5
End-To-End Design Example

Distributed Embedded Systems

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Where Are We Now?

- **Where we've been:**
  - General UML techniques

- **Where we're going today:**
  - An end-to-end distributed system design example similar to course project
  - **Importance of *traceability***

- **Where we're going next:**
  - Distributed + Embedded
  - Design reviews & inspections

Example System: Soda Vending Machine

- **High Level Requirements:**
  Make it work like a real vending machine
- **Simplification:**
  - Sodas cost some number of quarters
  - All other coins are rejected (invisible to your control system)
- **Assume a Distributed System per given class diagram**
  - Processor for each button, coin return controller, vending controller
  - You get the message dictionary and most of the requirements specification (the "Architecture")

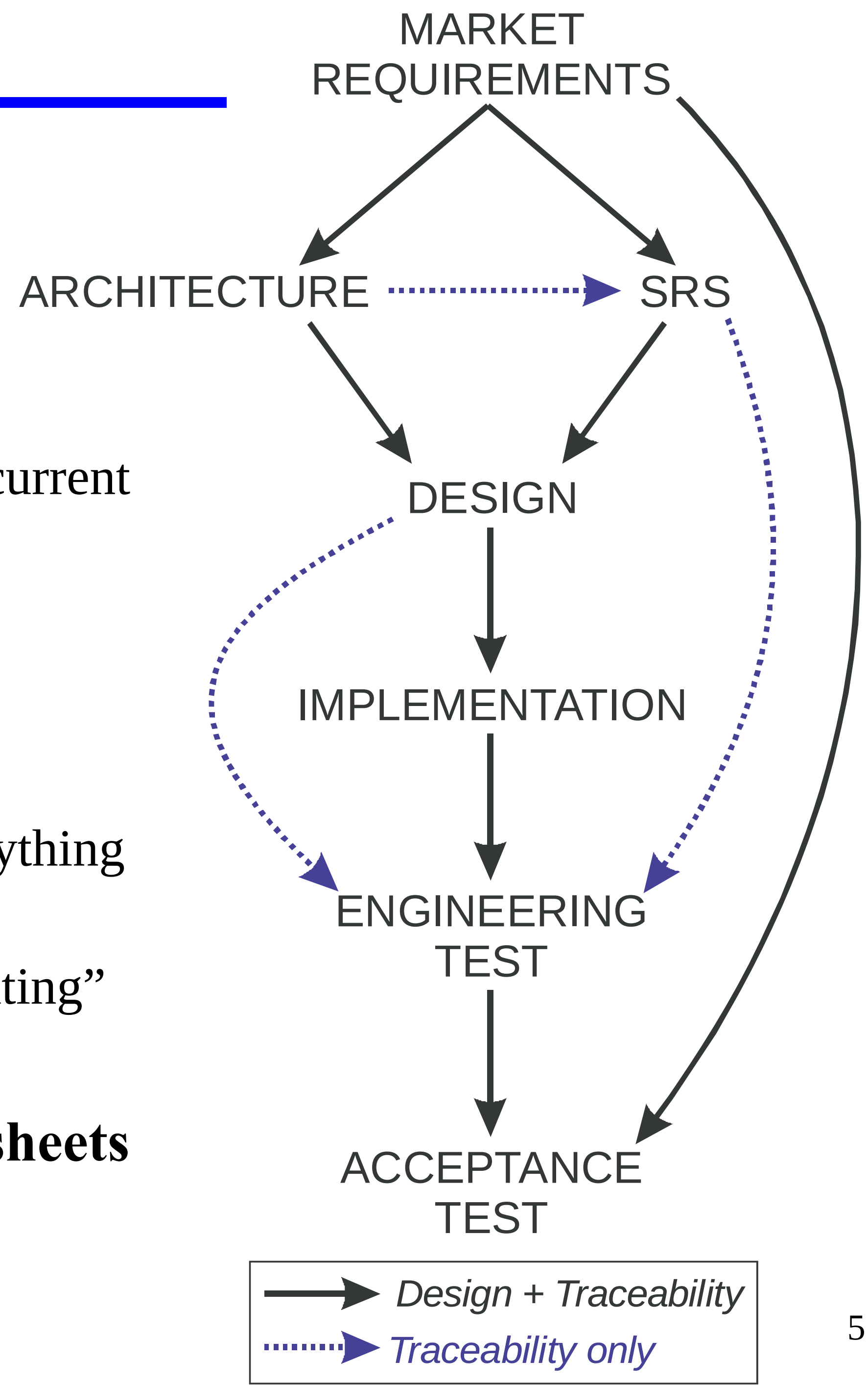
- **Complete worked out example available on course project web pages**

General Approach (Hybrid UML + Text)

- **“Requirements”**
  - Use cases (which are exemplary, but not necessarily coherent/definitive)
  - System-level text requirements
- **“Architecture”** (really just some parts of architecture)
  - Class Diagrams – model “nouns” in system as classes & “architecture diagram”
  - Define network variables that define architectural interfaces (message dictionary)
  - Sensors, actuators, software objects
- **Software Requirements**
  - Scenarios – details inside use cases
  - Sequence Diagrams
- **Design**
  - Detailed text behavioral requirements
  - State Charts (state transitions)
  - Test Design
- **Implementation**
  - Write the code
  - Module testing
- **Integration**
  - Integration tests; acceptance tests

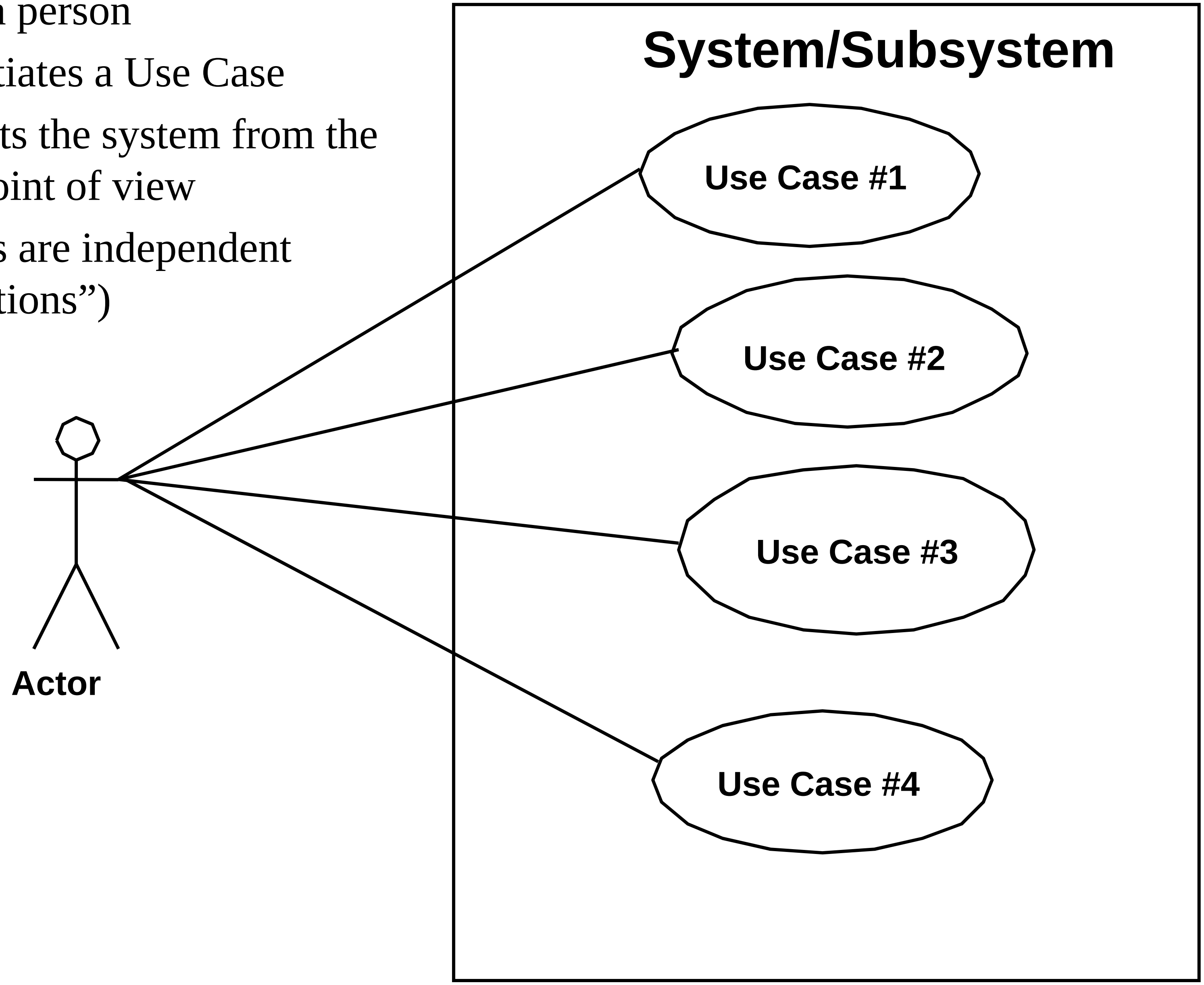
A Word On Traceability

- **Traceability is checking to ensure that steps of the process fit together**
- **Forward Traceability:**
  - Next step in process has everything in current step
  - "Nothing got left out"
- **Backward Traceability**
  - Previous step in process provoked everything in current step
  - "Nothing spurious included/no gold plating"
- **Lightweight traceability uses spreadsheets**
  - Examples in this talk



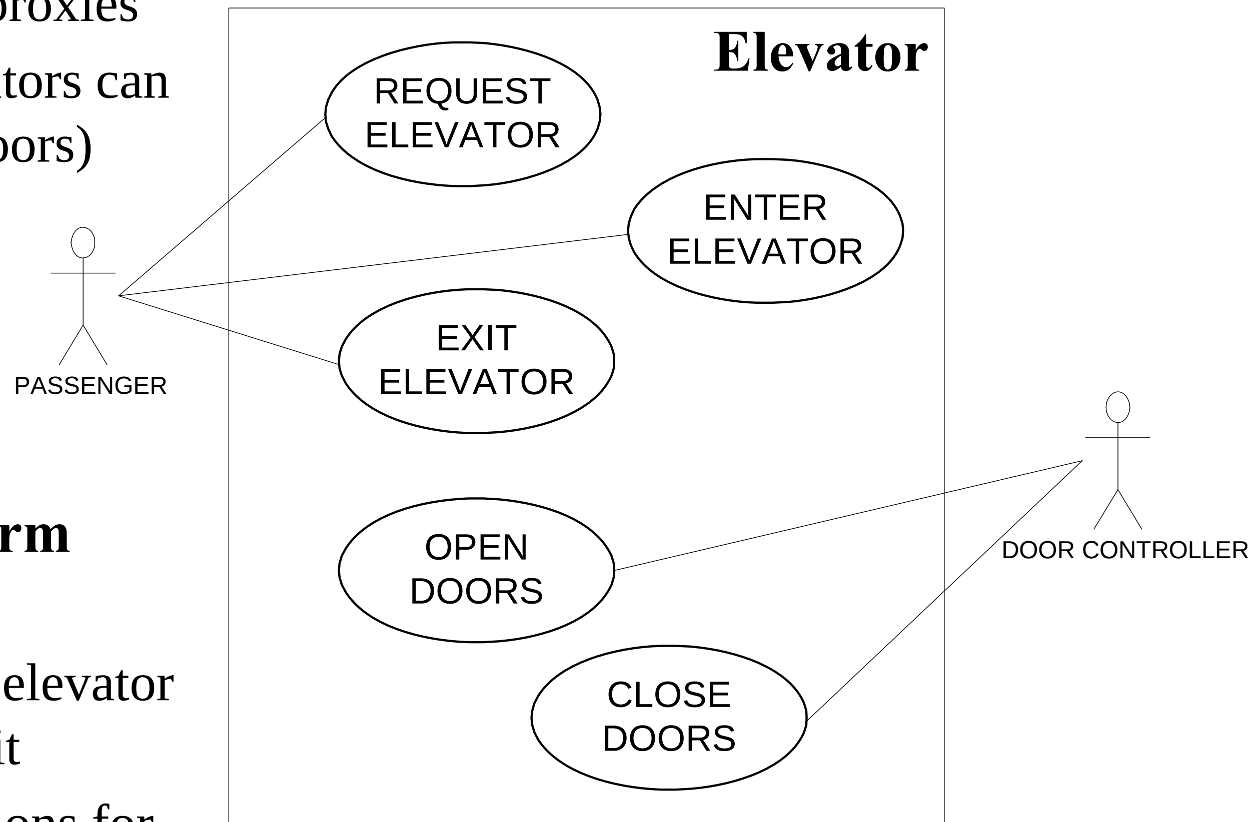
UML Use Cases For Requirements Development

