# Self-Healing Autonomous Vehicles

## Increasing System Resiliency with Automated Program Repair

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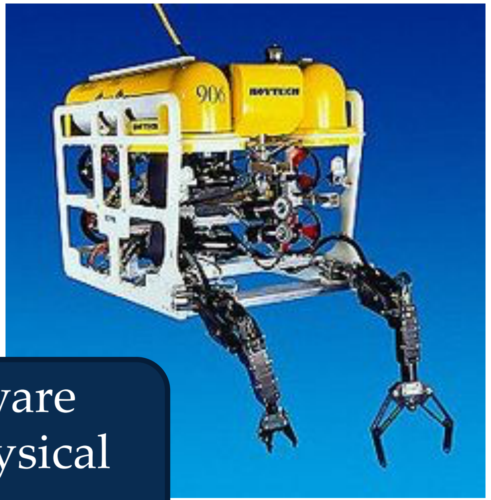
# Robots Go Where We Cannot



Redundant Hardware Protects Against Physical Damage

Spirit Rover Stopped Communication Due to Software Fault

Limited, Delayed, or Impeded Communication

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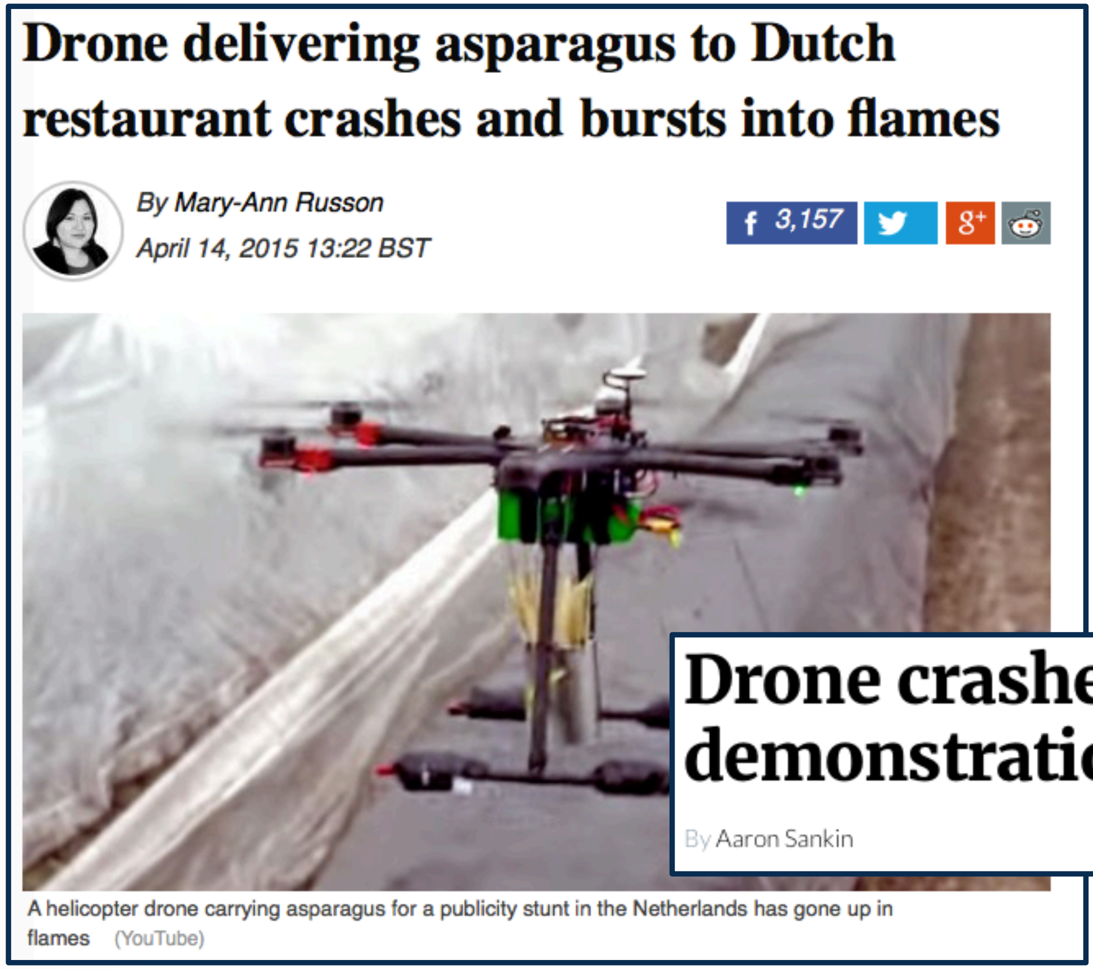
Let's focus on a similar system that costs **much** less…

# Quadcopters are not Immune



**Drone delivering asparagus to Dutch restaurant crashes and bursts into flames**

By Mary-Ann Russon
April 14, 2015 13:22 BST

A helicopter drone carrying asparagus for a publicity stunt in the Netherlands has gone up in flames (YouTube)

