



# **Evolvable Systems: *Using Artificial Evolution In NASA Applications***



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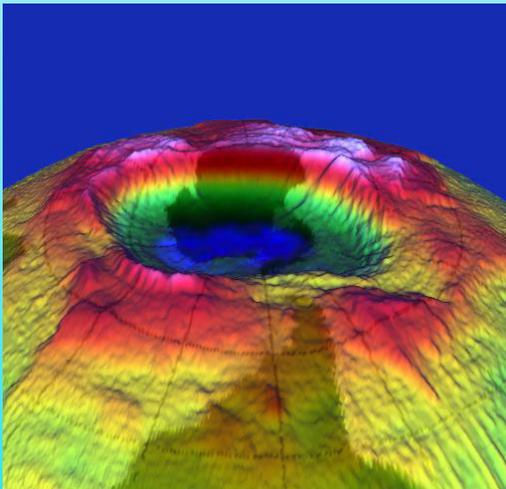
NASA Future Computing and  
Communications Technologies Course  
CICT Education  
<http://cictedu.arc.nasa.gov/courses/spring2003/>  
May 6, 2003

# The NASA Mission

To understand and protect our home planet  
To explore the Universe and search for life  
To inspire the next generation of explorers

... as only NASA can.

Sean O'Keefe  
NASA Administrator,  
April 12, 2002

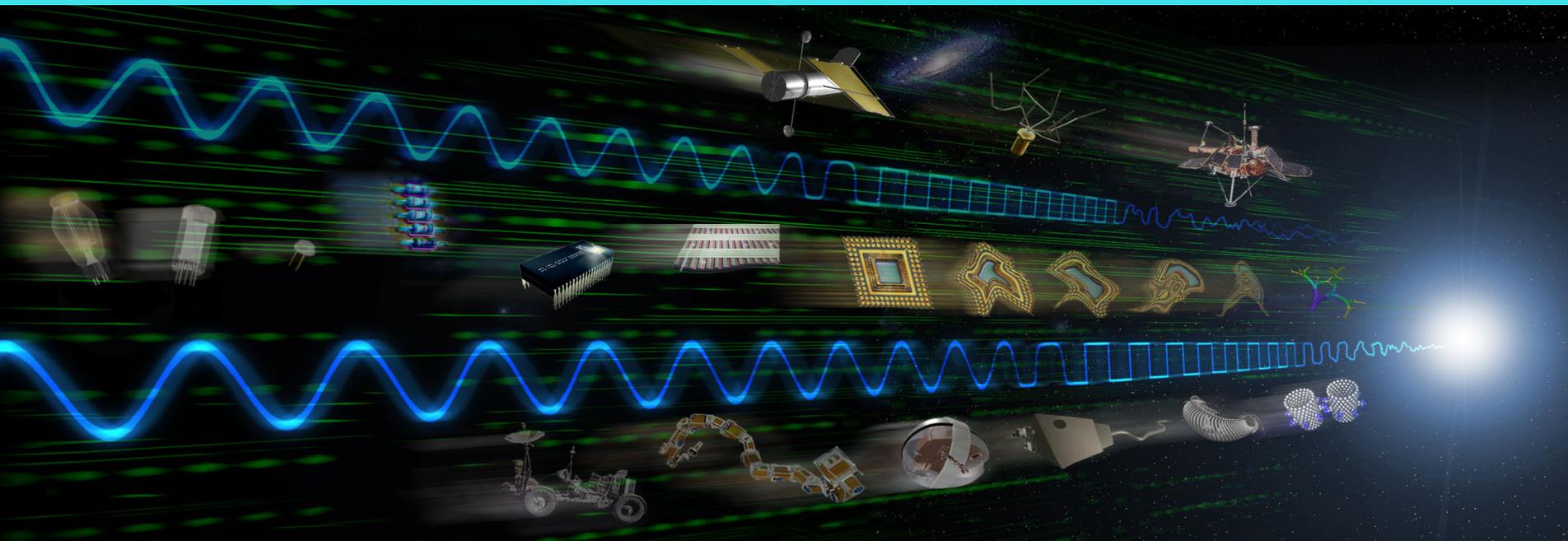


# What Are *Evolvable Systems*?

A system that changes over time to become better...

Changing its shape, its function, or becoming smarter...

All under the guidance of a process derived from biological evolution.

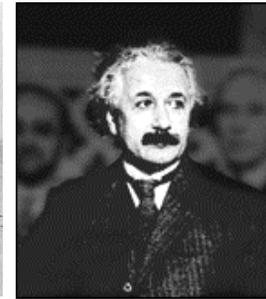
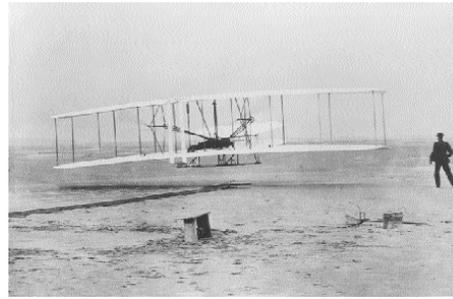


