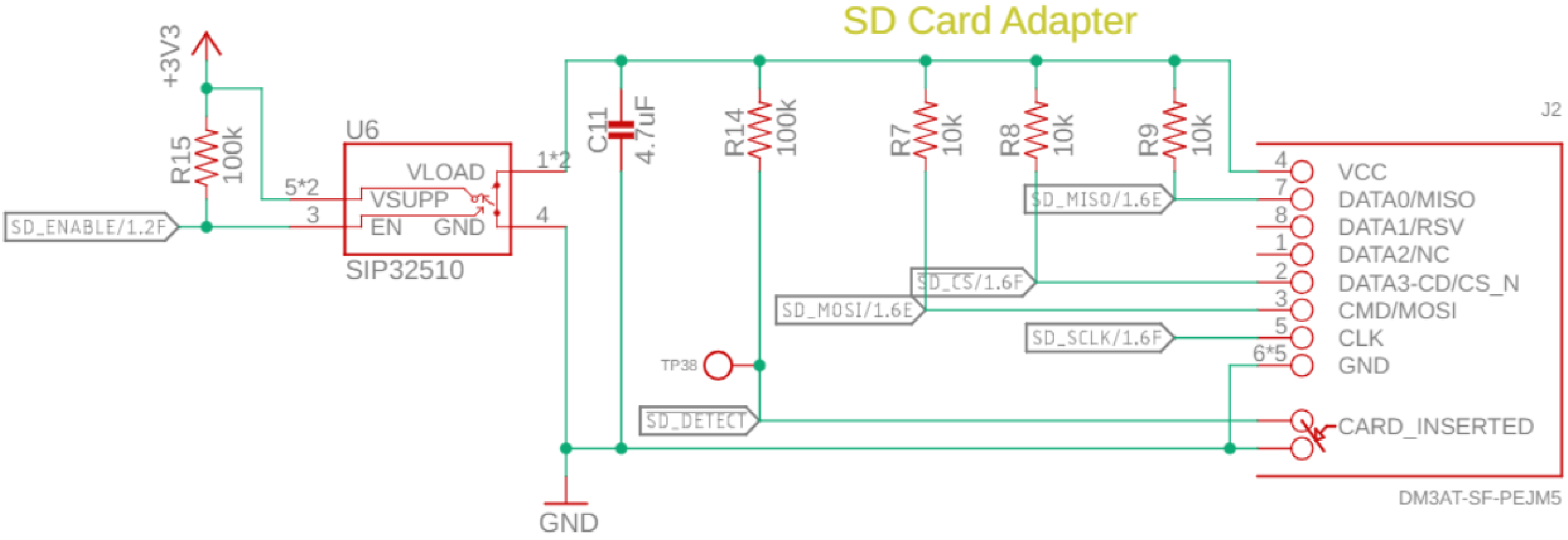
SD cards

- "Secure Digital" Card
  - Includes various formfactors
  - Flash memory
  - Capacities from 8 MB to 128 TB
    - 512 byte blocks
- Supports 1-bit SPI interface
  - As well as 4-bit SD bus protocol
- Easy to support in embedded systems
  - Cheap but high power