Hardware Resiliency

Software Resiliency

**Drone crashes into house wall in man's demonstration of software bug**

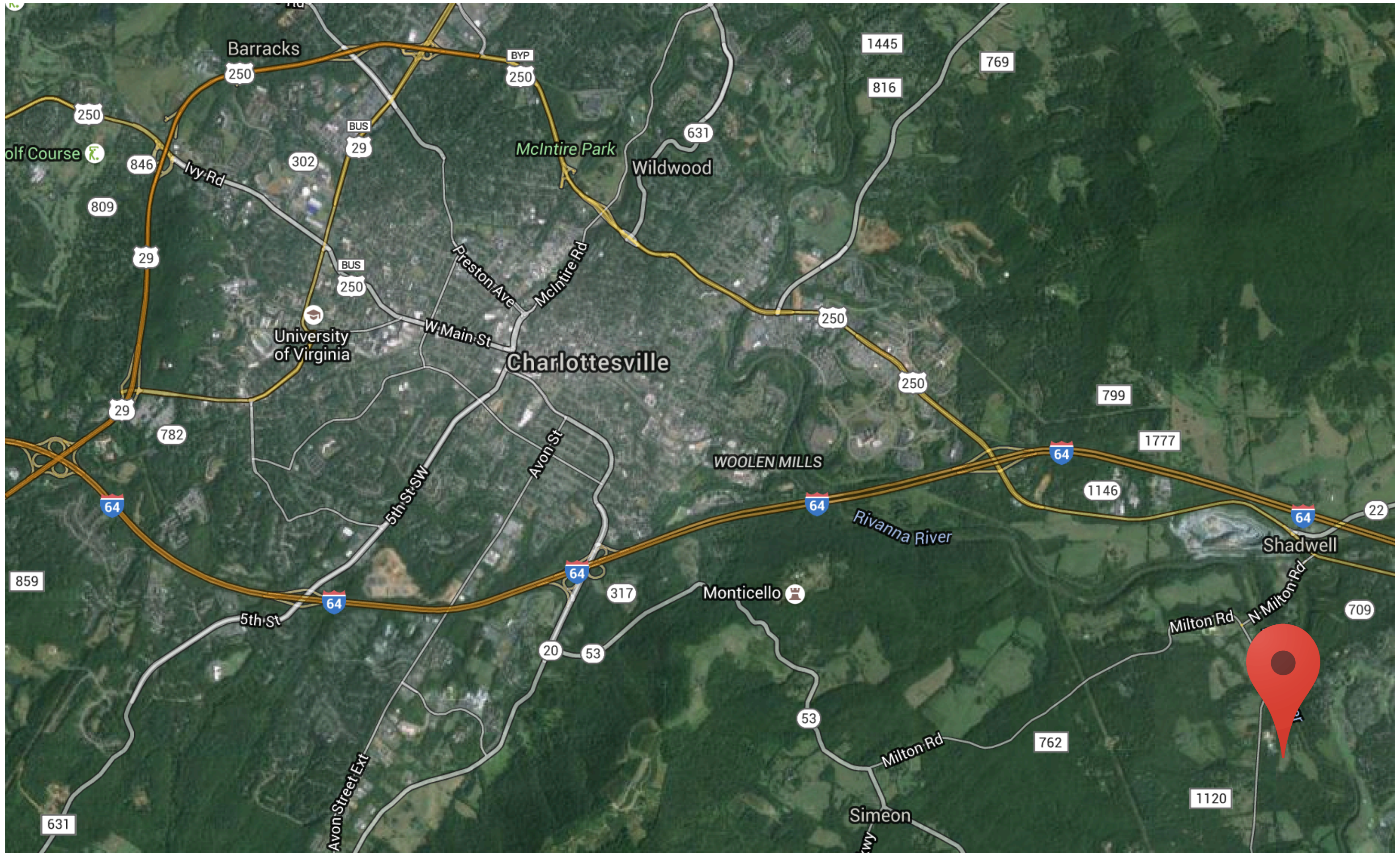
By Aaron Sankin

Jan 14, 2015, 8:20am CT | Last updated Jan 14, 2015, 11:34am CT

## Cutting to the Chase

- *Automated program repair* can generate software patches to increase system resiliency in autonomous vehicles
- We apply these patches *during operation* using special hardware

# Milton Airfield @ UVA



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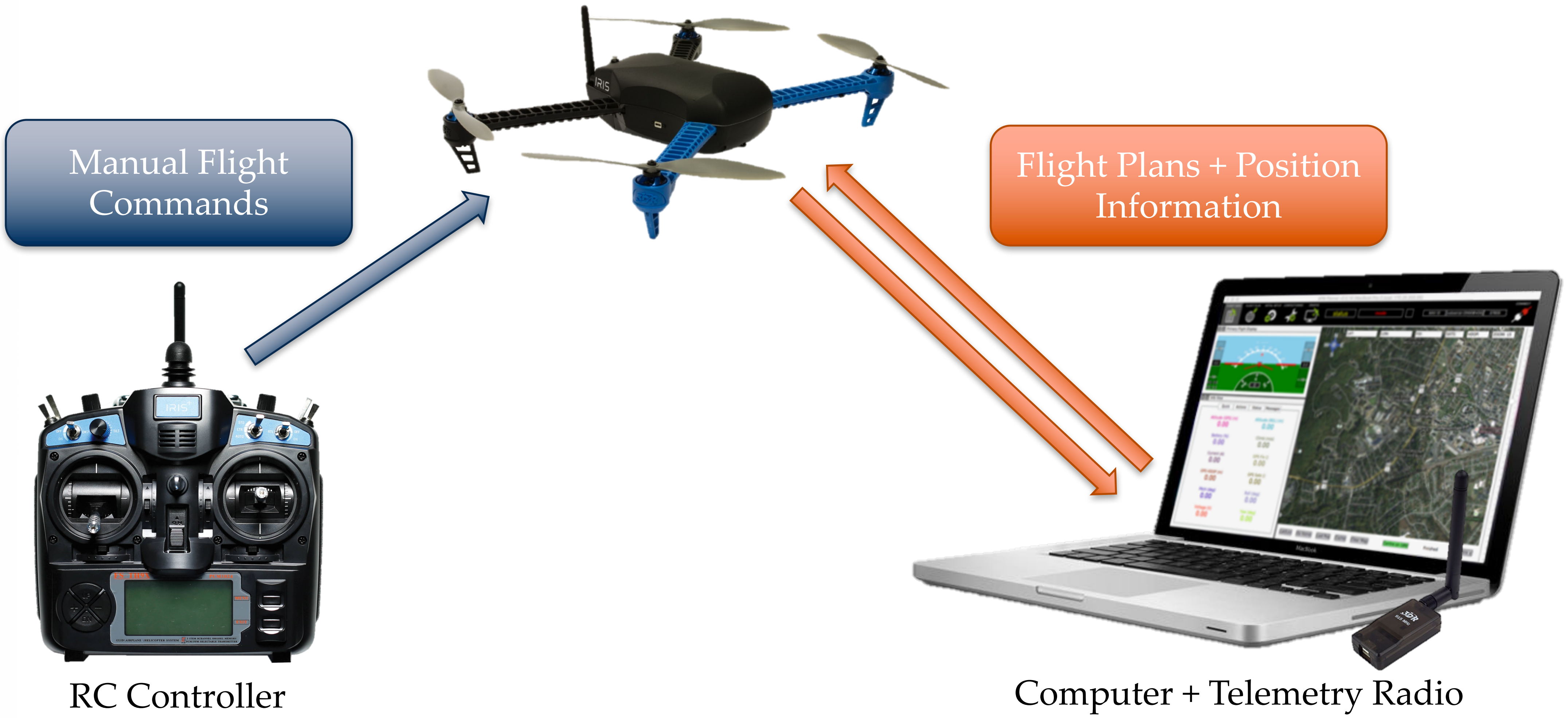
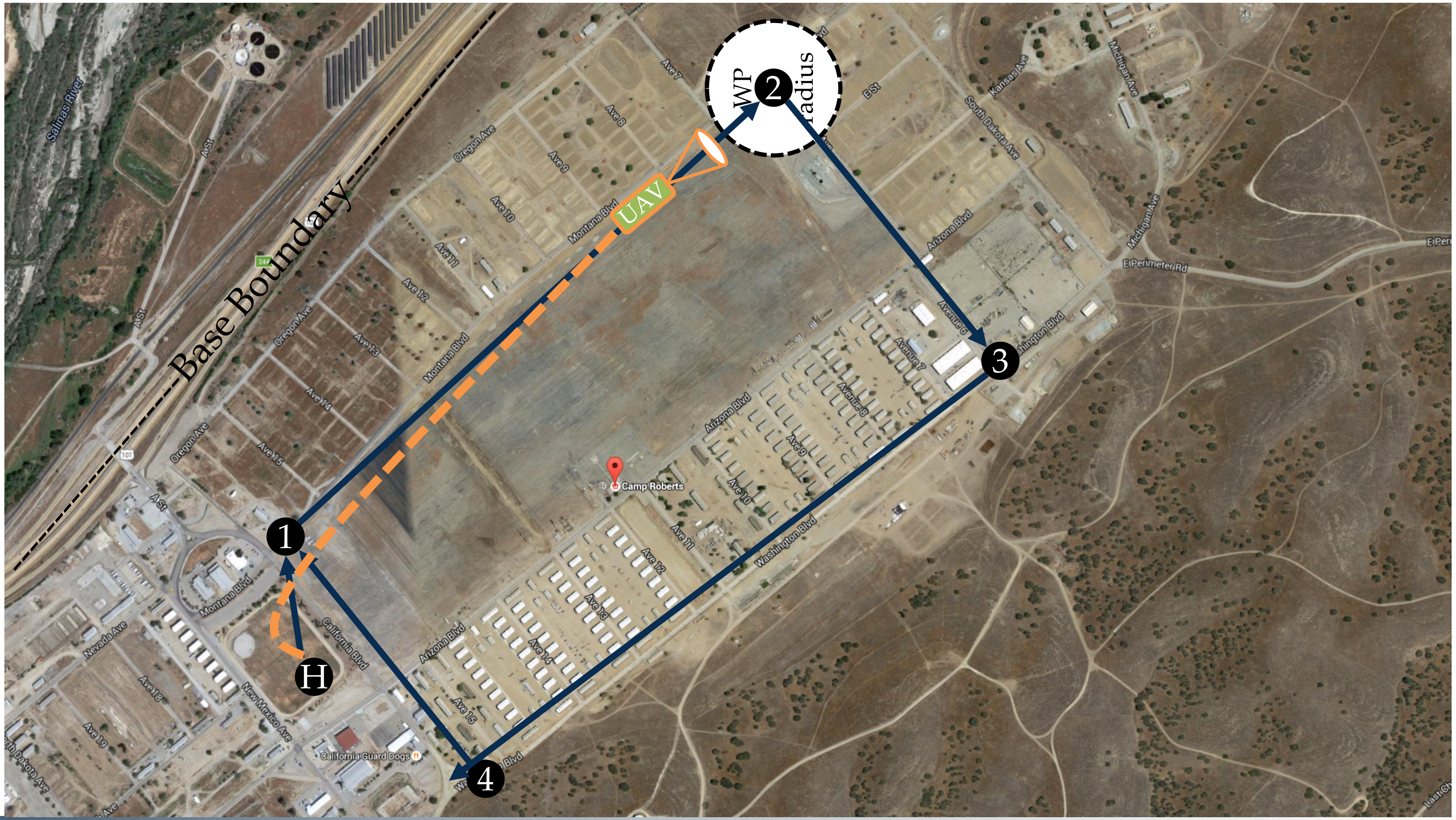
## Today's Action-Packed Episode