**Biological Evolution**

**and**

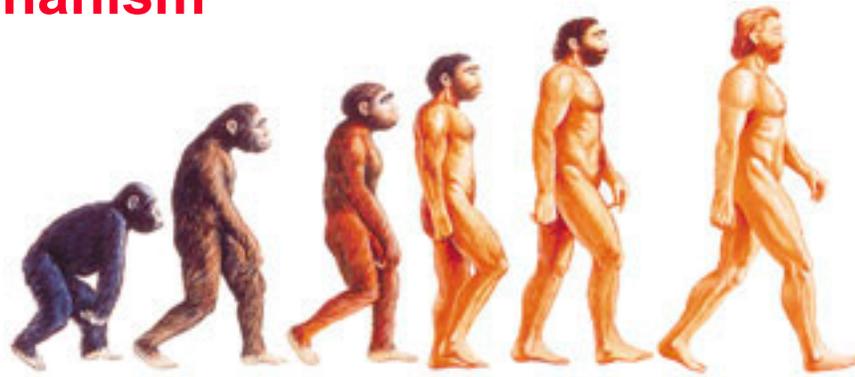
**Artificial Evolution**

## The Brain



Artificial Neural Networks used in many applications: fraud detection, image processing, navigation, robotics, many more...

## The Evolution Mechanism



Artificial Evolution is finding use in many applications: jet engine optimization, circuit and antenna design, many more...

# Evolution



**Evolution:** Cumulative changes a population or species undergoes over time

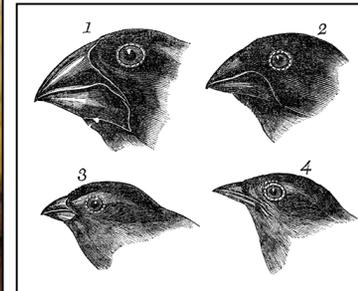
**Artificial Selection:** thousands of years of animal & plant breeding

## Darwinian Evolution

- Natural Selection: “survival of the fittest”
- surviving till you can reproduce (and pass on your genes)
- Result in new organisms and species

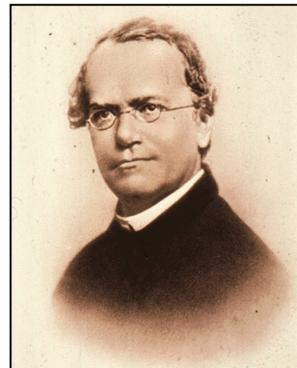


Charles Darwin



## Neo-Darwinism

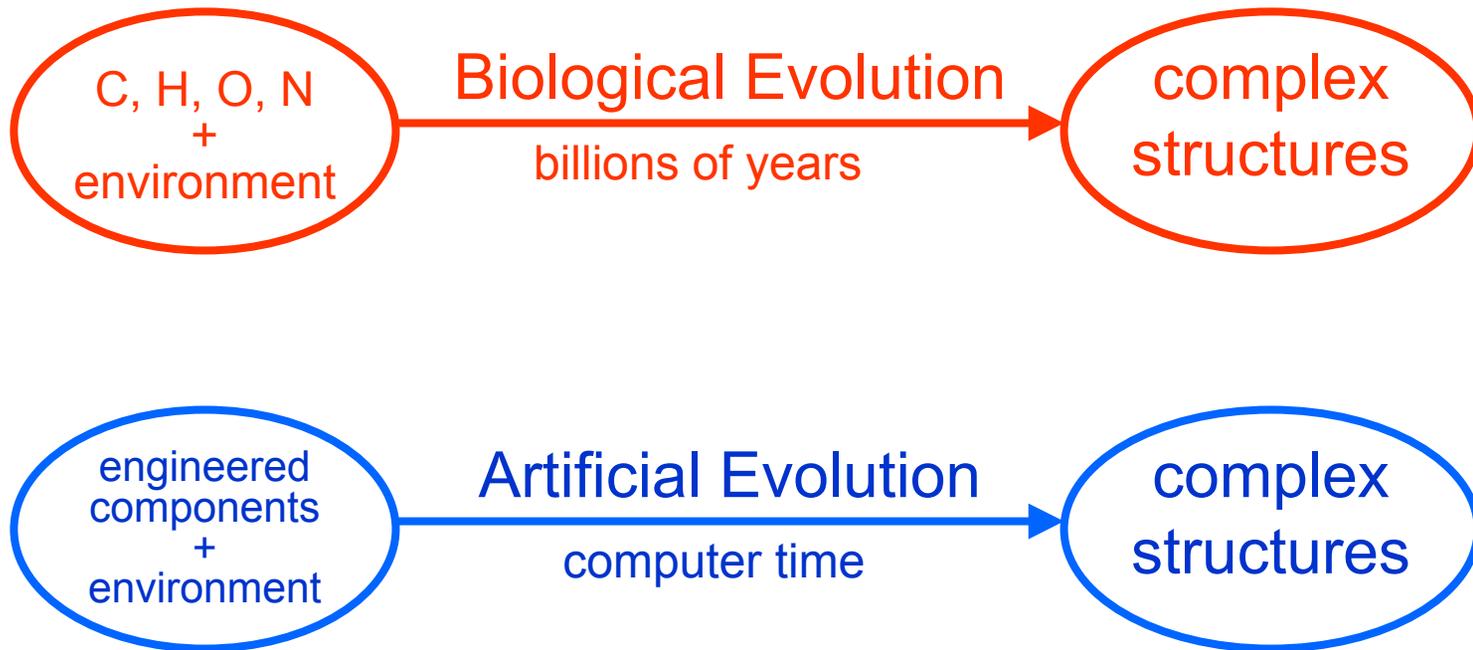
- Add genetics (Mendel)
- Natural Selection acting on genetic variations
- We will model this inside a computer