- Actor is a person
- Actor initiates a Use Case
- Represents the system from the actor's point of view
- Use cases are independent ("transactions")



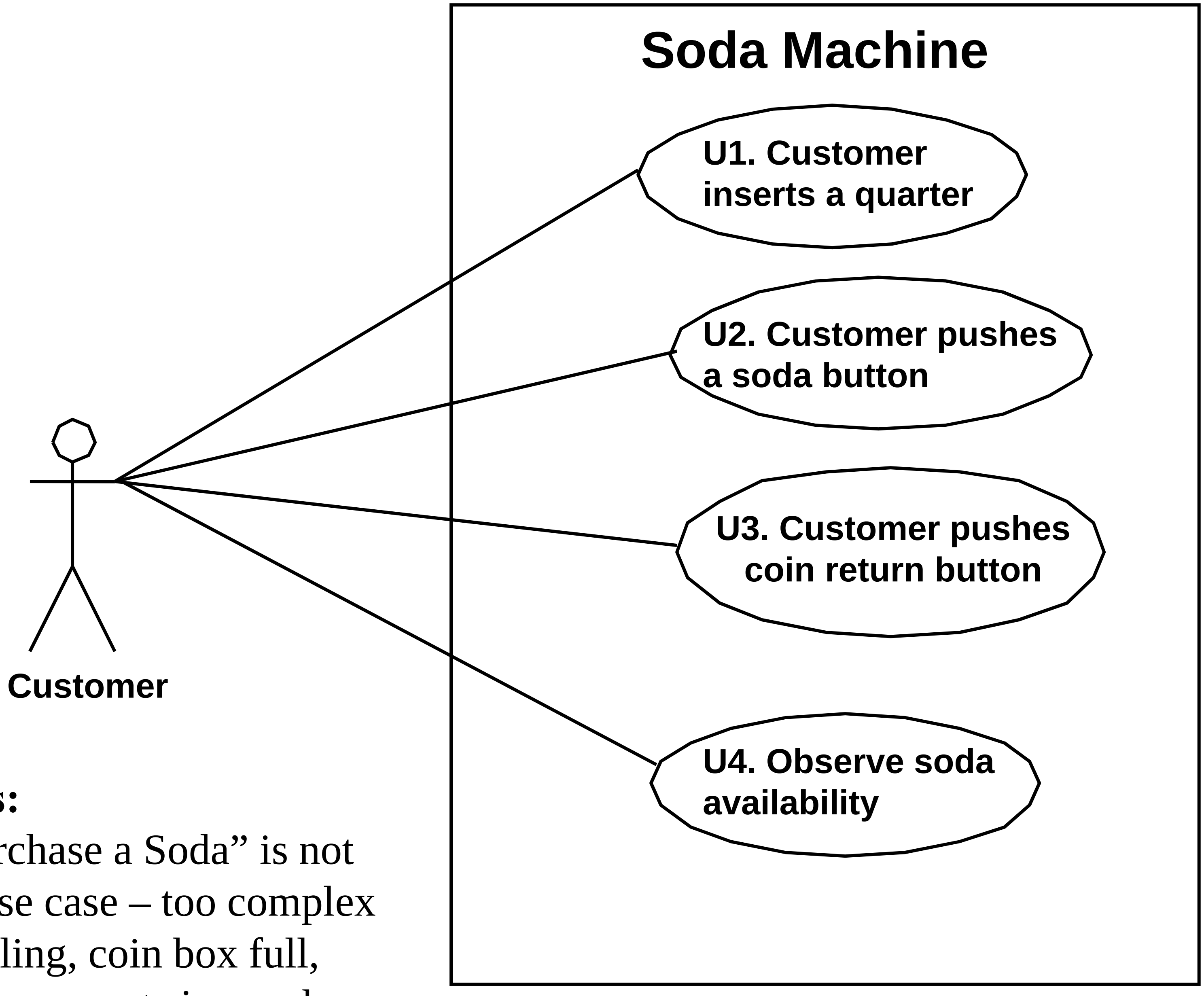
Adapting Use Cases For Distributed+Embedded

- **Actors might not be people**
  - Other computer systems can be actors
  - Sensors can be actor "proxies"
  - Timers, counters, monitors can be actors (e.g., close doors)



- **Sometimes use cases form sequences**
  - Example: can't exit an elevator if you haven't entered it
  - Shows up as preconditions for use case applicability

Solution: Use Cases



Notes:

- "Purchase a Soda" is not a use case – too complex
- Cooling, coin box full, other aspects ignored

System-Level Text Requirements

- **Goal: implement a soda vending machine**

  R1. Pushing a button shall vend a soda of the type corresponding to that button.

  R2. The machine shall permanently retain exactly SODACOST coins for each can of soda vended.

  R3. Coin return shall return all deposited coins since the last vend cycle.

  R4. The machine shall return all deposited money in excess of SODACOST coins before a vend cycle.

  R5. The machine shall flash the light for a selected item while vending is in progress to indicate acceptance of a selection to the buyer.

  R6. The machine shall illuminate the light for any out-of-stock item

- **Assume a Fully Distributed System**
  - Processor for each button, coin return controller, vending controller

Traceability: UML and Text Requirements

- Put an "X" in every box with a related Use Case and Requirements

	Text Requirements					
Use Cases	R1	R2	R3	R4	R5	R6
U1. Customer inserts a quarter				X		
U2. Customer pushes a soda button	X				X	
U3. Customer pushes coin return button			X			
U4. Observe soda availability						X

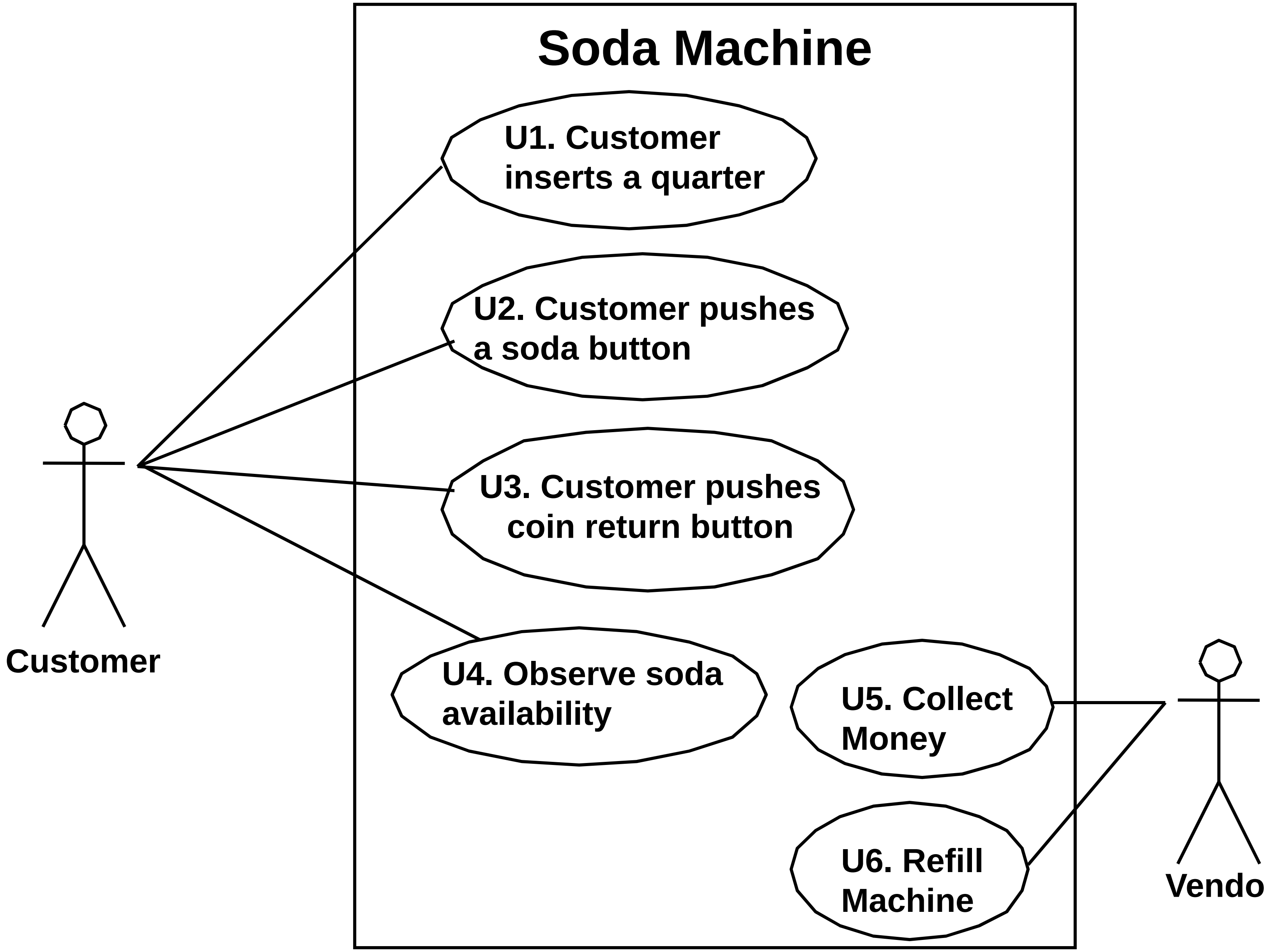
UML To Requirements Traceability Notes

- **Lack of backward traceability for R2**
  - There is a missing actor on the Use Case diagram – the soda delivery person
  - Could add “U5. Collect Money”
  - Possibly add “U6. Refill Machine”

- **Requirements must address off-nominal behaviors that are not apparent in use cases**
  - U1 – too many quarters inserted
  - U2 – soda button pressed without a quarter
  - U2 – two soda buttons pressed concurrently
  - U3 – coin return pressed with no money inserted

- **UML (as we are doing it) gradually eases from requirements to design**
  - Details of the use case become apparent as requirements are elaborated
  - Scenarios and sequence diagrams are partway between requirements and design

Revised Use Cases



Revised Traceability: UML & Text Requirements

- **Put an "X" in every box with a related Use Case and Requirements**

Use Cases	Text Requirements R1	R2	R3	R4	R5	R6
U1. Customer inserts a quarter				X		
U2. Customer pushes a soda button	X				X	
U3. Customer pushes coin return button			X			
U4. Observe soda availability						X
U5. Collect money		X				
U6. Refill machine		X				X