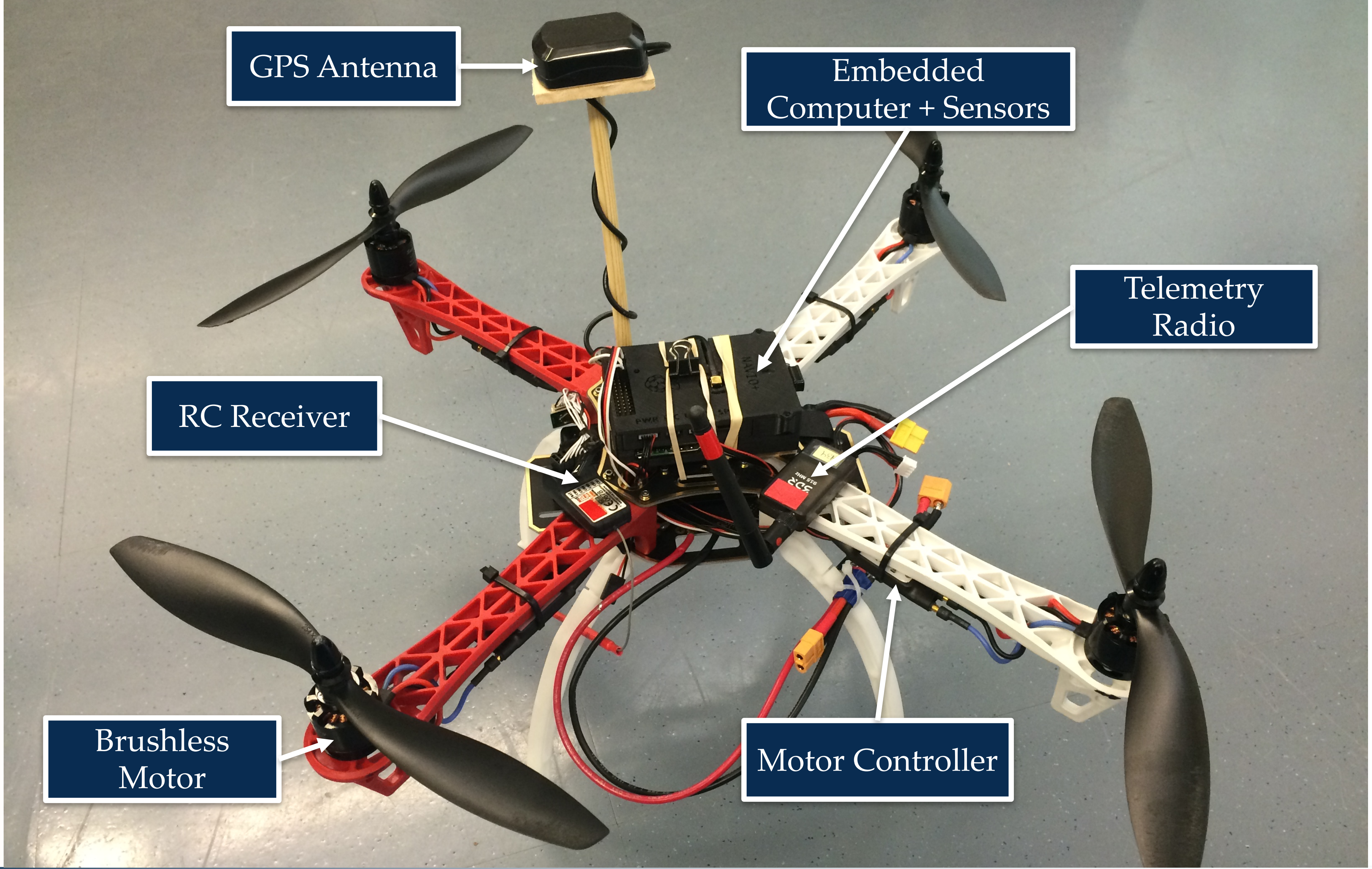
- Overview of Quadcopters
  - Hardware System
  - Software System
- An Example Bug
- Automated Program Repair Crash Course
- Understanding Processors and Patching
- Demo of Software Resiliency