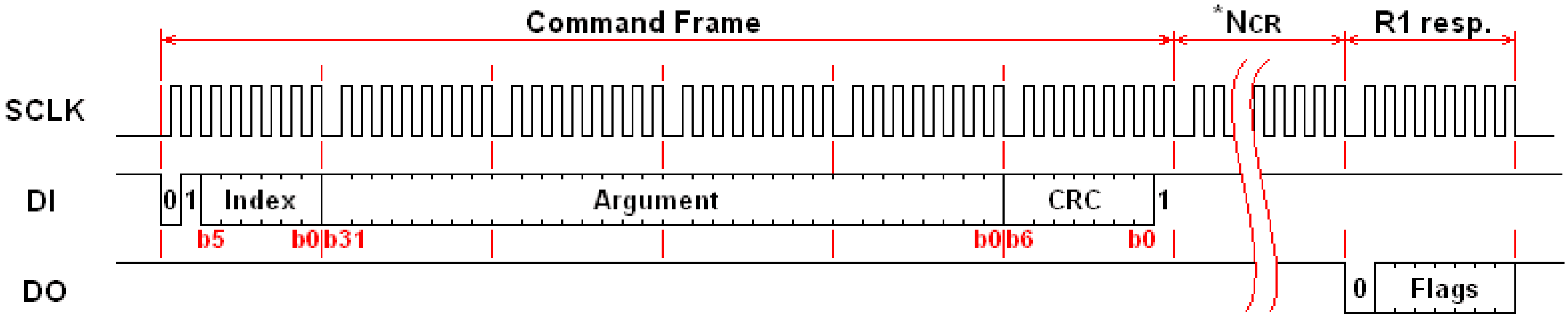
Electrical connections for an SD card

- SD Card connections
  - SPI SDI, SDO, CS, SCLK
  - Plus a switch to enable/disable the SD card and a detect signal



Controlling the SD card

- Index: 6-bit value of command being sent
- Argument: 32-bit value that may be arguments to commands
- CRC: checks for bit errors
- Response (after delay)

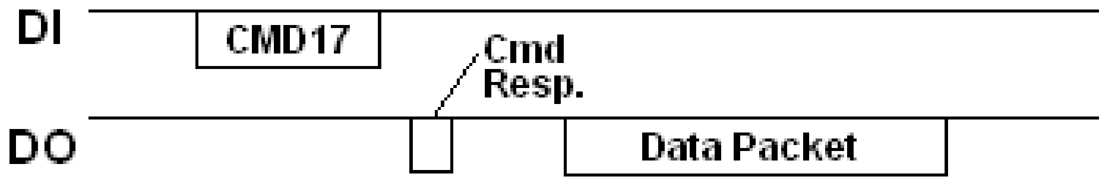


SD card SPI commands

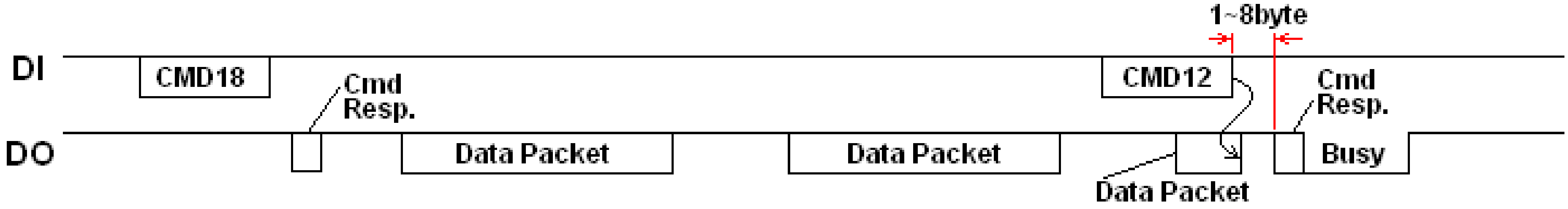
Command Index	Argument	Response	Data	Abbreviation	Description
CMD0	None(0)	R1	No	GO_IDLE_STATE	Software reset.
CMD1	None(0)	R1	No	SEND_OP_COND	Initiate initialization process.
ACMD41(*1)	*2	R1	No	APP_SEND_OP_COND	For only SDC. Initiate initialization process.
CMD8	*3	R7	No	SEND_IF_COND	For only SDC V2. Check voltage range.
CMD9	None(0)	R1	Yes	SEND_CSD	Read CSD register.
CMD10	None(0)	R1	Yes	SEND_CID	Read CID register.
CMD12	None(0)	R1b	No	STOP_TRANSMISSION	Stop to read data.
CMD16	Block length[31:0]	R1	No	SET_BLOCKLEN	Change R/W block size.
CMD17	Address[31:0]	R1	Yes	READ_SINGLE_BLOCK	Read a block.
CMD18	Address[31:0]	R1	Yes	READ_MULTIPLE_BLOCK	Read multiple blocks.
CMD23	Number of blocks[15:0]	R1	No	SET_BLOCK_COUNT	For only MMC. Define number of blocks to transfer with next multi-block read/write command.
ACMD23(*1)	Number of blocks[22:0]	R1	No	SET_WR_BLOCK_ERASE_COUNT	For only SDC. Define number of blocks to pre-erase with next multi-block write command.
CMD24	Address[31:0]	R1	Yes	WRITE_BLOCK	Write a block.
CMD25	Address[31:0]	R1	Yes	WRITE_MULTIPLE_BLOCK	Write multiple blocks.
CMD55(*1)	None(0)	R1	No	APP_CMD	Leading command of ACMD<n> command.
CMD58	None(0)	R3	No	READ_OCR	Read Operations Condition Register (OCR). Indicates supported working voltage range.