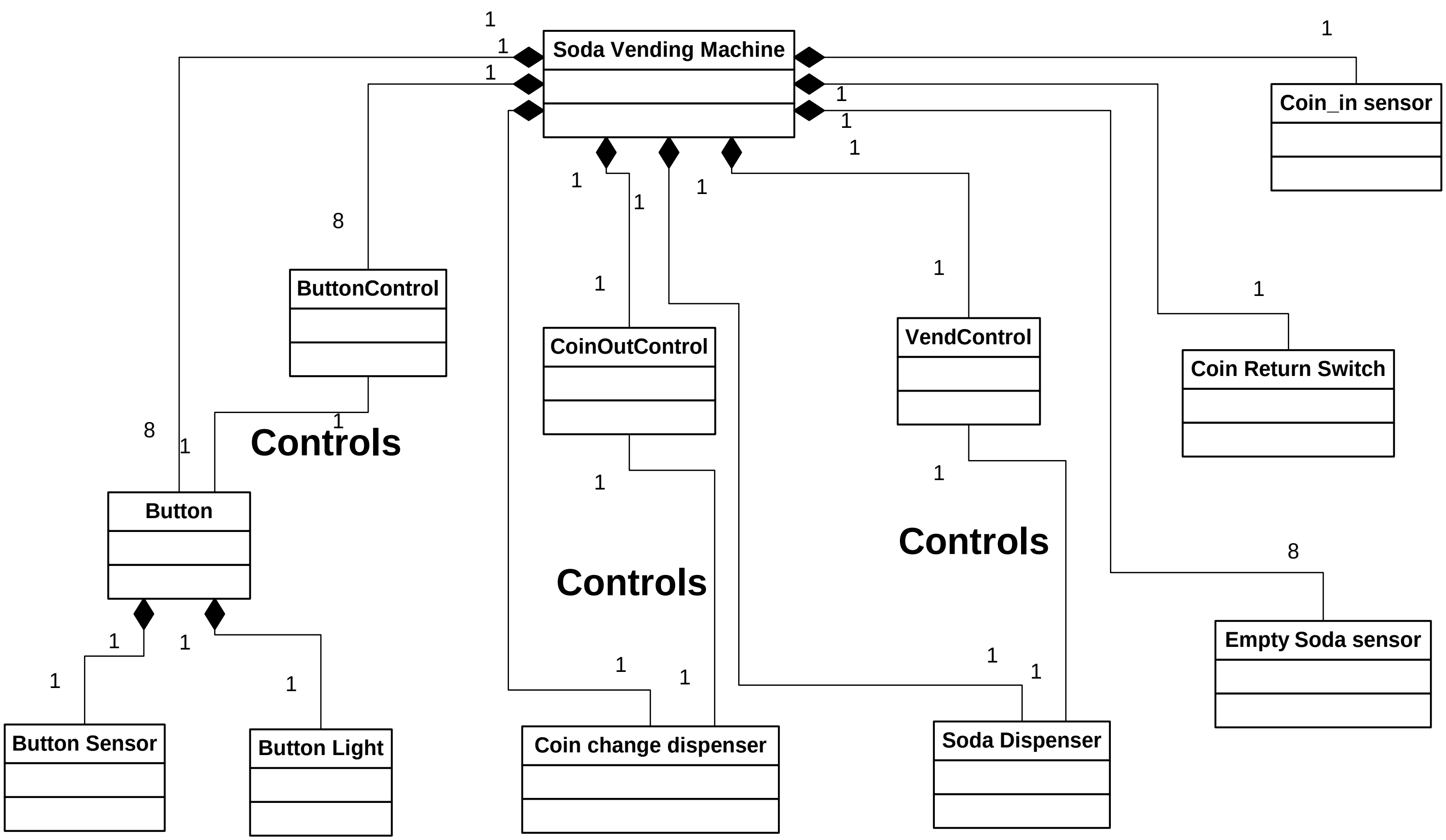
Architecture

One definition of architecture is:

Architecture = Objects + Interfaces

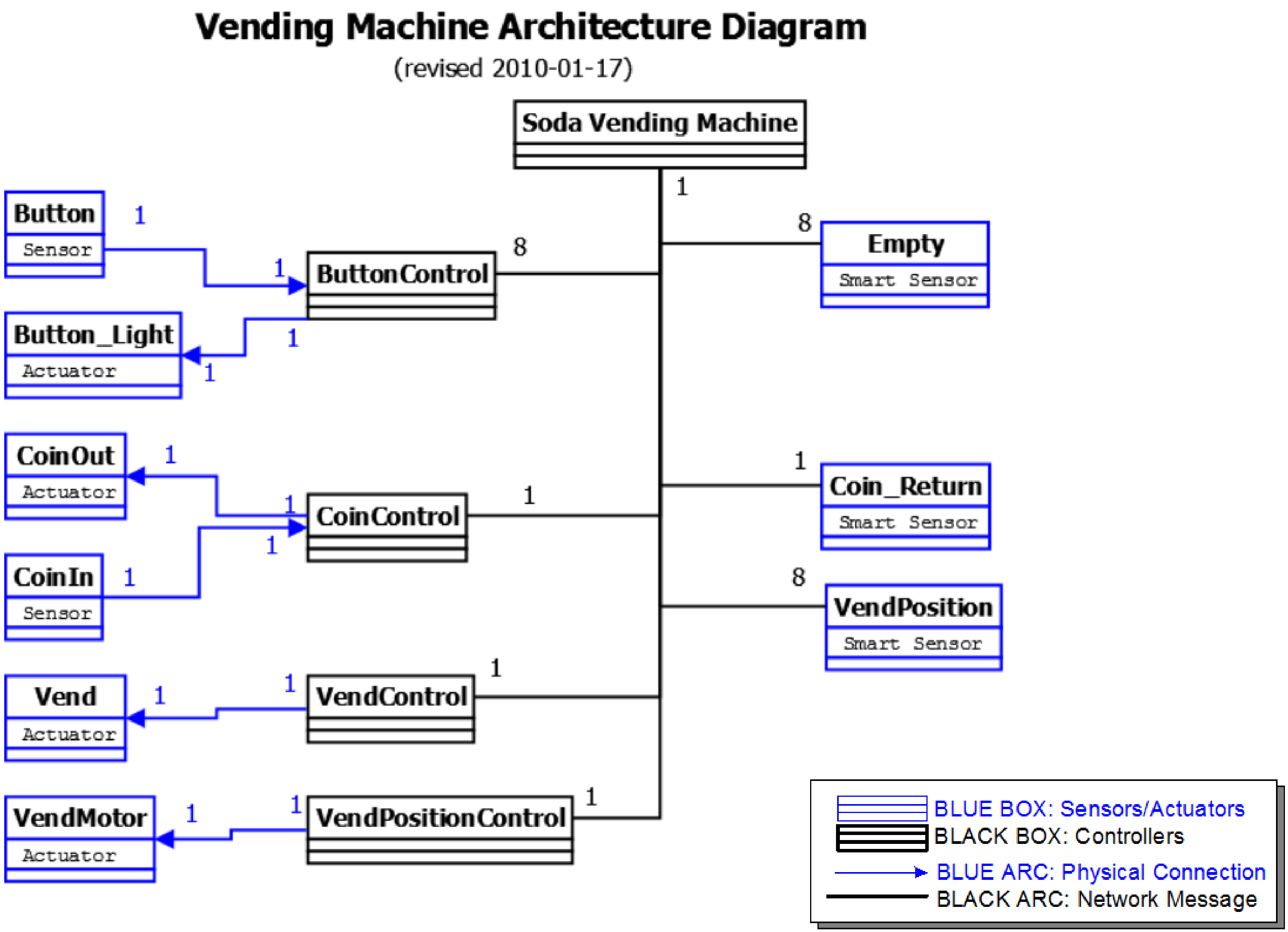
Architecture: UML Class Diagrams

- **Used to show system in terms of objects, attributes, and relationships**
  - Objects are “nouns” in the system; Attributes are local state data within objects
  - Implicit, trivial controllers are assumed built in to uncontrolled components
    - (This is a simplified class diagram – VendMotor and VendPosition not there)



Architecture Diagram

This isn't a terribly formal diagram, but it helps keep things straight



System Sensors

- **Button[s](v): Soda selection button -- Physical state sensor**
  - v={True, False}.
  - One button per type of soda. All are False at initialization. S is an integer 1..8
  - Button[s](True) is sent when button s is depressed; Button[s](False) is sent when button s is released.
  - The button sensors have a physical interlock that prevents more than one being pressed at a time.

- **Empty[s](v): Item empty sensor -- Smart Sensor**
  - v={True, False}.
  - One empty sensor per type of soda vended. True when out of stock. S is an integer [1]..[8]
  - One per type of soda. Initialized to be False.
  - This is a smart sensor, so its implicit function is:
    transmit mEmpty[s](v) = Empty[s](v)
    (i.e., broadcast state to rest of system)

Environment-Only System State

- **SodaCount[s](n): The number of sodas in each chute**
  - Each count is set to 50 at startup

- **What does “environment-only” mean?**
  - We have a simulator in Java that simulates the entire system
    - Computing nodes
    - Network
    - Sensors & actuators
    - Physical world
  - The physical world model keeps track of how many sodas are in a chute
  - The embedded computers do not know now many sodas are in the chute
    - They only can infer it from sensors and build a model of the physical world
    - In this system, they only know if a chute is empty or not empty
    - In some other, fancier system the delivery person might program in number and the controllers could keep count – but they still wouldn’t “know” the actual value of SodaCount – they would be inferring it from external information.

System Actuators

- **ButtonLight[s](v):** Soda selection light.
  - v={True, False}.
  - One per type of soda. When set to True turns on the light in the button for soda s; when set to False turns that light off. S is an integer 1..8
  - All lights set to False at initialization.

- *Note: soda refill & money collection is done manually*

- Note – there are more sensors and actuators in the full example

Software Control Objects

- **ButtonControl[s]**
  - One per soda selection (S is an integer [1]..[8])
  - Controls button lights
  - Controls sending button selections to VendControl
- **CoinControl**
  - Controls coin return dispenser
- **VendControl**
  - Controls dispensing the soda cans
- **VendPositionControl**
  - Controls the movement of the VC
    (this is a mechanical device that moves across chutes to select a soda)

Message Dictionary

- **Notation:**
  - s is button index number: s=1..8

Environmental Object Messages

These messages are sent by environmental objects and smart sensors provided in the system

Source Node Name	Message Name	Replication	Number of fields	Description
Empty	mEmpty	s	1	See Object Description
Coin_Return	mCoinReturn	none	1	See Object Description
VendPosition	mVendPosition	s	1	See Object Description

Controller Messages

These messages are sent by the controllers that you will design. In the later projects, you will be allowed to modify the message dictionary for the controllers in a limited way, but for the time being, you must implement the message dictionary given below:

Source Node Name	Message Name	Replication	Number of Fields	Description
ButtonControl	mButton	s	1	State of the soda selection button
VendControl	mVend	none	1	True when vending a soda
CoinControl	mCoinCount	none	1	Integer number of coins received.
VendPositionControl	mVendMotor	none	1	State of the vend motor.