Gregor Mendel



# Metaphors

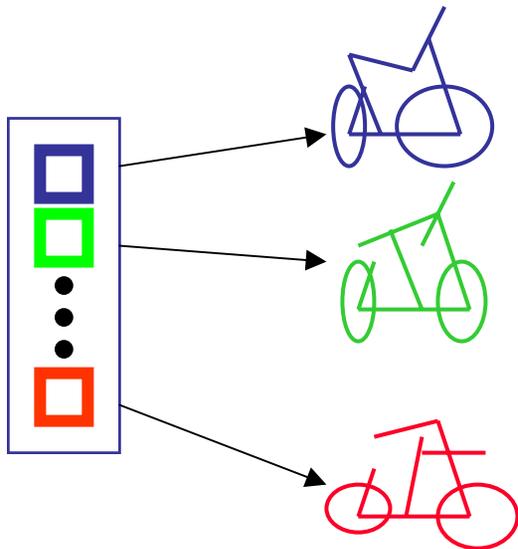


The Computer Program  
that Simulates Artificial  
Evolution is Called an  
“Evolutionary Algorithm”

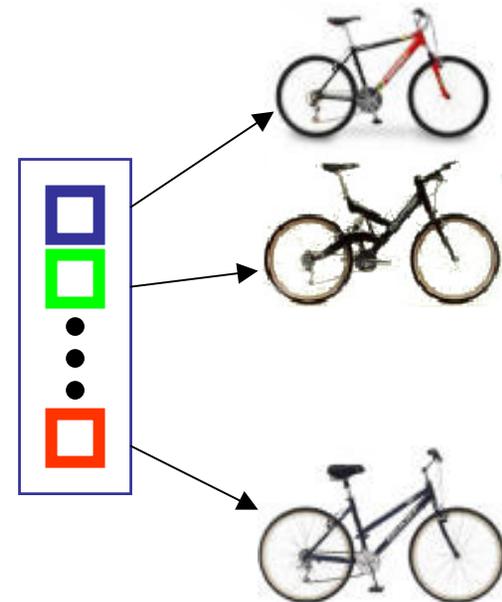
# Evolutionary Algorithm

Let's say you want to design bicycles:

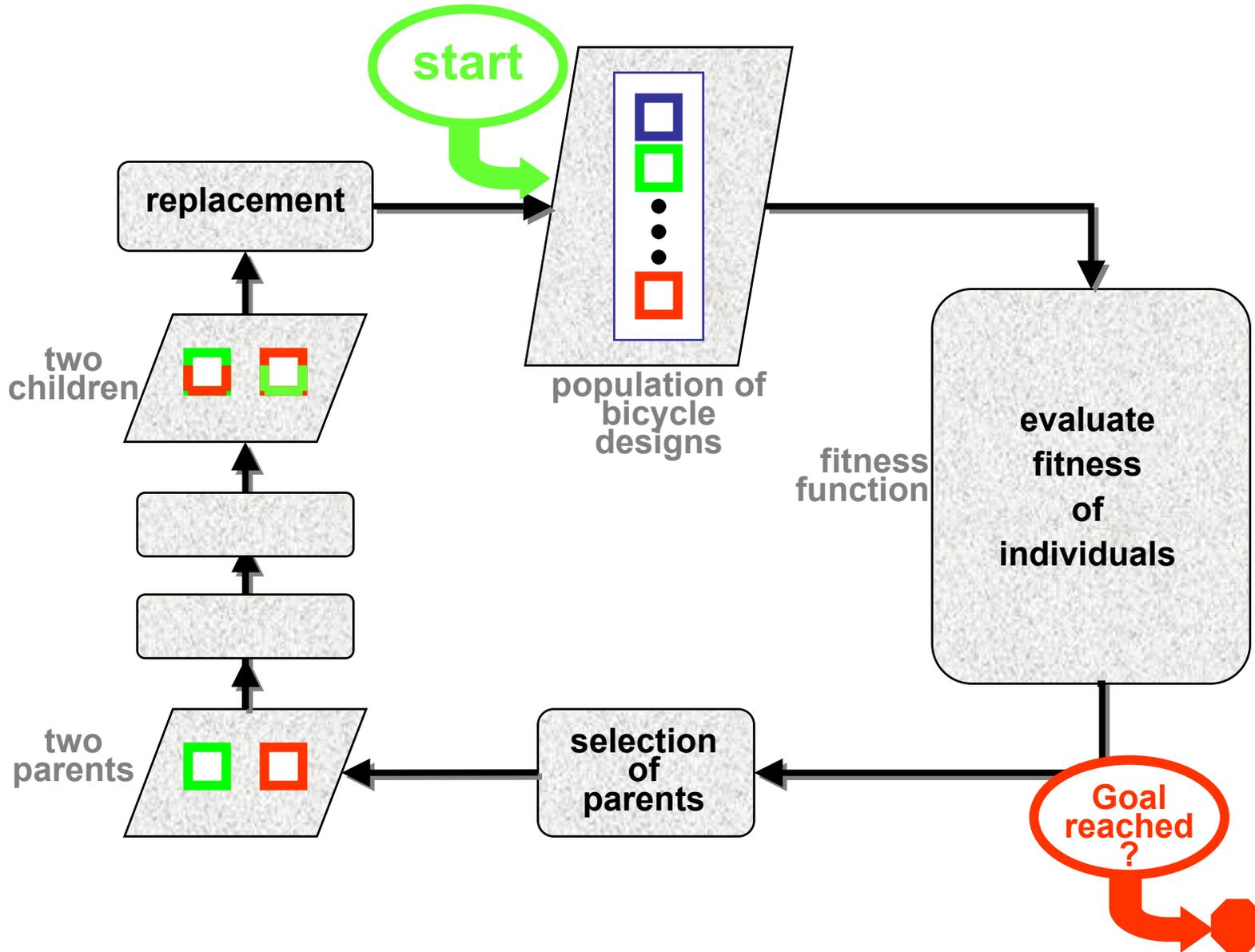
The algorithm would start with a set of randomly-designed bicycle "chromosomes"