# Quadcopter Communication


Manual Flight Commands
Flight Plans + Position Information
RC Controller
Computer + Telemetry Radio

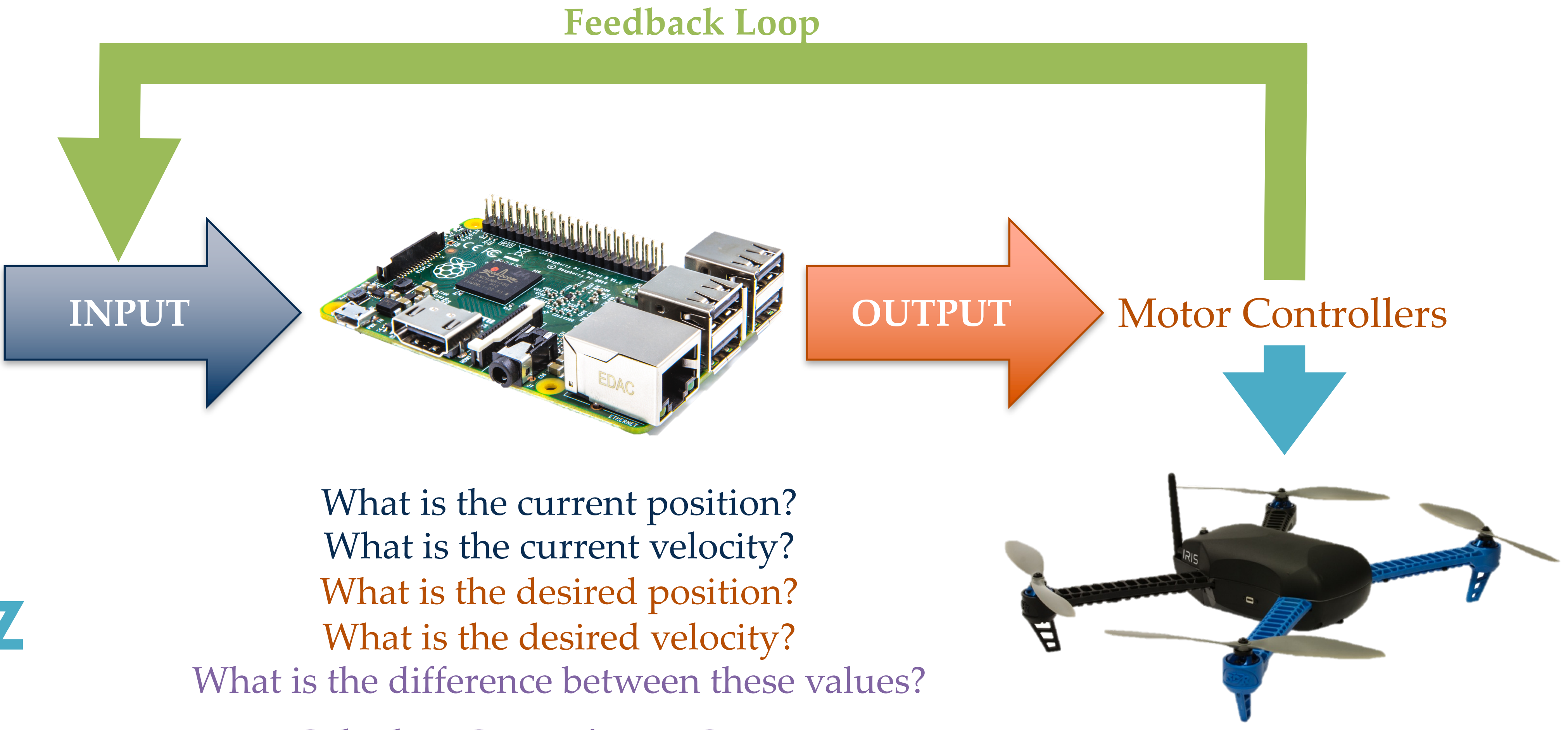
# Flying a Mission




GPS Antenna
Embedded Computer + Sensors
Telemetry Radio
RC Receiver
Brushless Motor
Motor Controller