Software Requirements

- Structured representation of control objects
- Scenarios
- UML Sequence Diagrams
- A stylized detailed requirements template

2. ButtonControl[s]

- **Replication:**
  - There is one button controller per Button/Button_Light pair (8 total).
- **Instantiation:**
  - ButtonControl[s] commands Button_Light[s] to False at initialization.
- **Assumptions:**
  - Only one Button[s] is sent as True at a time to VendControl.
  - Each ButtonControl[s] has a physical interface to exactly one Button[s] and ButtonLight[s].
- **Input Interface:**
  - Button[s](v)
  - mEmpty[s](v)
  - mVend[s](v) (assume that any Vend message received indicates an actual vend event)
- **Output Interface:**
  - mButton[s](v)
  - ButtonLight[s](v)

Continued 2. ButtonControl[s]

- **Constants:**
  - FlashLimit (integer): determines the rate that the light flashes during vend.
- **State:**
  - IsEmpty (True, False); initialized to False; indicates when selection has no soda cans left.
  - ButtonState (True, False); initialized to False; indicates whether the button has been pressed.
  - FlashCounter: used to keep track of time while flashing the light druing Vend
- **Constraints:**
  - None

Use Case 2: Customer pushes a soda button

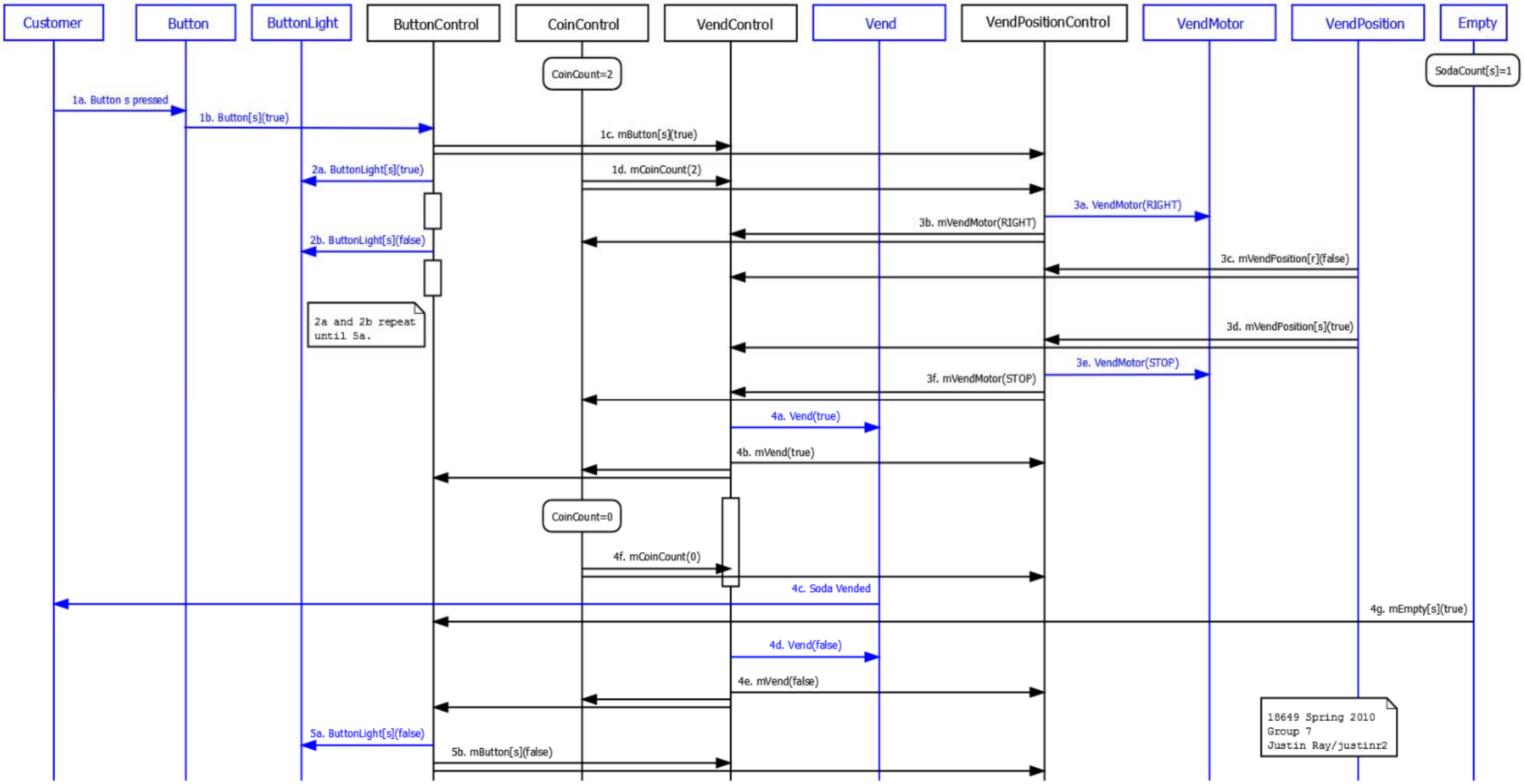
- **<u>Scenario 2A:</u> Customer pushes a soda button when the correct amount has been paid**

- **Pre-Conditions:**
  - The soda machine is not vending.
  - No button is pressed.
  - The system has received the correct number of coins for the cost of a soda since the last vend cycle.
  - The VendCarriage is parked in front of chute r, r < s.

- **Scenario:**
  1. The Customer pushes soda button s.
  2. The light on the soda button s begins flashing.
  3. The VendPositionControl aligns with soda chute s.
  4. The soda is vended.
  5. The light on the soda button s stops flashing.

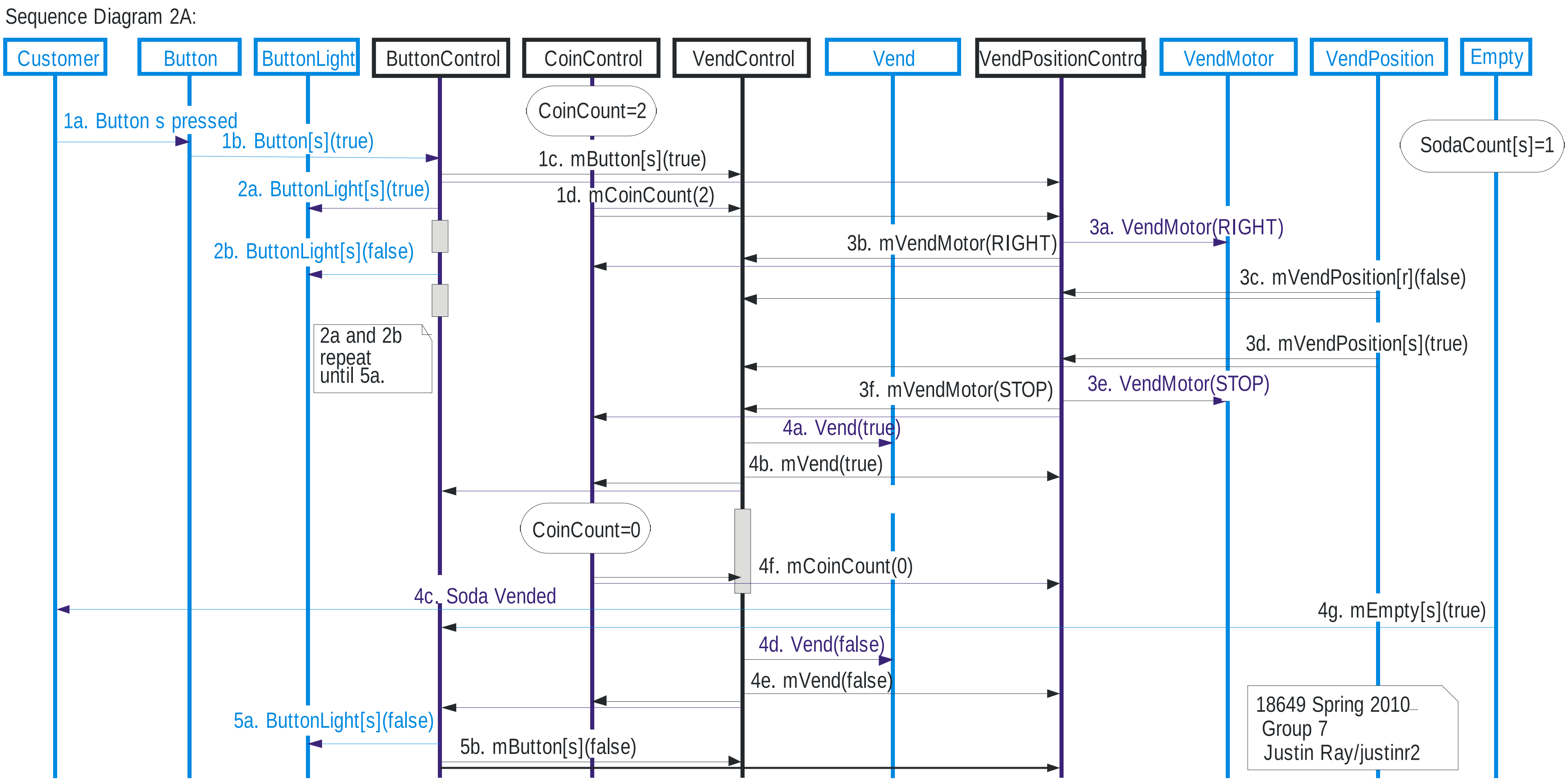
- **Post-Conditions:**
  - The system retains the cost of the soda and has one less soda of type s
  - The system is out of soda of type s

Sequence Diagram 2A Using Typical Graph Software



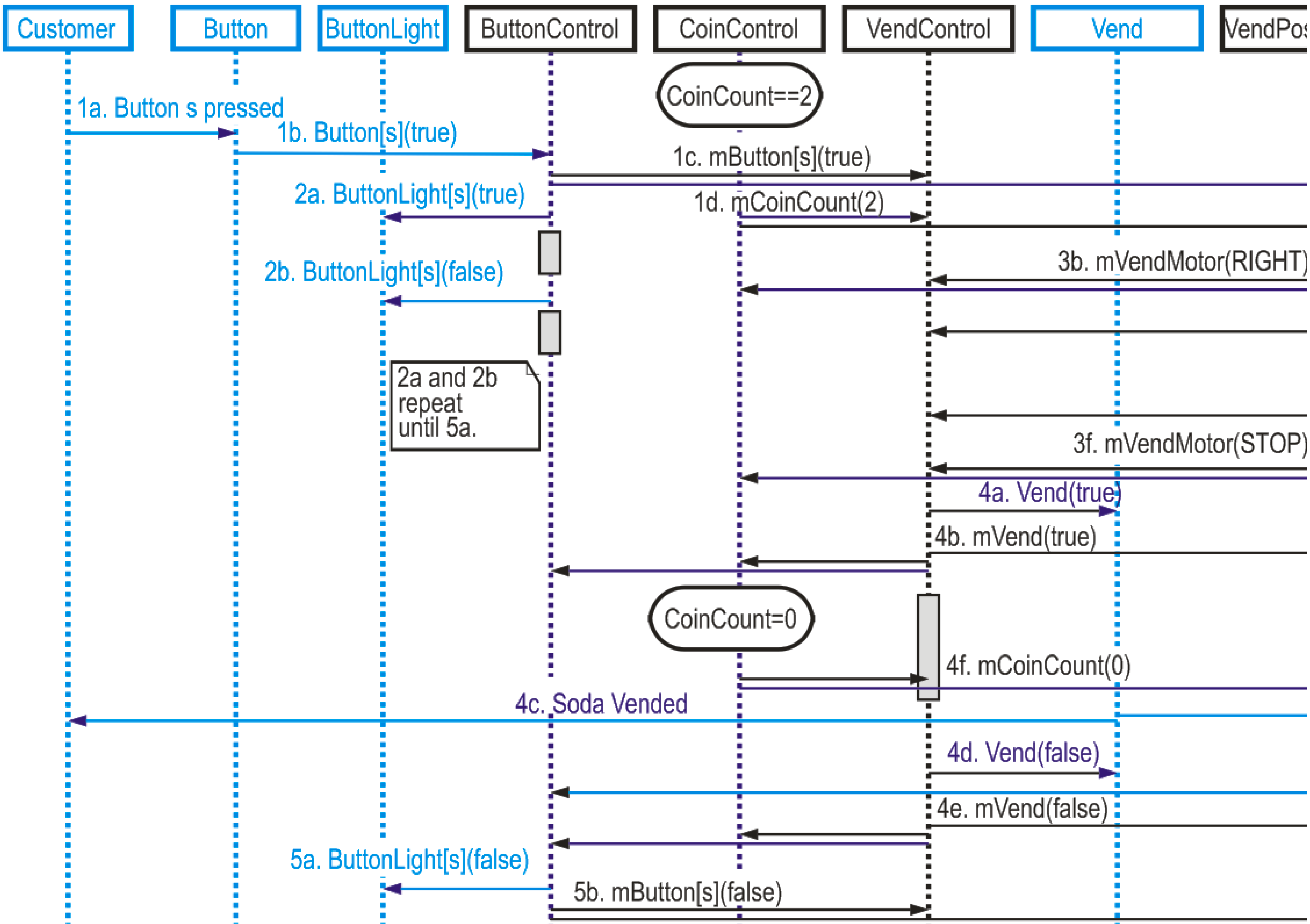
These fonts are too small – don’t do this on your presentations!