The algorithm might find bicycle "chromosomes" that performed as desired



# Evolutionary Algorithm

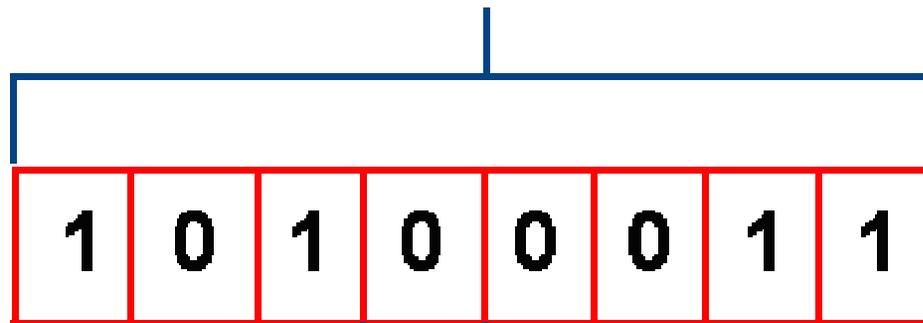


# Representing Designs to the Evolutionary Algorithm



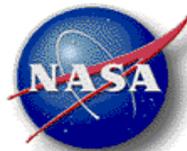
- Representation of an individual can be using discrete values (binary, integer, or any other system with a discrete set of values).
- Binary representation:

## Chromosome



**GENE**

# Chromosome Example



Phenotype could be integer numbers

**Genotype:**

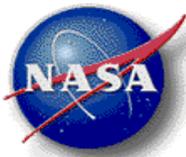
1	0	1	0	0	0	1	1
---	---	---	---	---	---	---	---

**Phenotype:**

**= 163**

$$1 \cdot 2^7 + 0 \cdot 2^6 + 1 \cdot 2^5 + 0 \cdot 2^4 + 0 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 =$$
$$128 + 32 + 2 + 1 = 163$$

# Mutation



before

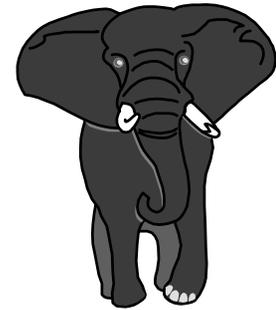
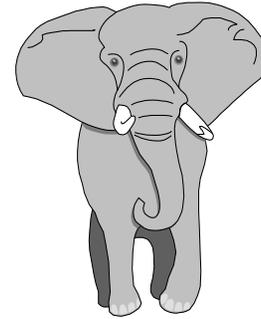
1 1 1 1 1 1 1

after

1 1 1 0 1 1 1



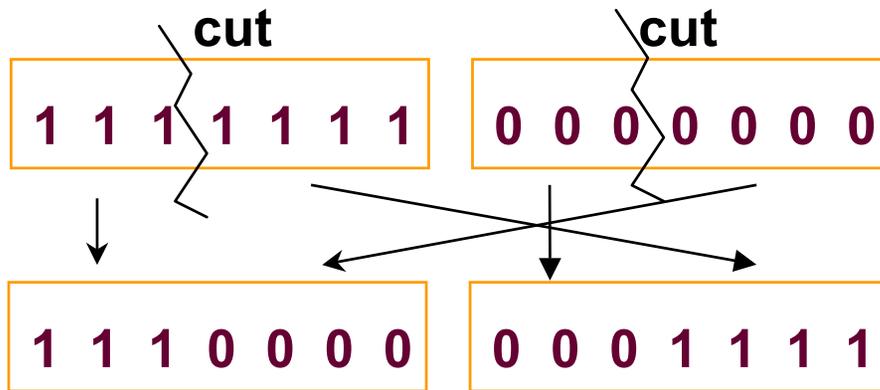
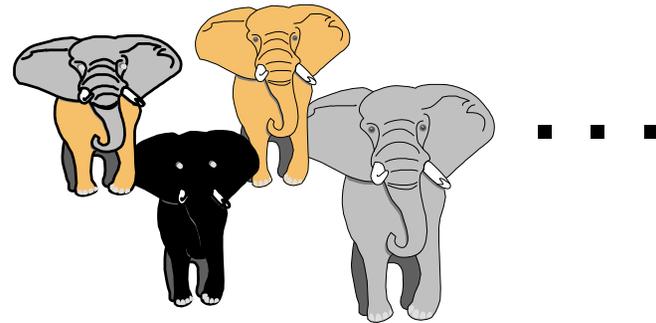
mutated gene