Reading from the SD card

- Single block read

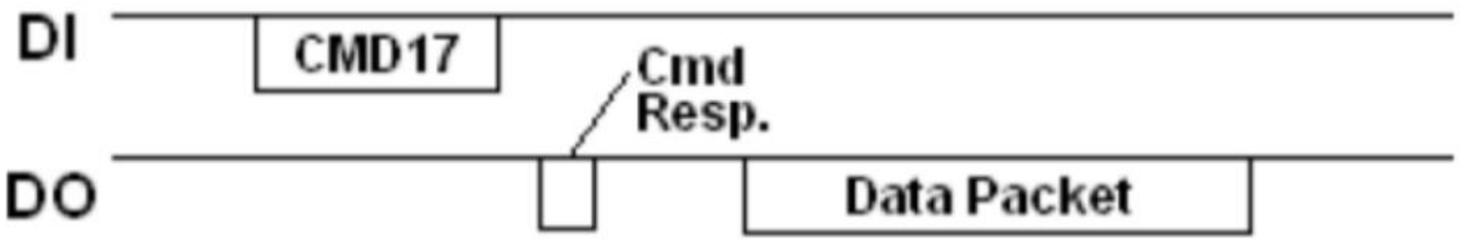


- Multiple block read (CMD12 – Stop Transmission)



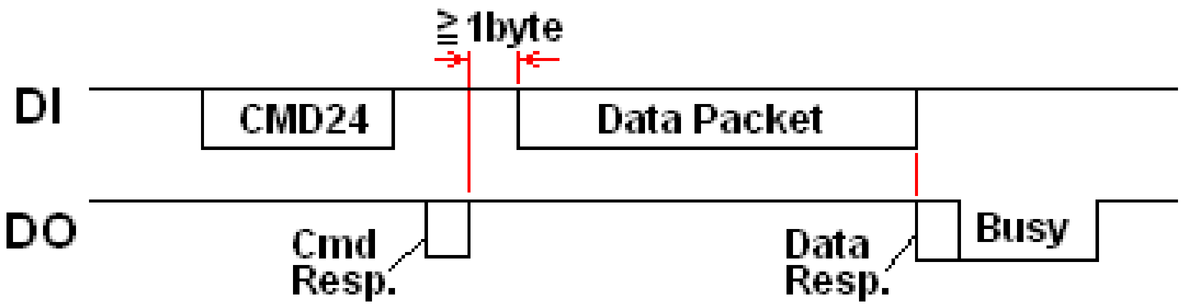
SD card delays can be significant

- Performing a single byte read
  - Almost 300 μs before the SD card *starts* sending data
  - ~200 μs additional time to send the 512 bytes (20 Mbps data, 8 Mbps total)