# How does a Quadcopter Fly?

GPS Data
Accelerometer
Compass
Altimeter
RC Input
Motor Speed



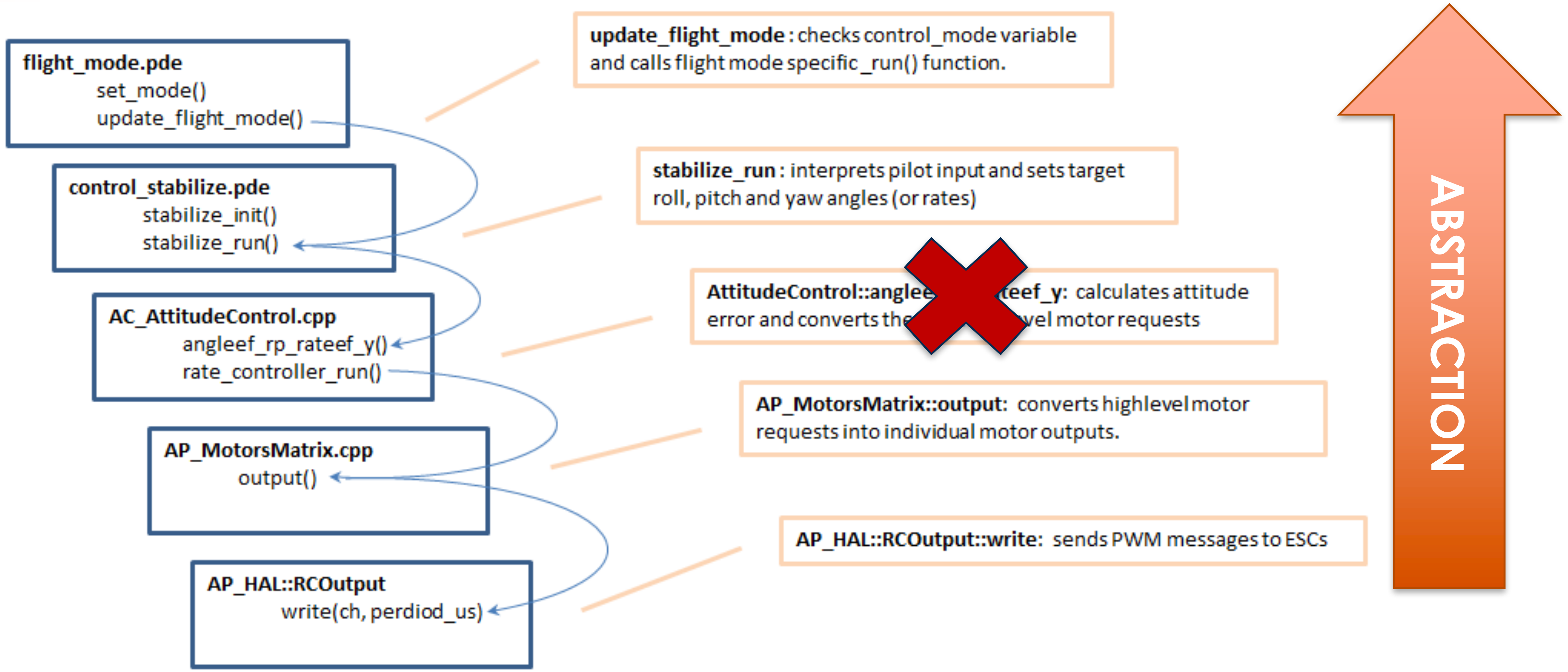
**400Hz**

What is the current position?
What is the current velocity?
What is the desired position?
What is the desired velocity?
What is the difference between these values?

**Calculate Correction to Output**

Quadcopter Moves

# Quadcopters are Like Ogres



**flight_mode.pde**
set_mode()
update_flight_mode()

**control_stabilize.pde**
stabilize_init()
stabilize_run()

**AC_AttitudeControl.cpp**
angleef_rp_rateef_y()
rate_controller_run()

**AP_MotorsMatrix.cpp**
output()

**AP_HAL::RCOutput**
write(ch, perdiod_us)

**update_flight_mode** : checks control_mode variable and calls flight mode specific _run() function.

**stabilize_run** : interprets pilot input and sets target roll, pitch and yaw angles (or rates)

**AttitudeControl::anglee teef_y:** calculates attitude error and converts the vel motor requests

**AP_MotorsMatrix::output:** converts high level motor requests into individual motor outputs.

**AP_HAL::RCOutput::write:** sends PWM messages to ESCs

source: dev.ardupilot.com

How do we fix this bug?

”What we would like ideally […] is the automatic detection and correction of bugs” –R. J. Abbott

## AUTOMATED PROGRAM REPAIR

# Defining the Problem

- Source code written by developers
- Binary that processor executes

Generate a list of changes to the program that, when applied, result in passing all tests or only normal runs

**Given a program and evidence of a bug, fix that bug.**

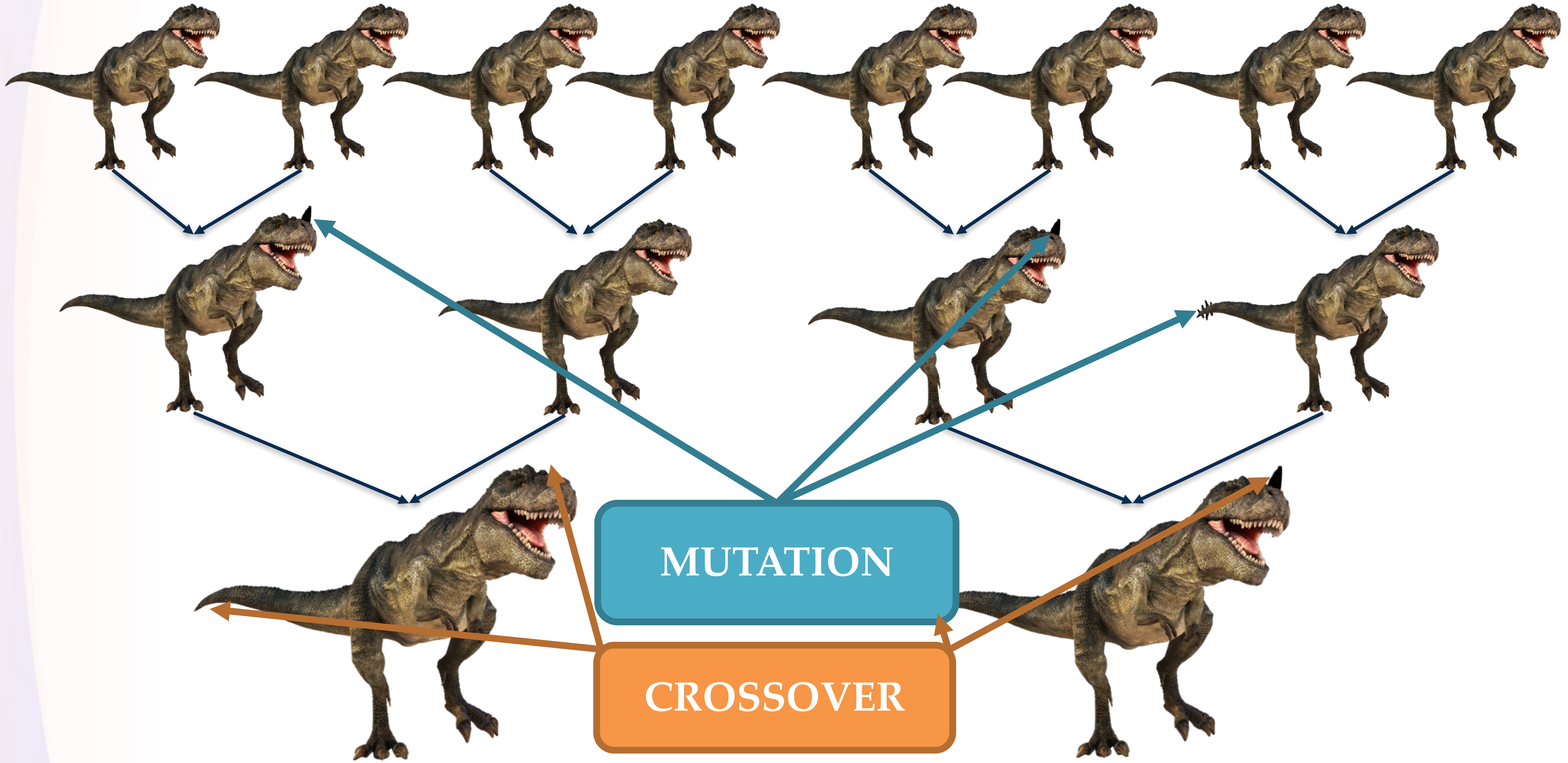
- Passing tests and one failing test
- Normal and anomalous runs