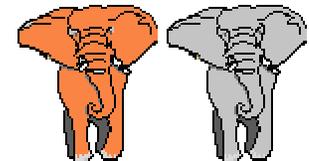
# Crossover



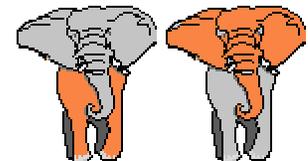
Population:



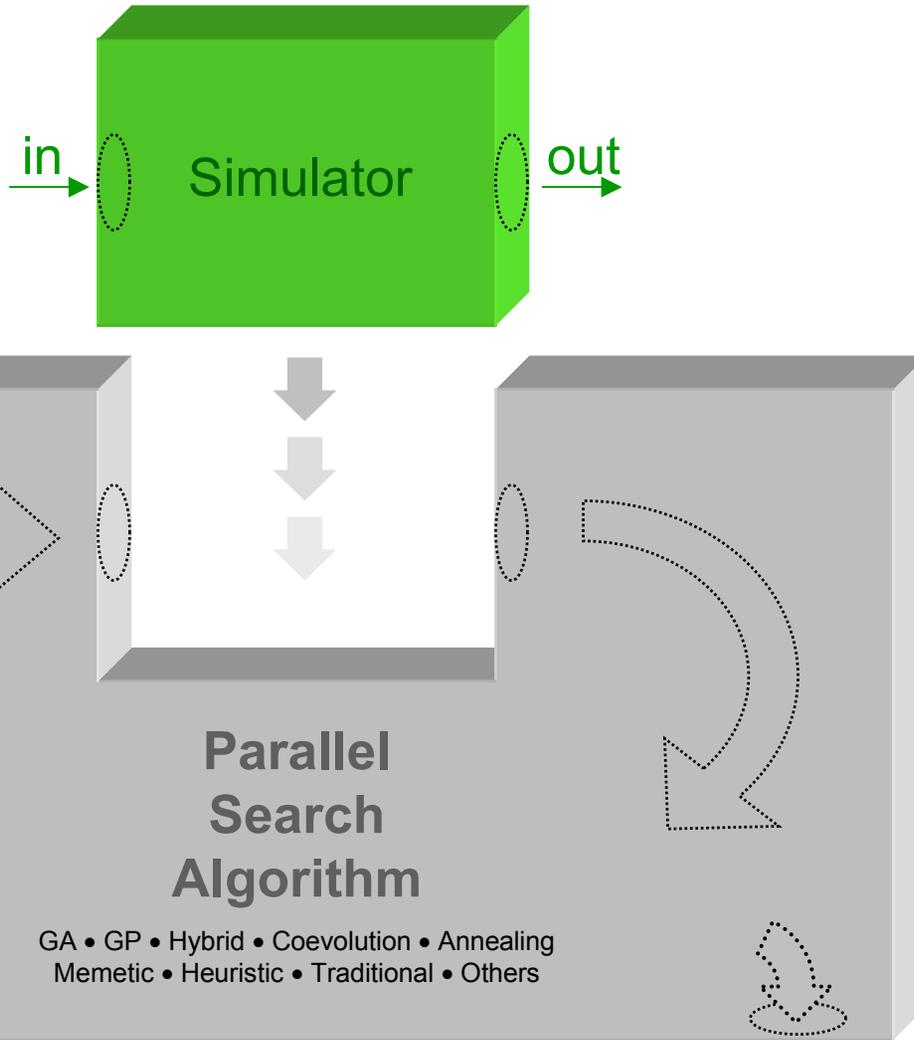
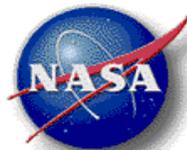
parents



offspring



# Evolutionary Design Computer



- Supercomputer: 32 PCs running Linux

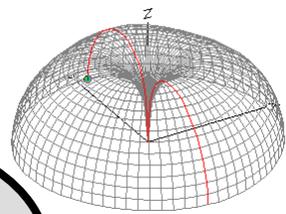
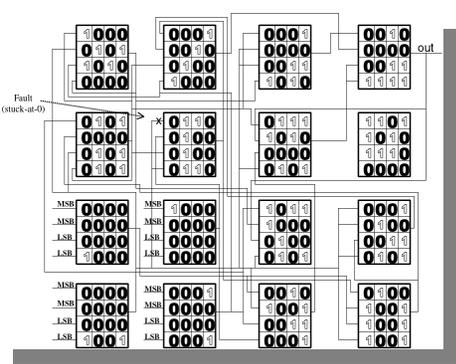