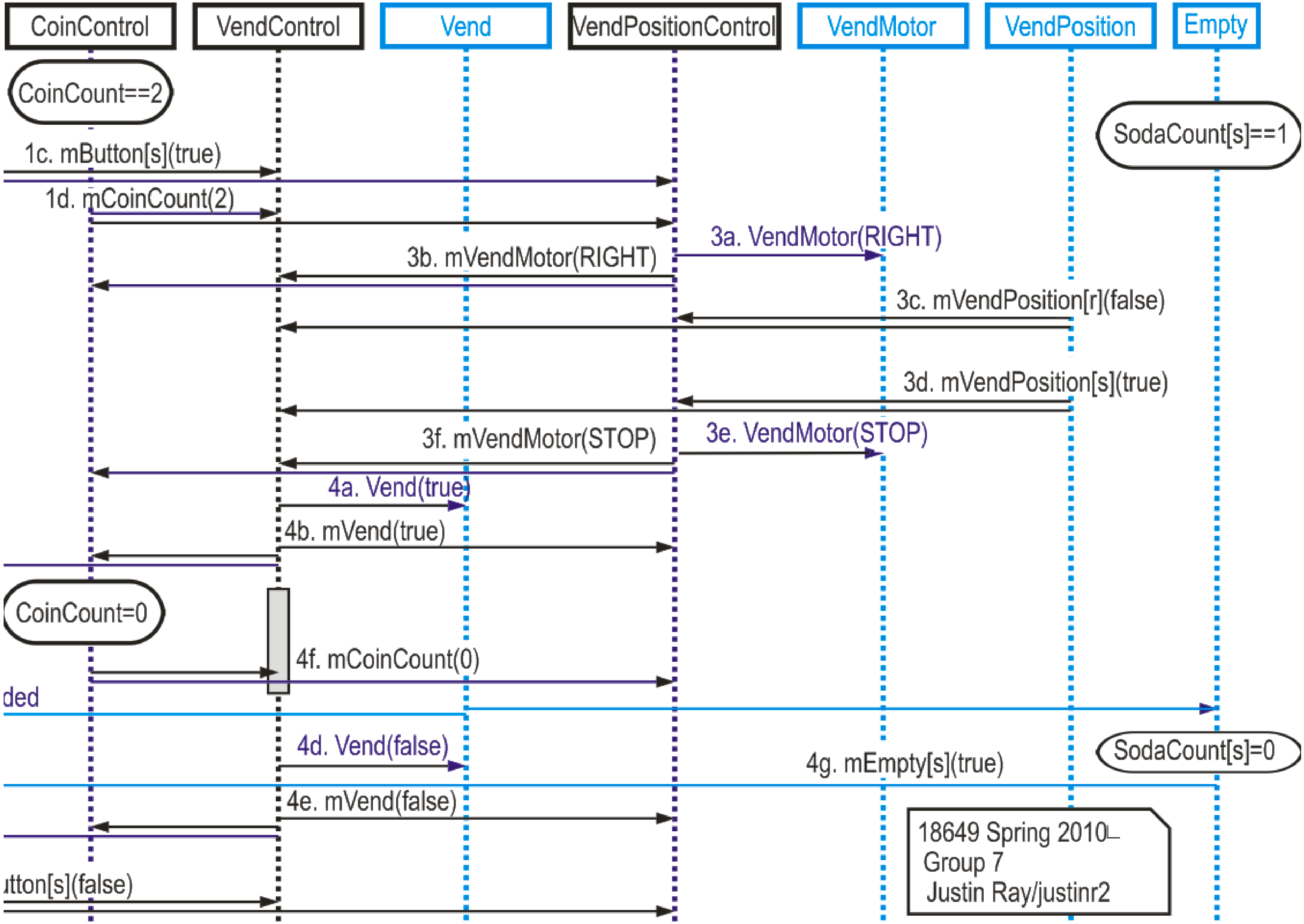
Better Font Size



This is better, but you still need to zoom in to see things

Sequence Diagram 2A:





CoinControl
VendControl
Vend
VendPositionControl
VendMotor
VendPosition
Empty
CoinCount==2
SodaCount[s]==1
1c. mButton[s](true)
1d. mCoinCount(2)
3a. VendMotor(RIGHT)
3b. mVendMotor(RIGHT)
3c. mVendPosition[r](false)
3d. mVendPosition[s](true)
3f. mVendMotor(STOP)
3e. VendMotor(STOP)
4a. Vend(true)
4b. mVend(true)
CoinCount=0
4f. mCoinCount(0)
ded
4d. Vend(false)
SodaCount[s]=0
4g. mEmpty[s](true)
4e. mVend(false)
utton[s](false)
18649 Spring 2010
Group 7
Justin Ray/justinr2

Critique of Preceding Sequence Diagram

- **Pro: Everything is there**
  - You can see all the components of the system interacting
- **Con: It is complex**
  - If it is difficult to show in powerpoint, it is difficult to understand (the “Powerpoint Engineering” principle)
  - It is a very specific case (e.g., what if it wasn’t the last soda?)
- **Possible ways to improve**
  - Break it up vertically into multiple steps
  - Break it up vertically by not showing every piece interacting
  - There is no perfect, “best” way to do this – these are just ideas
- **Project grading note**
  - Not graded on whether your SDs are complex or simple or “best”
  - You are graded on whether your SDs trace properly
  - You are graded on whether the final project passes acceptance tests

How Many Sequence Diagrams?

- **Examples:**
  - Scenario 2A: Customer pushes a soda button when the correct amount has been paid
  - Scenario 2B: Customer pushes a soda button when the correct amount has NOT been paid

…

  - Scenario 1C: Customer pushes a soda button, holds it, and then deposits a coin
    - This is a combination of Use Case 1 & Use Case 2 – no clean distinction

- **Most Use Cases have more than one scenario for use**
  - And therefore more than one sequence diagram

- **Keep making scenarios until you cover all the functions that matter**
  - There is no single right way to do it …
    … but in general, simpler and fewer scenarios are better than many complex ones

Sequence Diagram Traceability

- **Sequence Diagrams to Use Cases**
  - Is there at least one sequence diagram for each Use Case number?
  - If so, you've satisfied traceability

- **Sequence Diagrams to objects**
  - Are all objects in at least one sequence diagram?

- **Sequence Diagrams to messages**
  - Are all messages in at least one sequence diagram?

- **Traceability doesn't prove you have everything; but it helps you avoid "stupid" mistake gaps**
  - For example, if there were no scenario 4A, then Use Case 4 isn't covered

Design

- “Design requirements” – has proven to be a useful step
- UML Statecharts

Two Step Design Process

(Attempts to reduce the size of the “miracle” in that process step)

1. **Write down constraints & behaviors**
   - Constraints are assumptions that other components can make
   - Behaviors are functions designed in to the component

2. **Synthesize a statechart**
   - Transitions have to account for all behavior triggers
   - Transitions have to account for all behaviors
     (alternately, states could account for all behaviors; depends on approach)

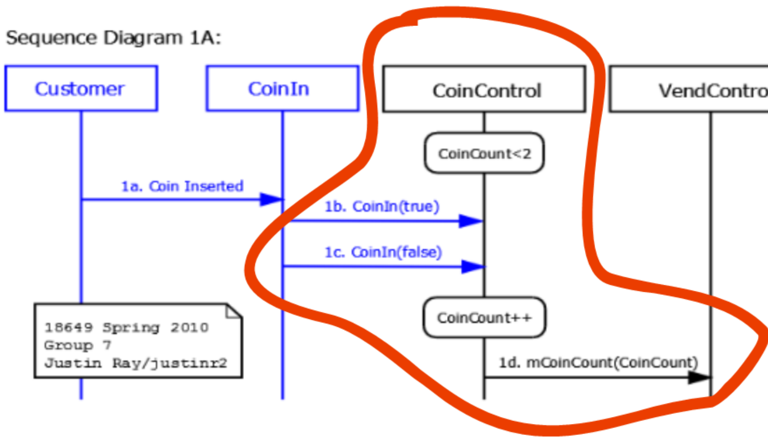
- **Alternate Approaches**
  - Tools can synthesize statecharts from <u>*a complete*</u> set of sequence diagrams
  - People can do that too, even if sequence diagrams are incomplete