## How do we do this automagically?

Given a program and evidence of a bug, fix that bug.

THINK EVOLUTION

Imagine dinosaurs rather than programs…


MUTATION
CROSSOVER

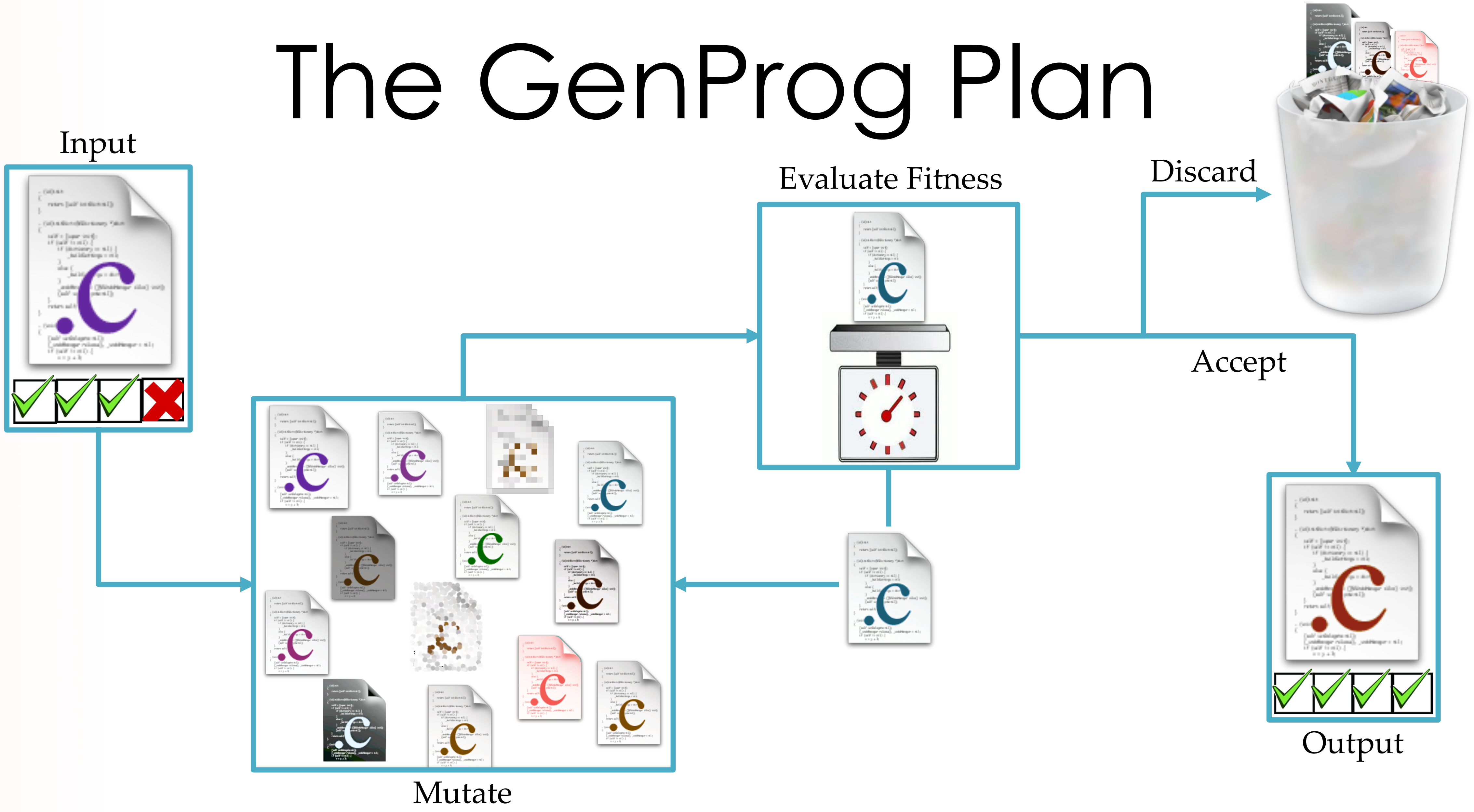
# Dinosaurs vs. Program Repair

Genetic code for next generation contained within current generation ⟷ Code to correct the bug can be found elsewhere in the code

Environmental factors result in survival of the fittest ⟷ Test suites and indicative workloads result in survival of the fittest

Many combinations of genetic material possible ⟷ Search space for programs in enormous

# The GenProg Plan



# Open Problems

- Fitness evaluation
  - How do we test quadcopter code (simulation?)
- Patch application
  - ***Easy***: Land quadcopter, reflash, restart
  - ***Hard***: What if the quadcopter cannot land? How do we apply a patch without reflashing and restarting the software?