**Best Solution Found**

**Evolvable Systems**

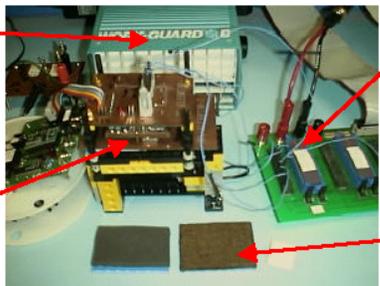
**&**

**Applications**



**Fault Recovery for Reconfigurable Systems**

**Automated Antenna Design**

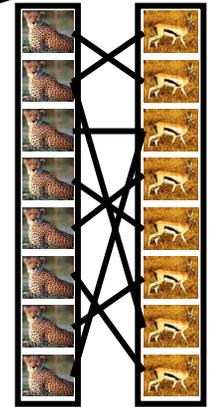
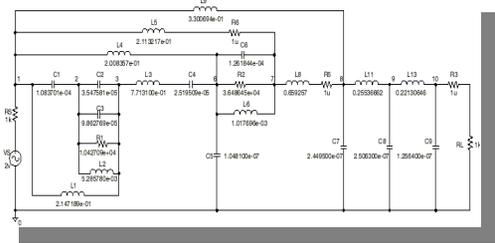
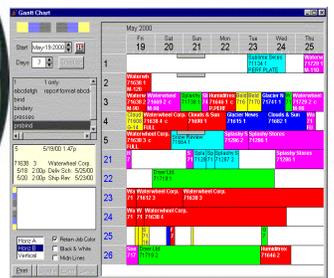
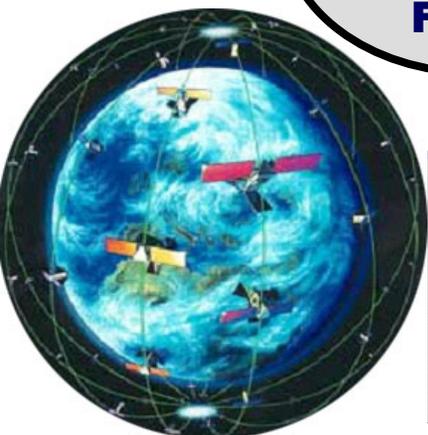
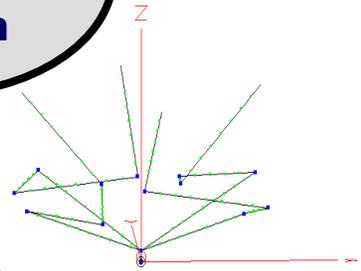


**Evolutionary Scheduling for Satellite Fleets**

**Automated Circuit Design**

**Coevolutionary Algorithms**

# *Evolvable Systems*



# Why Evolvable Systems?



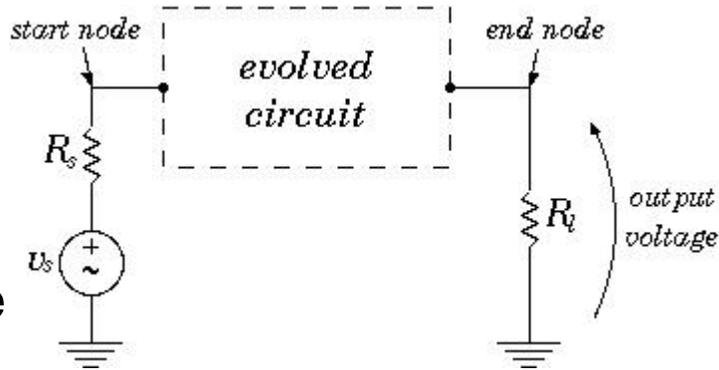
## *Motivation*

- Building reliable complex systems with unreliable parts is an unsolved problem (designability)
- Nature solved it long ago – evolution is primary force
- Automated design a pre-requisite for certain nanotechnologies
- Benefits: Fault-tolerance/Survivability, Designability, Autonomy

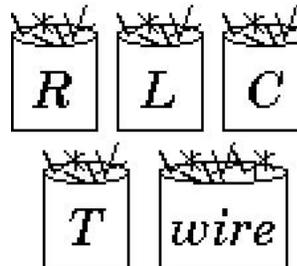
# Automated Circuit Design

# Circuit Construction

- Template circuit



- Set of selectable

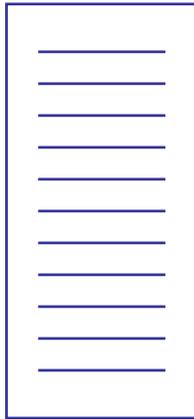


*parts bins*

# Evolving Circuits



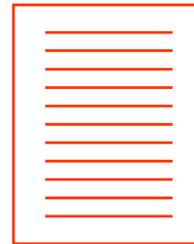
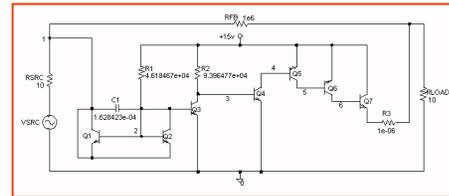
genetic  
representation