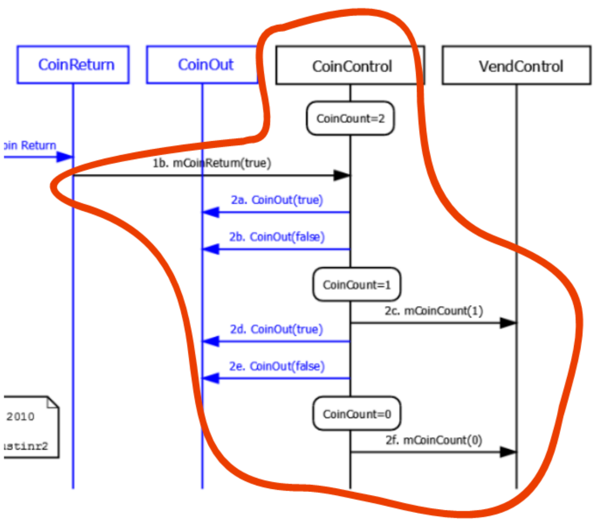
Formula for Event-Driven Systems

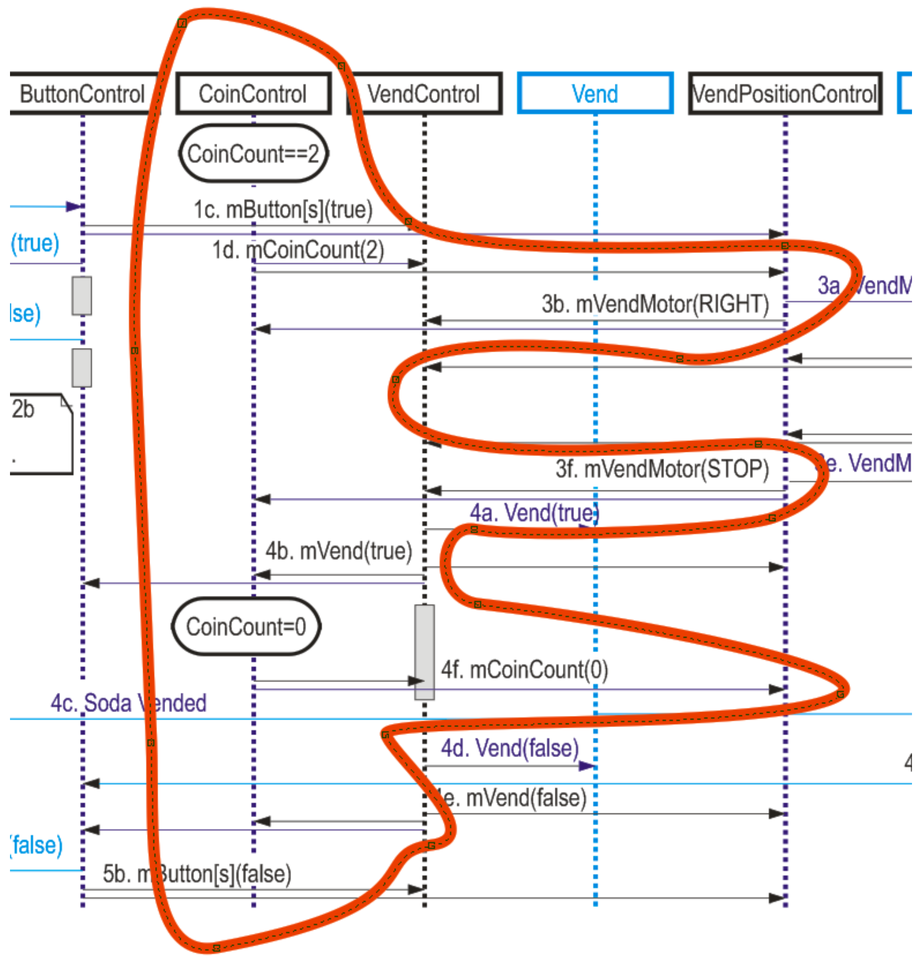
- **Behavioral Requirements:**
  - ***<ID> <message received>*** shall result in ***<message transmitted> …***
    . and/or ***<variable value assigned> …***
  - ***OR***
  - ***<message received>*** and ***<variable value test(s)>***
    shall result in ***<message transmitted> …***
    and/or ***<variable value assigned> …***
  - Account for all possible messages received; OK to restrict by value
    - E.g., <message received> with value V shall result in …
  - Account for all possible messages that need to be transmitted outbound
  - Make sure all variables are set as required in right hand sides
  - ***EXACTLY ONE*** received message per requirement (network serializes messages; simultaneous reception of multiple messages is ***impossible***)
  - OK to have: multiple messages transmitted; multiple variables assigned

Sequence Diagram To Behavioral Requirements

- **For each object in system**
  - Consider every sequence diagram
  - Create rules that explain behaviors of arcs ***for that object***
- **What matters for an object?**
  - All ovals with conditions/assignments
  - All arrows exiting the object
  - All arrows entering the object







ButtonControl[s] Event Triggered Requirements

- **ER2.1. If mEmpty[s] is received as v, then IsEmpty shall be set to v.**
- **ER2.2. If mEmpty[s] is received True and ButtonState ← False, then**
  - ER2.2a. ButtonLight[s](v) shall be commanded to False.
  - ER2.2b. mButton[s] shall be set to False.
- **ER2.3. If mEmpty[s] is received False and ButtonState ← False, then**
  - ER2.3a. ButtonLight[s](v) shall be commanded to True.
  - ER2.3b. mButton[s] shall be set to False.
- **ER 2.4. If Button[s] is received True and IsEmpty is False, then**
  - ER2.4a. ButtonState shall be set to True.
  - ER2.4b. ButtonLight[s] shall be commanded to blink with a period of 0.25s.
  - ER2.4c. mButton[s] shall be set to True.
    ER 2.5. If mVend[s] is received True and IsEmpty is False, ButtonLight shall be commanded to True.
- **ER 2.6. If mVend[s] is received True and IsEmpty is True, ButtonLight shall be commanded to False.**
- **ER 2.7. If mVend[s] is received True, then**
  - ER 2.7a mButton[s] shall be set to False.
  - ER 2.7b ButtonState shall be set to False.

Statechart Design

- **We now have a (we think) complete behavioral requirements specification**
  - Really you can just call these "behaviors", but we use the word requirements to remind you that "shall" and "should" are mandatory words.
- **Design Statecharts for each software object**
  - Design states for each object
  - Behavior requirements become conditions for state transitions
  - Cover every behavior requirement in state chart
- **Traceability**
  - Every behavior requirement should map to a state transition arc
- **Note: we're not covering control loop design with these**
  - Statecharts sometimes implement sequential logic
  - But, sometimes they cause mode transitions for control loops

ButtonControl Time Triggered Statechart

Transition #	Guard
T2.1	mButton[s] ← True AND mEmpty[s] ← False
T2.2	mVend ← True AND mEmpty[s] ← False
T2.3.	mVend ← True AND mEmpty[s] ← True
T2.4.	FlashCounter > FlashLimit
T2.5.	FlashCounterLimt ← 0
T2.6.	mEmpty ← True
T2.7.	mEmpty ← False

Important – show guard conditions with statechart diagram!

Use 12 point+ font

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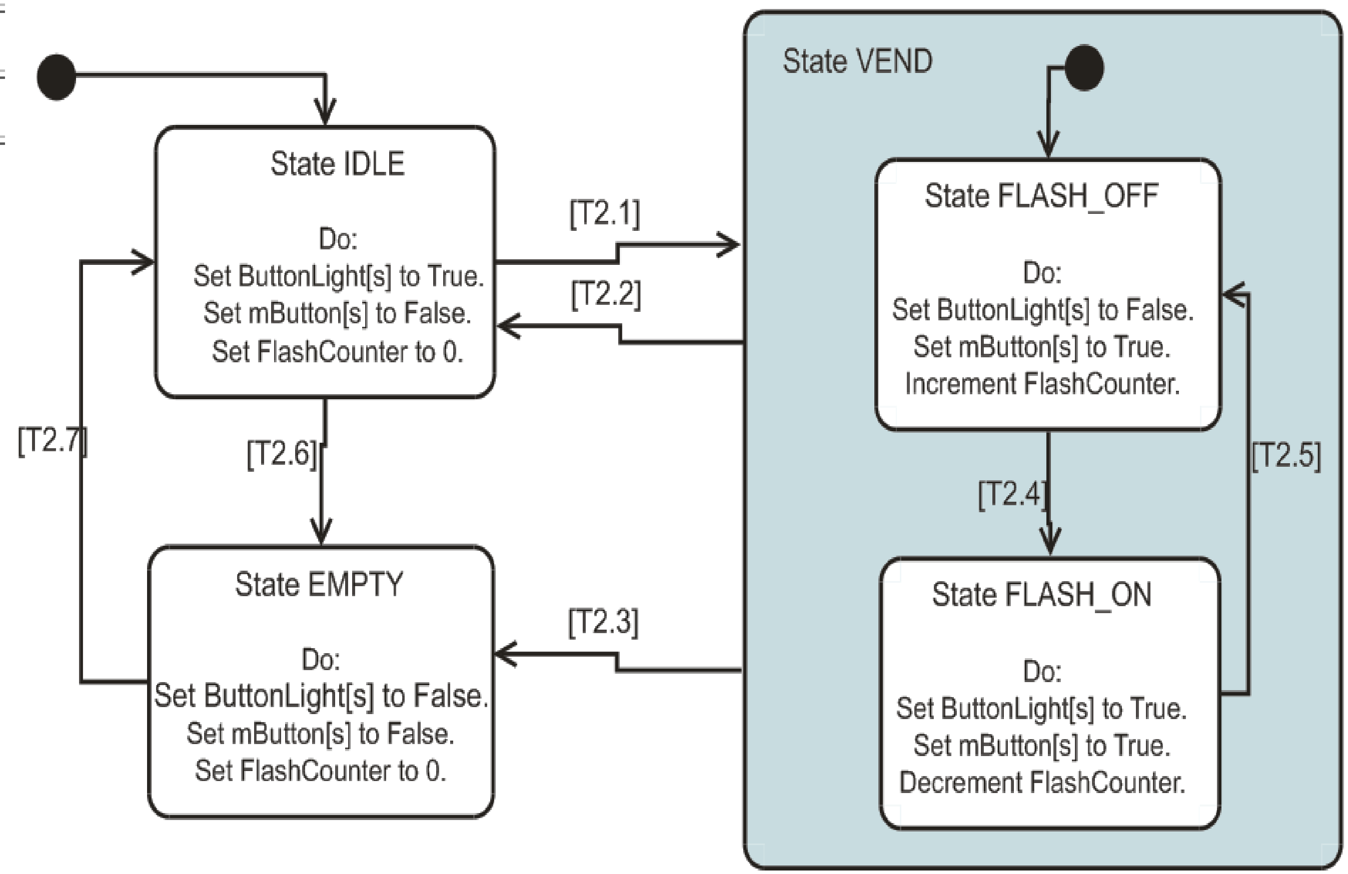
14 POINT FONT

12 POINT FONT

10 POINT FONT

8 POINT FONT



Event Triggered vs. Time Triggered?

- **Event triggered**
  - Exactly one message on left hand side of “shall”
  - Each message arrival is an “event” which triggers a statechart transition
  - Networks deliver only one message at a time, so that’s the way it is
  - “Asynchronous state machines” from hardware design

- **Time triggered**
  - Arriving message values put into memory buffers
  - State chart transitions based on most recent message value
  - “Synchronous state machines” from hardware design

- **Project sequence is**
  - Event triggered project 3
  - Convert to time triggered project 4
  - Why? Because every time we skipped event triggered half the class got lost
    - Once you see it, it’s not too bad, but it is not easy to “see” if you skip this step
    - You’ll see more about this as we go

Traceability

- Does every requirement map to at least one state or transition?
- Does every state or transition map to at least one requirement?