# Patching an Executing Binary

- *Programming languages* provide abstractions to help humans write software
- A *compiler* converts this high-level program into a *binary* that a processor can execute
- Since the processor executes the binary, we must apply the patch to this version of the program

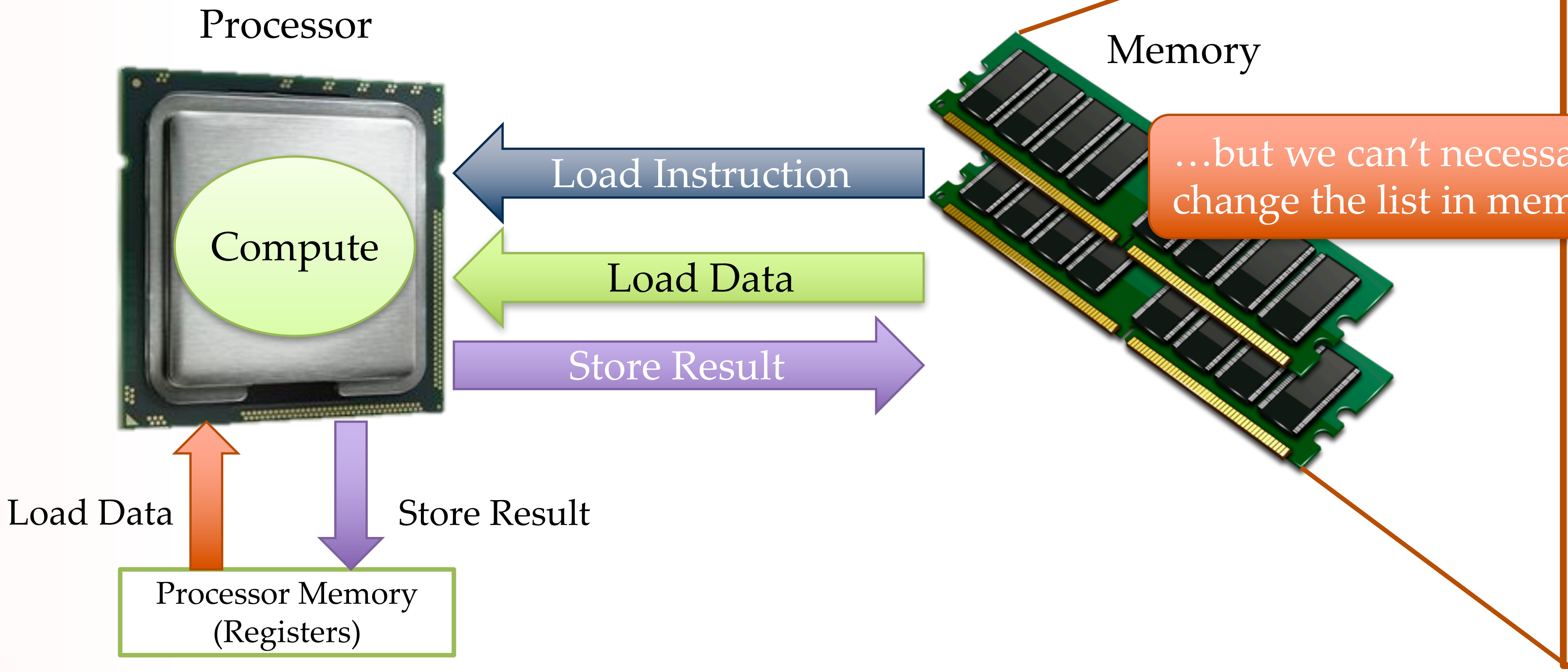
# What can a processor do?

- Execute a list of instructions
- *Instruction:* perform operation using one or two pieces of data
  - Add/Subtract/Divide/Multiply
  - Load a piece of data from memory
  - Store a piece of data to memory (sometimes)
  - Jump to a new location in the list of instructions
- Human-readable form is known as *assembly language*

```
  .text
main:
  add $t0, $zero, 496
  add $t1, $zero, $zero
  add $t2, $zero, 1

loopbegin:
  beq $t0, $t2, loopend
  div $t0, $t2
  mfhi $t3
  one $t3, $zero, loopcont
  add $t1, $t1, $t2

loopcont:
  add $t2, $t2, 1
  bet $t0, $t1, summer
  add $t7, $zero, $zero
  j loopbegin

summer:
  add $t7, $zero, 1
  j loopbegin

loopend:
  jr $ra
```

# Von Neumann Architecture

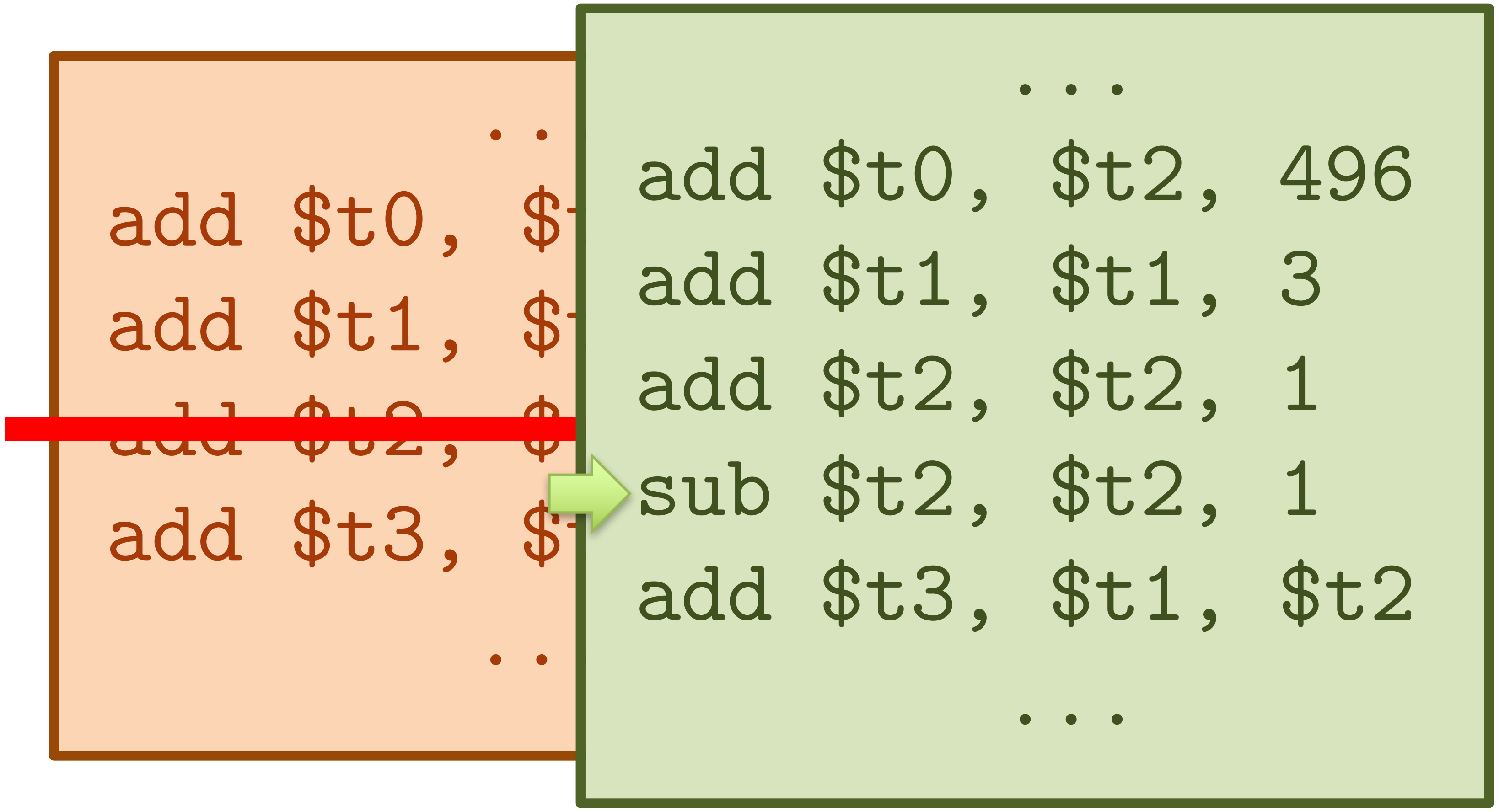
We can patch a binary by *inserting* into or ~~*deleting*~~ from the instruction list…