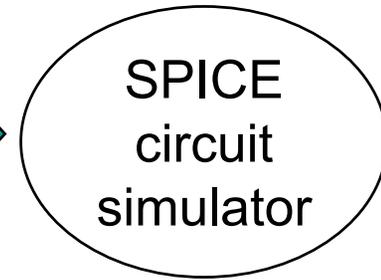
circuit-constructing  
program



circuit  
design

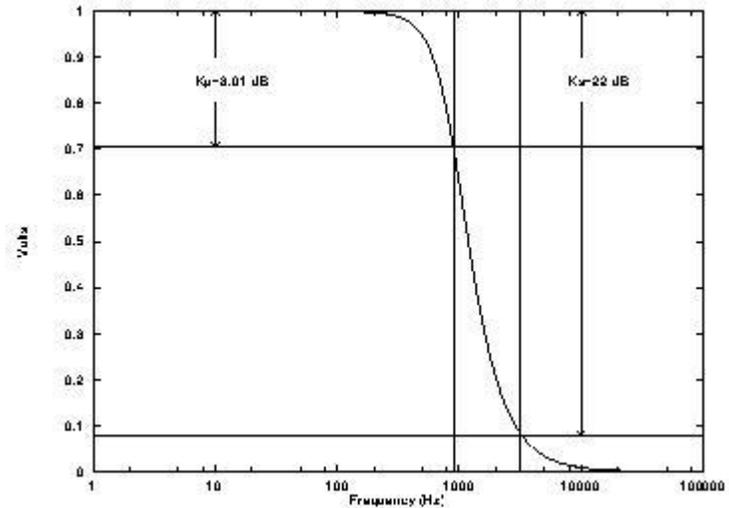
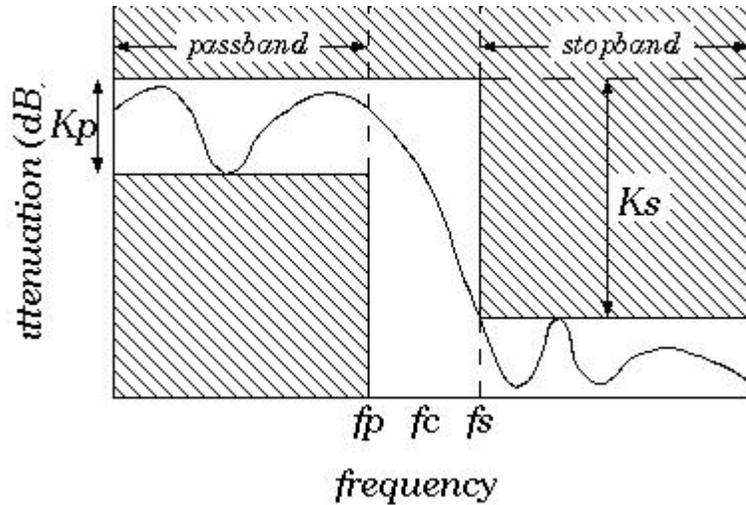