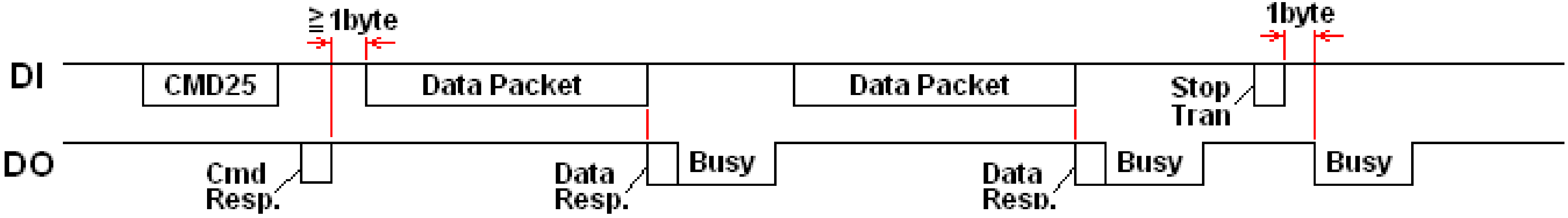


Writing to the SD card

- Single block write

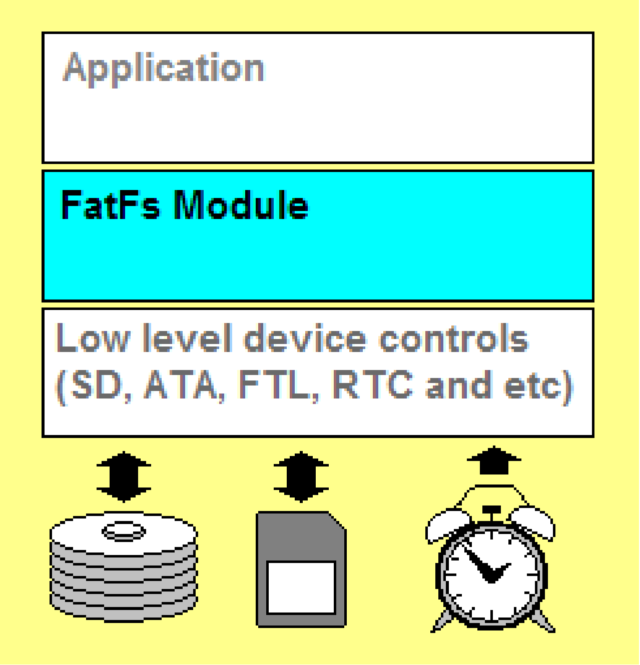


- Multiple block write



Layering a filesystem on top of an SD card

- FatFs library implements the filesystem agnostic of application and storage medium
- Enables the use of file system calls:
  - Open, Close, Read, Seek
- Connects to generic interface for low-level implementation
  - disk_status, disk_init, disk_read, disk_write



Outline

- **Bonus: Task/Event Chaining with PPI**

Software stops when the processor does, but peripherals continue

- Problem: when the processor is off, no code is running

- Solutions
  - Peripherals can wake it up again
    - Can probably go for milliseconds to minutes without any actions
    - Timer interrupt can wake processor to do things

  - Have hardware handle some parts in the background without the processor's involvement
    - DMA
    - PPI

Controlling peripherals while processor sleeps

- DMA (Direct Memory Access)
  - Set up a pointer to memory and a length
  - Peripheral can load/store memory without processor’s involvement
  - Usually use completion interrupt to wake processor

- PPI (Programmable Peripheral Interconnect)
  - Any Event can be tied to any Task within the nRF52
  - Allows for complicated actions to be chained together