…but we can't necessarily change the list in memory

```
 .text
main:
  add $t0, $zero, 496
  add $t1, $zero, $zero
  add $t2, $zero, 1

loopbegin:
  beq $t0, $t2, loopend
      $t0, $t2
       $t3
      $t3, $zero, loopcont
      $t1, $t1, $t2

loopcont:
  add $t2, $t2, 1
  bet $t0, $t1, summer
  add $t7, $zero, $zero
  j loopbegin

summer:
  add $t7, $zero, 1
  j loopbegin

loopend:
  jr $ra
```

# Insertion-Only Patch



```
. .
add $t0, $
add $t1, $
~~add $t2, $~~
add $t3, $
. .
```

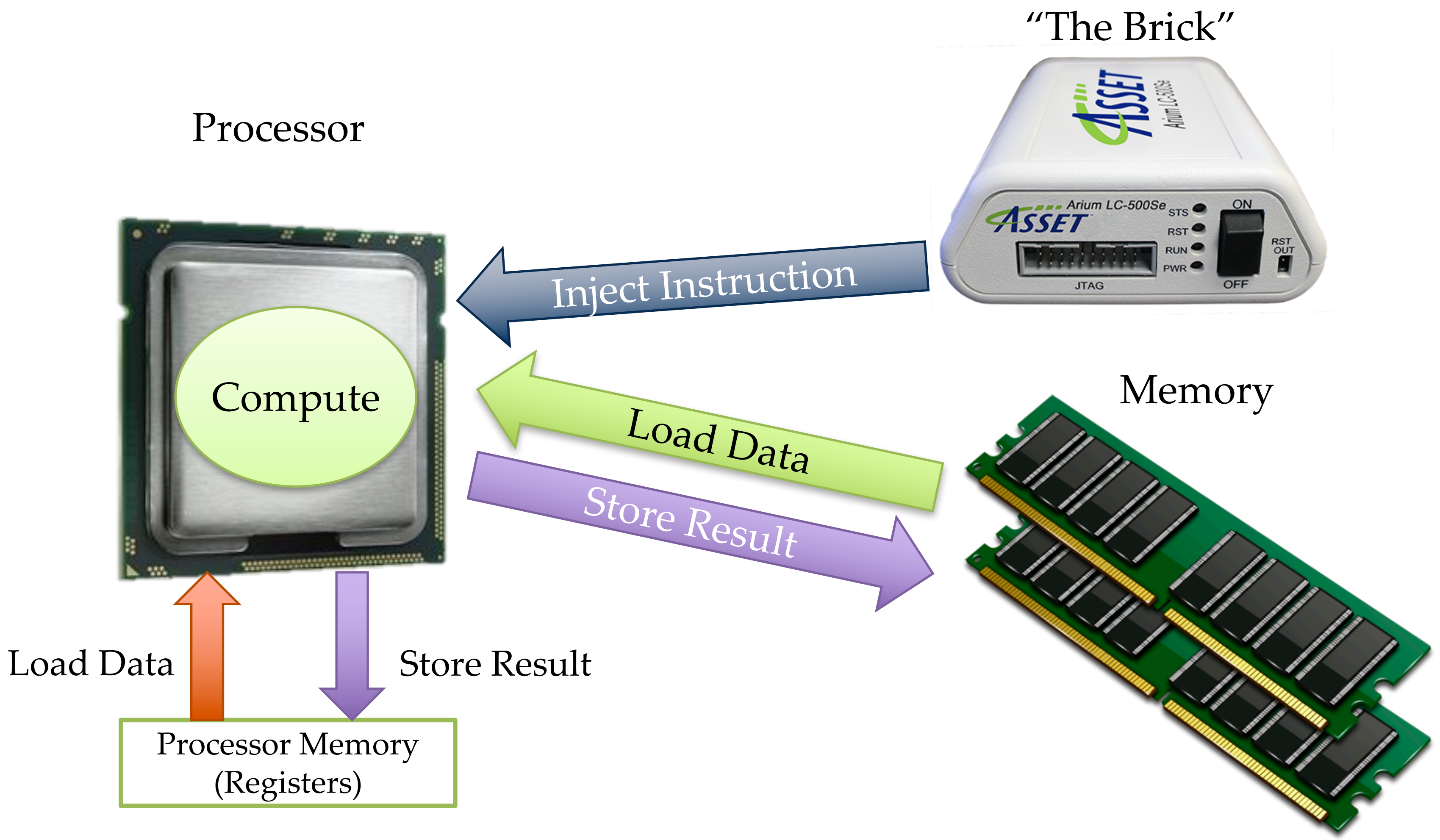
```
...
add $t0, $t2, 496
add $t1, $t1, 3
add $t2, $t2, 1
sub $t2, $t2, 1
add $t3, $t1, $t2
...
```

# Modifying the Instruction List

"The Brick"

- Use a special piece of hardware to connect directly to the processor
- Bypasses other system components
- Used to control the processor and inspect data during testing
- **Can also execute an instruction *not contained in the instruction list***

# Injecting Instructions



## Technical/Conceptual Challenges

- How do we convert a patch generated by GenProg to a *list of instruction insertions*?
- "The brick" is not always accurate
  - How much error can the program tolerate (*acceptability envelope*)?

## DEMO

# Putting This All Together

- Quadcopter software utilizes a *feedback loop* and several layers of *abstraction* to sustain flight
- A programming error in one of these layers can cause *undesired behavior*
- *Automated program repair* borrows notions from evolution to search for patches to software
- Such a patch must be applied to the quadcopter software while still maintaining flight
- Special hardware can be used to inject instructions from the patch directly into the processor

# THANK YOU!

Questions?