Requirements-to-Statecharts Traceability

	Requirements					
States	R2.1	R2.2	R2.3	R2.4a	R2.4b	R2.5
IDLE	x		x			x
EMPTY	x	x				x
VEND	x			x	x	
FLASH_OFF	x			x	x	
FLASH_ON	x			x	x	
Transitions						
T2.1				x	x	x
T2.2			x			
T2.3		x				
T2.4					x	
T2.5					x	
T2.6		x				
T2.7			x			

(Implementation) CoinOutControl Code

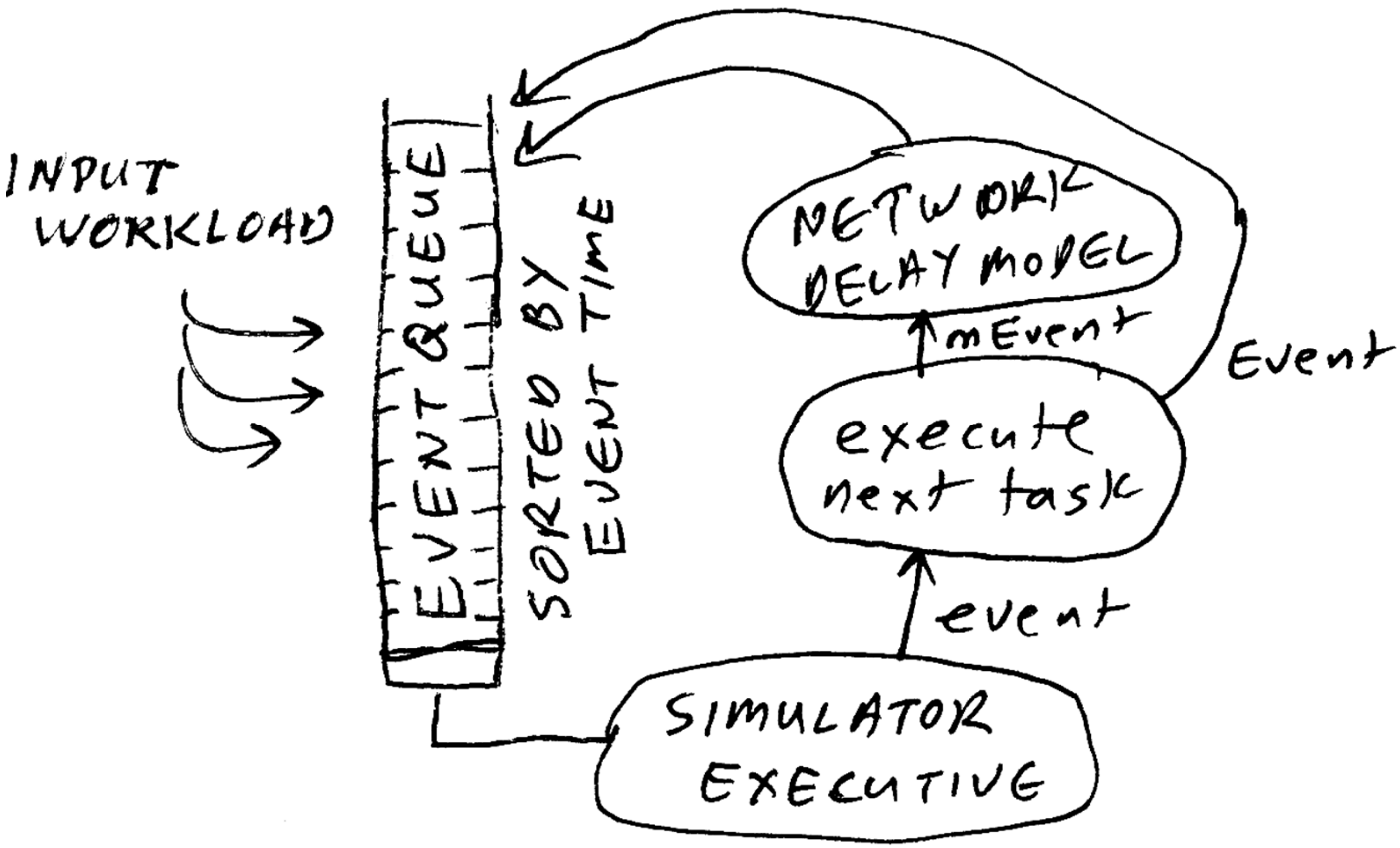
```
class CoinOutControl {
	state = No_Money_Inserted;
	COUNTER = 0;
…
public void msgReceived(msg M) {
	switch state { // make transitions
	case No_Money_Inserted:
		if (M = = Coin_in.TRUE) state = One_Quarter_Inserted;		//*** Transition S2.a1
		break;
	case Coin_Inserted:
		if (M == Coin_in.TRUE) sendMsg(Coin_out.TRUE);			//*** Transition S2.a4
		else if (M == Vend[s].TRUE) state = No_Money_Inserted;		//*** Transition S2.a2
		else if (M == Coin_return.TRUE) {				//*** Transition S2.a3
				sendMsg(Coin_out.TRUE);
				state = No_Money_Inserted; }
		break;
	default:  Error condition
	}

	switch state { // behavior in state
	case No_Money_Inserted:				//*** State S2.s1
		COUNTER = 0; break;
	case One_Quarter_Inserted:			//*** State S2.s2
		COUNTER = 1; break;
	default: Unknown state
	}
}
```

Note traceability of code to statechart
This is code from an older example

Discrete Event Simulator

- **Everything is an "event"**
  - Framework events wait until their time to execute, then generate other events
  - Message events only differ in that they go through a network delay model
  - Note that the event queue is sorted by time – earliest event runs next
    - In case of a time value tie, order is arbitrary (and may be randomized)



Traceability of Statecharts

- **Sequence Diagram Arcs trace directly to statechart arcs**
  - An arrow coming into an object can cause a state transition
  - That traces to changing the state variable value in the code

- **Behaviors trace to statechart arcs too**
  - This is why text behaviors are skipped by some designers
  - But we’ve informally found they reduce errors

- **Statecharts are more “complete” than most sequence diagrams**
  - Statecharts have to account for all transitions to actually work
  - Extra transitions might be necessary in design

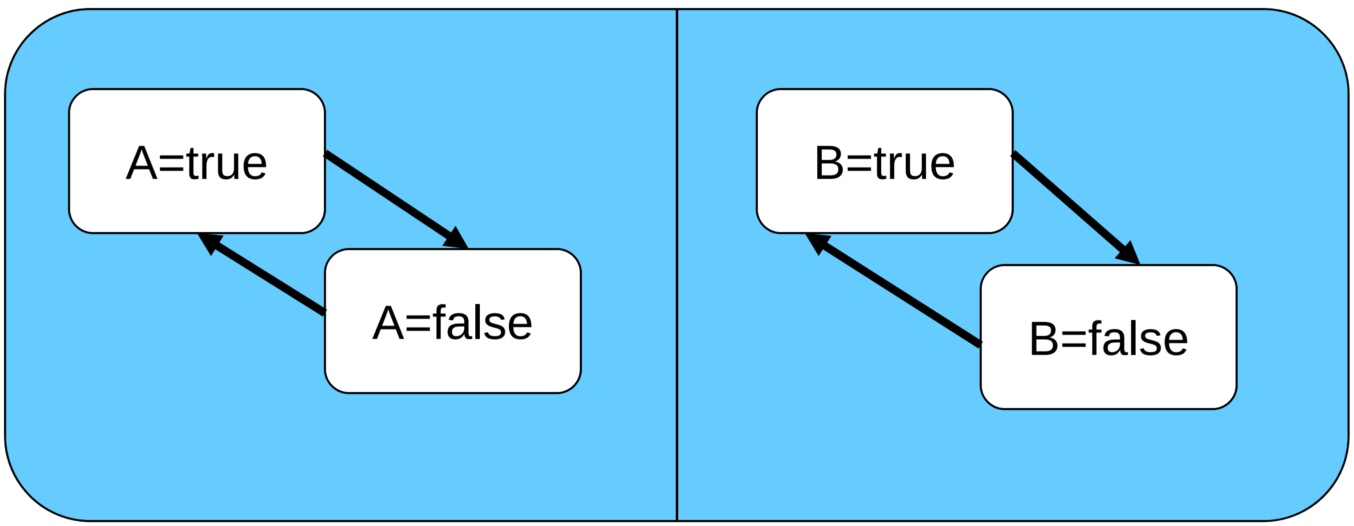
  - Advice for non-traced arcs & states is *either*:
    - Invent new sequence diagrams to cover all arcs in statecharts
      OR
    - Be very careful to test non-traceable arcs to avoid undesired side effects

Statechart Construction Rules

- **Statechart transition conditions/arcs shall contain**
  - Guard conditions **only**!
  - No actions on transitions
  - In hardware, this would make them Moore FSMs
- **Even though actions on arcs are allowed by UML…**
  - This makes it easier to obtain clean time triggered design
  - It makes the code itself have a much cleaner structure
  - In the long run it reduces number of bugs
- **If you feel you must execute an action on a transition…**
  - Use an intermediate state instead
  - Usually a state with an action and one always-true exit arc

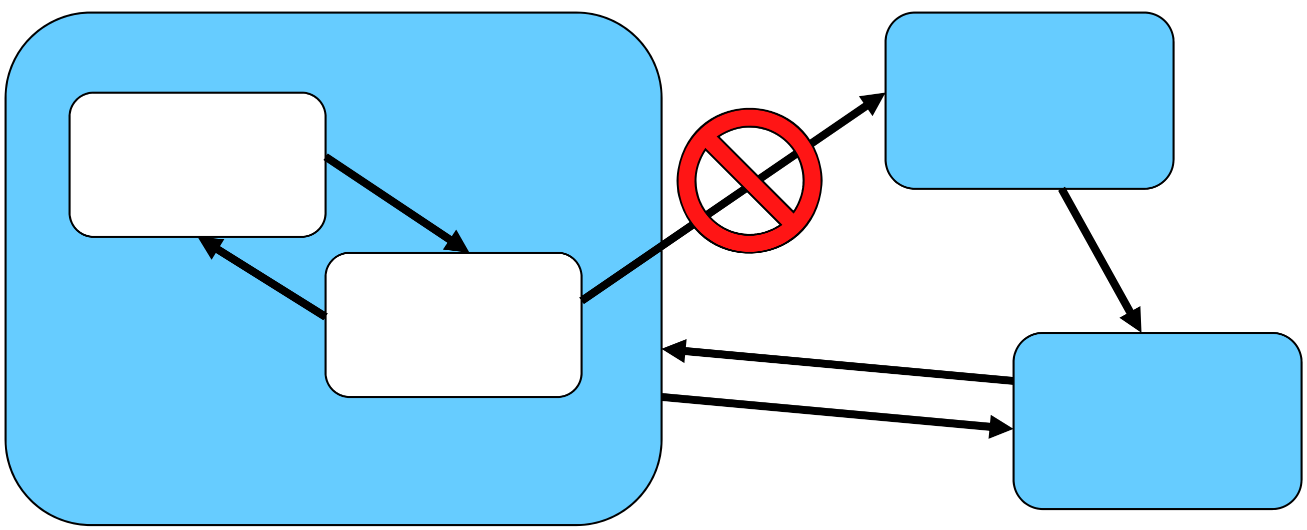
Concurrent Statecharts

- OK to have two or more statecharts executing in parallel
- Parallel statecharts shall not write to the same outputs or state variables



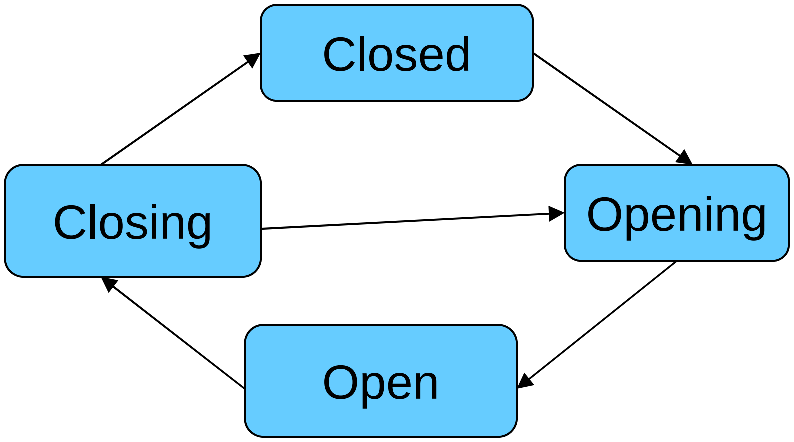
Nested Statecharts

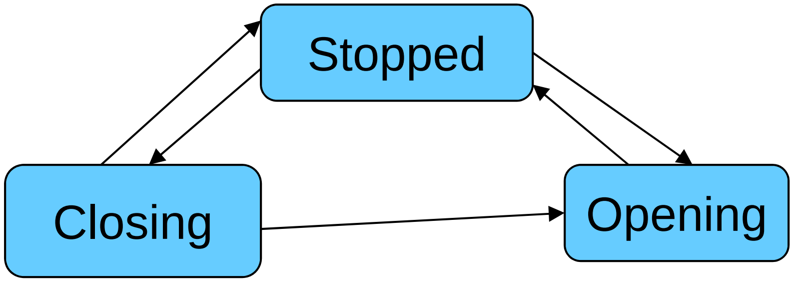
- **Avoid using them!**
  - Difficult to implement in code
  - Requires multiple, nested switch statements
- **If you *must* use them**
  - You may *not* transition in to or out of the superstate from an inner state