nRF52 Tasks and Events

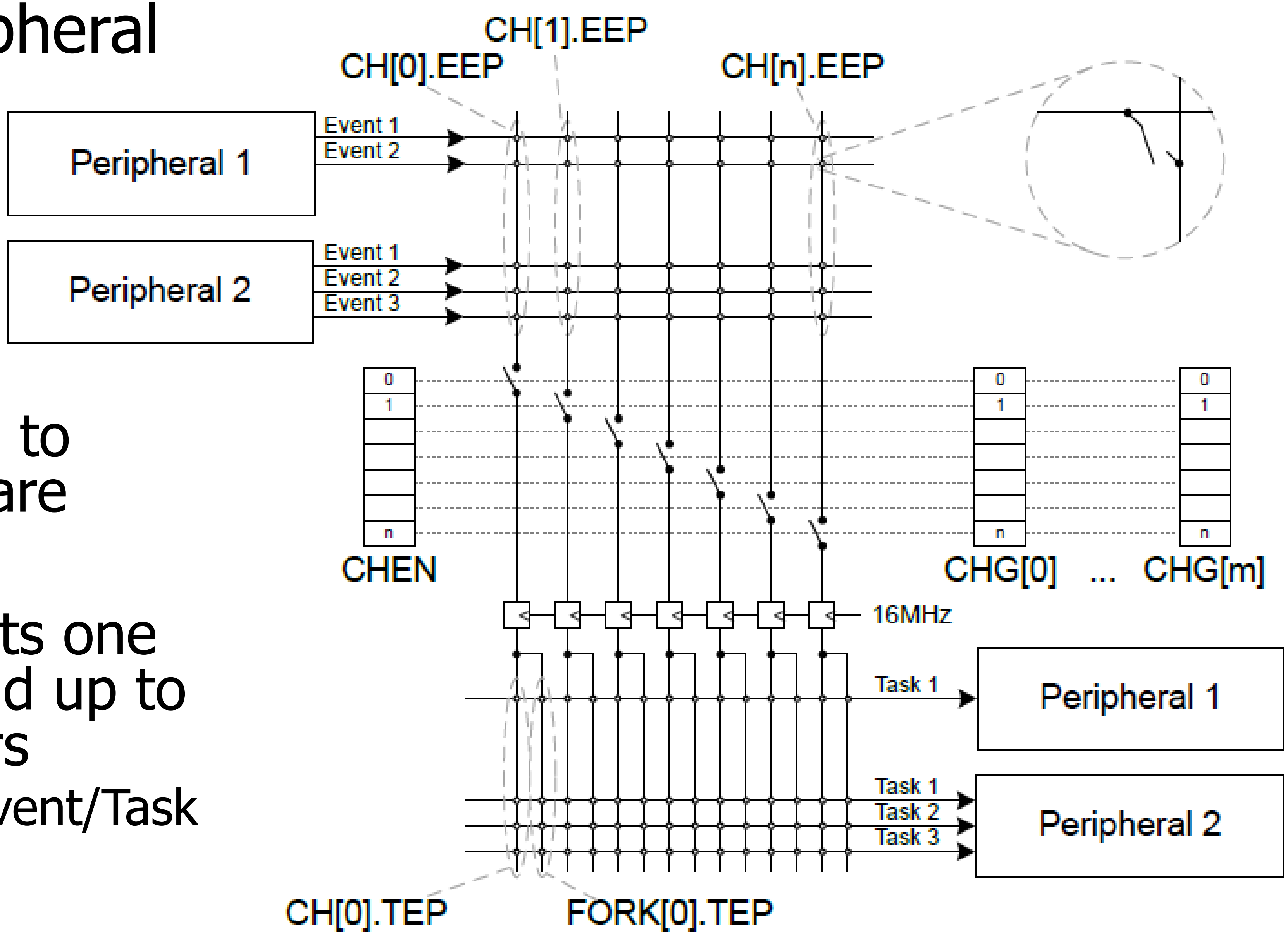
- Tasks are used to perform some operation
  - Often written to by software
- Events change value when some change in status occurs
  - Often used to trigger interrupts
- PPI peripheral can connect any TASK to any EVENT

Example: Timer peripheral

Register	Offset	Description
TASKS_START	0x000	Start Timer
TASKS_STOP	0x004	Stop Timer
TASKS_COUNT	0x008	Increment Timer (Counter mode only)
TASKS_CLEAR	0x00C	Clear time
TASKS_SHUTDOWN	0x010	Shut down timer
TASKS_CAPTURE[0]	0x040	Capture Timer value to CC[0] register
TASKS_CAPTURE[1]	0x044	Capture Timer value to CC[1] register
TASKS_CAPTURE[2]	0x048	Capture Timer value to CC[2] register
TASKS_CAPTURE[3]	0x04C	Capture Timer value to CC[3] register
TASKS_CAPTURE[4]	0x050	Capture Timer value to CC[4] register
TASKS_CAPTURE[5]	0x054	Capture Timer value to CC[5] register
EVENTS_COMPARE[0]	0x140	Compare event on CC[0] match
EVENTS_COMPARE[1]	0x144	Compare event on CC[1] match
EVENTS_COMPARE[2]	0x148	Compare event on CC[2] match
EVENTS_COMPARE[3]	0x14C	Compare event on CC[3] match
EVENTS_COMPARE[4]	0x150	Compare event on CC[4] match
EVENTS_COMPARE[5]	0x154	Compare event on CC[5] match

nRF52 PPI peripheral

- Connects Events to Tasks via hardware
- Each channel gets one Event pointer and up to two Task pointers
  - Must point to Event/Task registers



Example PPI use case

- Automatic high-speed ADC sampling

- Software configures and sleeps
  - ADC (buffer and enable)
  - Timer (prescaler, compare value, short from compare to clear, and start)

- PPI: When Timer fires (EVENTS_COMPARE[0]),
  - Sample ADC (TASKS_SAMPLE)

- PPI: When ADC buffer full (EVENTS_END),
  - Stop Timer (TASKS_STOP)
  - Fork: wake processor (via software interrupt from EGU)