States vs. State Variables

- **State variables are appropriate for:**
  - Integers (counters, floors numbers, etc)
- **NOT suitable for:**
  - Boolean flags (doorIsClosed)
  - Boolean flags should show up as states, not variables
- **Statechart for door should represent the state of the door, not the state of the door motor**





Test Design

- Testing statecharts
- Acceptance tests
- (A full description of testing would be an entire tutorial)

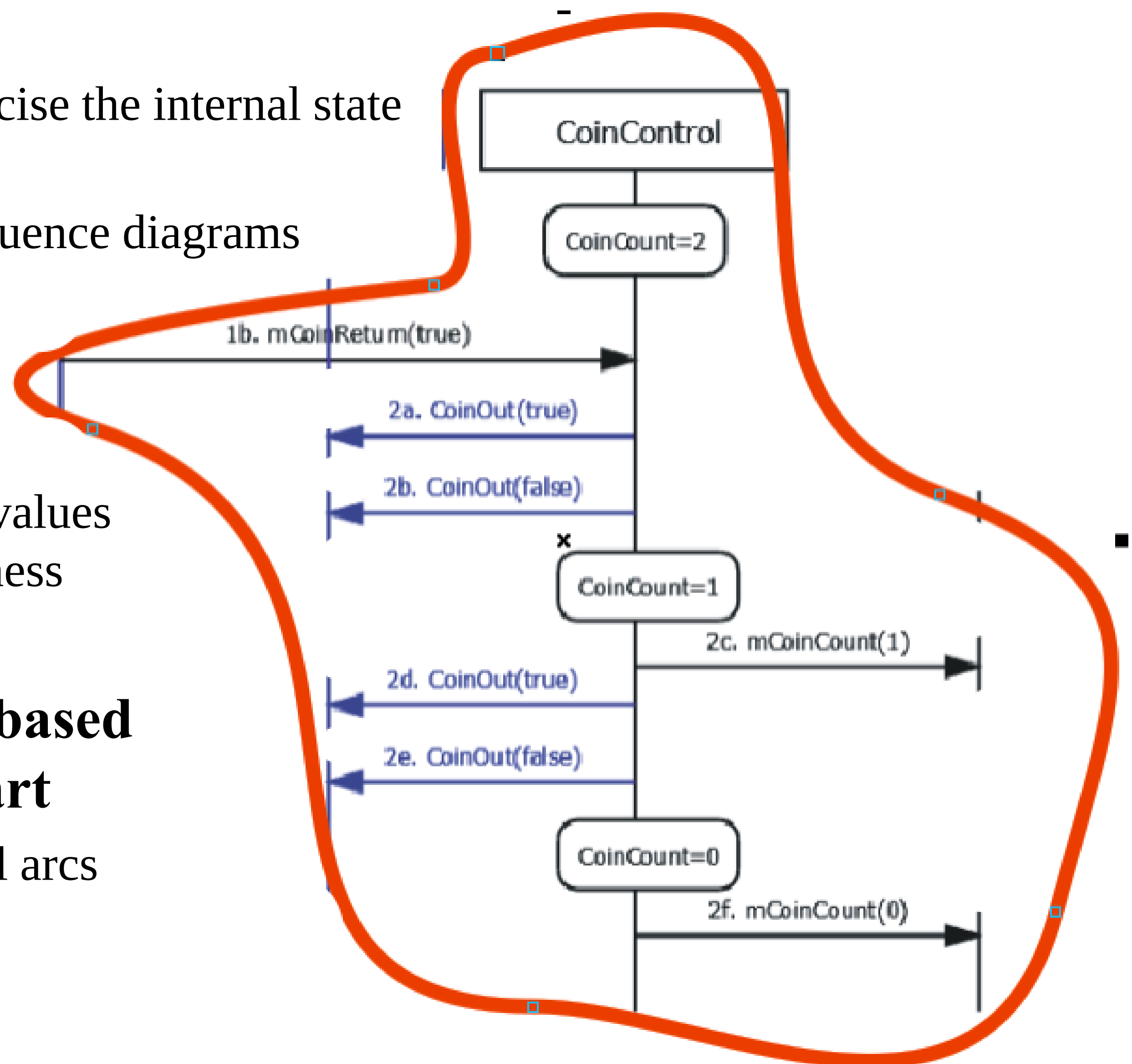
Test Design

- **Suggestion: design tests before actual implementation**
  - May uncover errors in your design before coding
- **Test *at least* two levels before you run a full simulation**
  - Unit/module tests
  - System integration tests
- **Unit Tests**
  - Design tests to cover every state transition in every state chart
  - Make sure erroneous state transitions aren't taken
  - Cover every possible message/event received by each object
- **Traceability**
  - Document traceability between tests and state transitions for unit tests
- **System Integration Tests**
  - Test specified operation sequences / UML scenarios

Idea Behind Unit Test

- **Isolate single module and feed it direct inputs**
  - Feed in inputs that exercise the internal state machine
  - Base tests on single sequence diagrams

Test Input

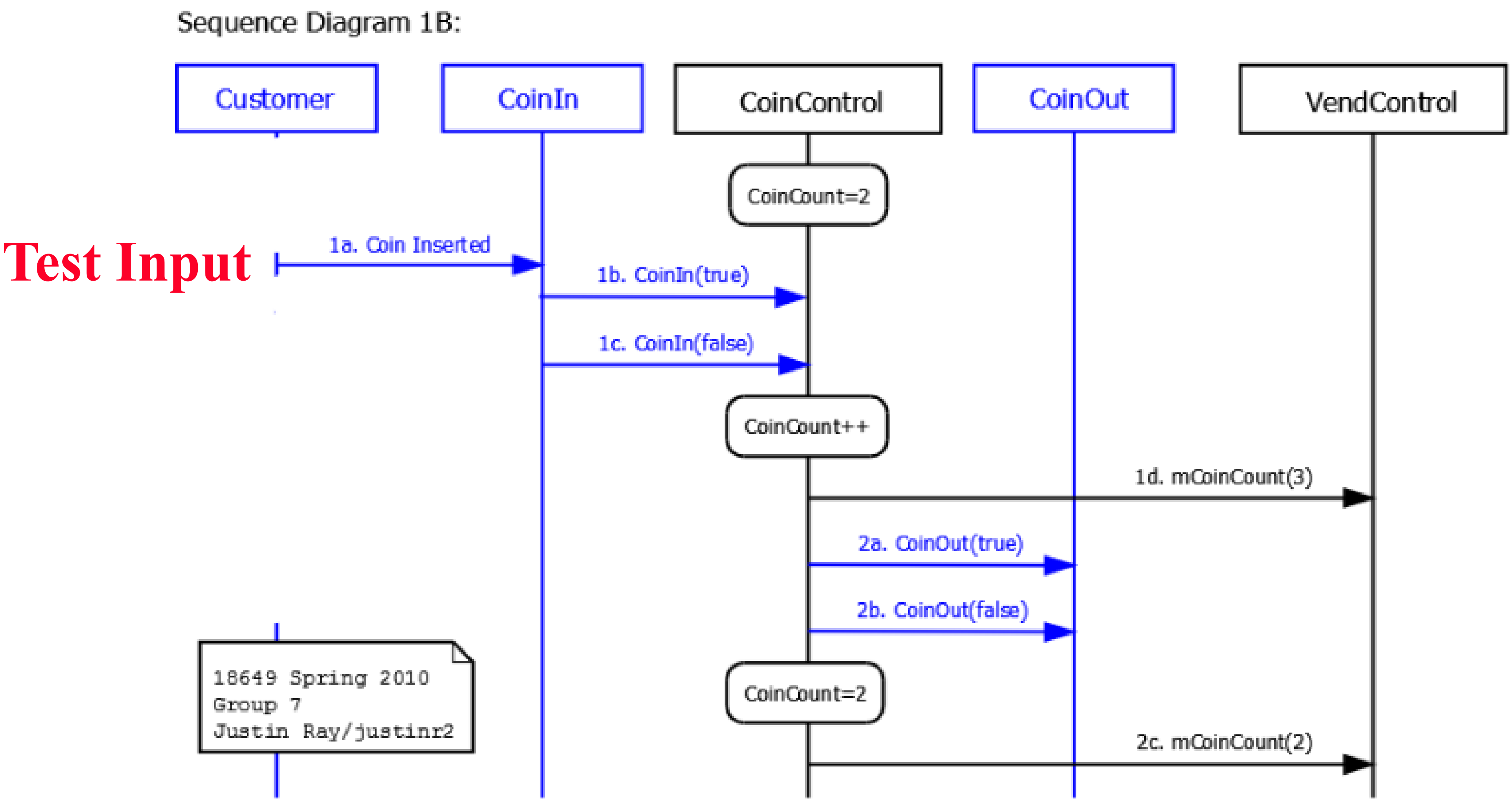


  - Monitor state machine values and outputs for correctness

- **Can also design tests based on looking at statechart**
  - Make sure you cover all arcs and enter all states

Idea Behind Integration Test

- **Run all modules in a Sequence Diagram except selected inputs**
  - Artificially set up state information to meet preconditions
  - Feed primary inputs from test harness; let rest of arcs run on their own
  - Make sure other arcs perform as expected



Acceptance Test

- **Ensure system as a whole actually meets requirements**
  - In simple systems, testing all scenarios suffices
  - In real systems, need to test sequences of Use Cases
- **First define meaningful sequences of use cases**
  - Example: insert coin, push soda button
  - Example: insert coin, push coin return, push soda button
- **Next, execute tests and compare results to system requirements**
  - Generate many simulated customers and see what happens
  - Were each of R1 - R6 met during the course of each test?
- **Additional test strategies:**
  - Design tests to attempt requirement failure
  - Reset system partway through a scenario or between use cases
  - …

Traceability of Tests

- **Trace Unit Tests to statecharts**
  - All states & arcs in statecharts covered by a test
  - Probably want additional tests … simple coverage is just a starting point
  - Be careful about variable values since variables store “state” beyond FSM

- **Trace Integration Tests to sequence diagrams**
  - Every sequence diagram should be covered by a test
  - Probably want additional tests, especially for undocumented off-nominal situations

- **Trace acceptance tests to:**
  - Marketing requirements – that is the whole point of acceptance tests, especially testing all use cases

and if possible:

  - Engineering requirements – should have high coverage
  - Sequence diagrams – all nominal and some off-nominal should be covered

Review: General Approach (Hybrid UML + Text)

- **"Requirements"**
  - Use cases (which are exemplary, but not necessarily coherent/definitive)
  - System-level text requirements
- **"Architecture"** (really just some parts of architecture)
  - Class Diagrams – model "nouns" in system as classes & "architecture diagram"
  - Define network variables that define architectural interfaces (message dictionary)
  - Sensors, actuators, software objects
- **Software Requirements**
  - Scenarios – details inside use cases
  - Sequence Diagrams
- **Design**
  - Detailed text behavioral requirements
  - State Charts (state transitions)
  - Test Design
- **Implementation**
  - Write the code
  - Module testing (unit tests)
- **Integration**
  - Integration tests; acceptance tests