SPICE  
netlist

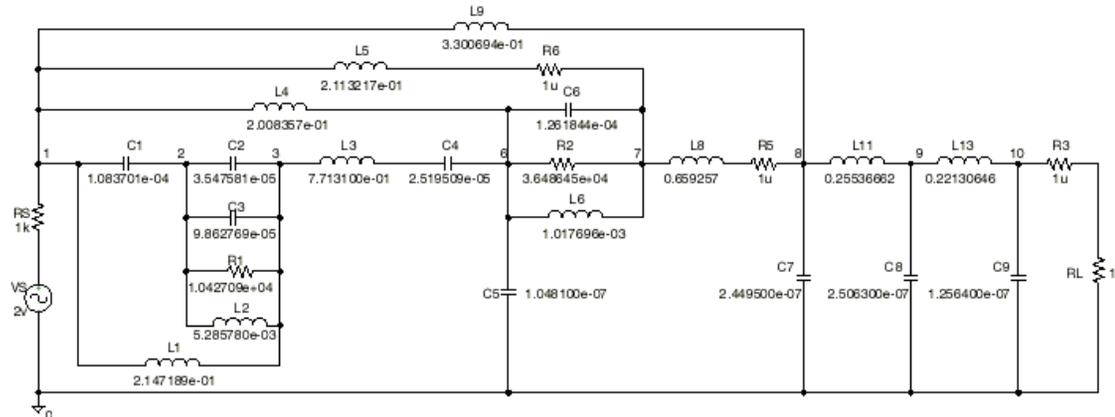


Fitness  
Calculation

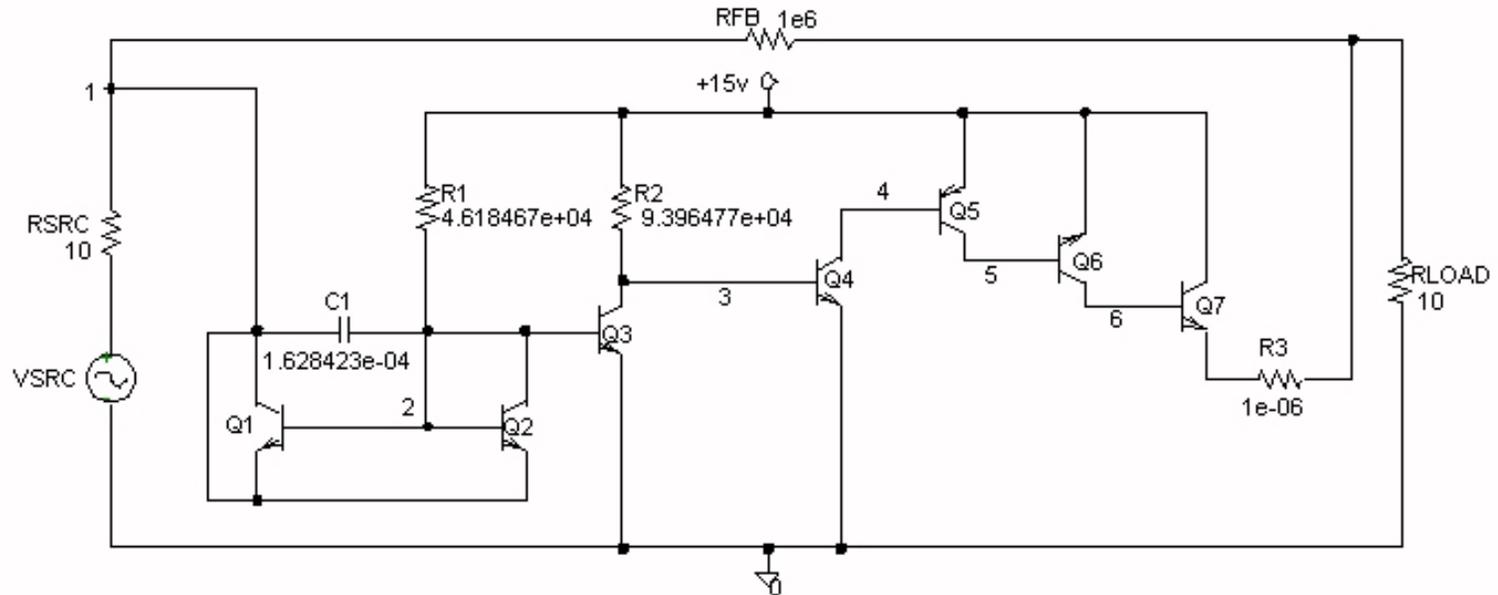
- Design and optimization



evolved circuit



# Evolved 85 dB Amplifier



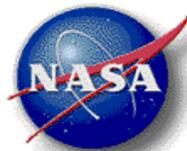
## Evolved Circuit-Constructing Program

```

transistor(N, ACTIVE_NODE, NEW_NODE, INPUT_NODE);
transistor(N, BASE, ACTIVE_NODE, PREVIOUS_NODE);
resistor_cast_to_ps(4.618467e+04);
capacitor_cast_to_input(1.628423e-04);
transistor(N, NEW_NODE, ACTIVE_NODE, GROUND_NODE);
resistor_cast_to_ps(9.396477e+04);
transistor(N, NEW_NODE, ACTIVE_NODE, GROUND_NODE);
transistor(P, NEW_NODE, ACTIVE_NODE, PS_NODE);
transistor(N, NEW_NODE, ACTIVE_NODE, PS_NODE);
transistor(N, PS_NODE, ACTIVE_NODE, NEW_NODE);
resistor_move_to_output(1e-06);
    
```

# Antenna Design

# Evolutionary Antenna Design



- Can evolutionary techniques automatically design and optimize antennas that outperform antennas from expert antenna designers?
- Can evolutionary techniques design antennas where humans are unable to?

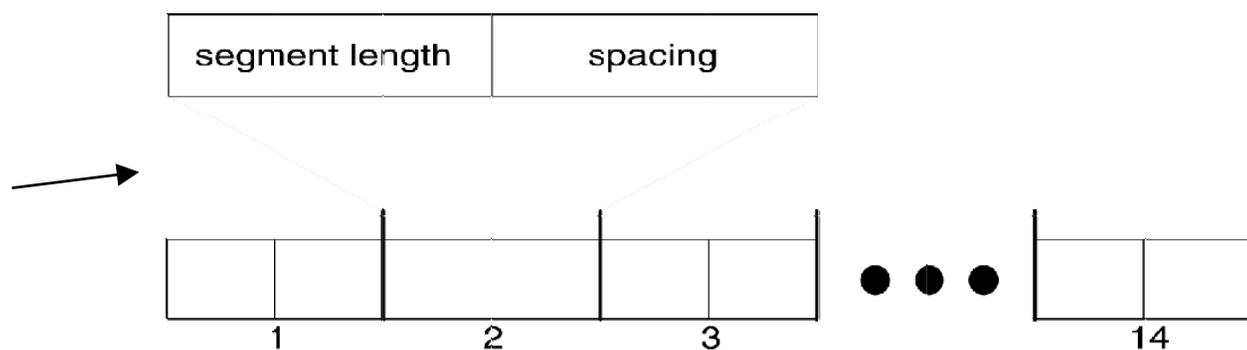
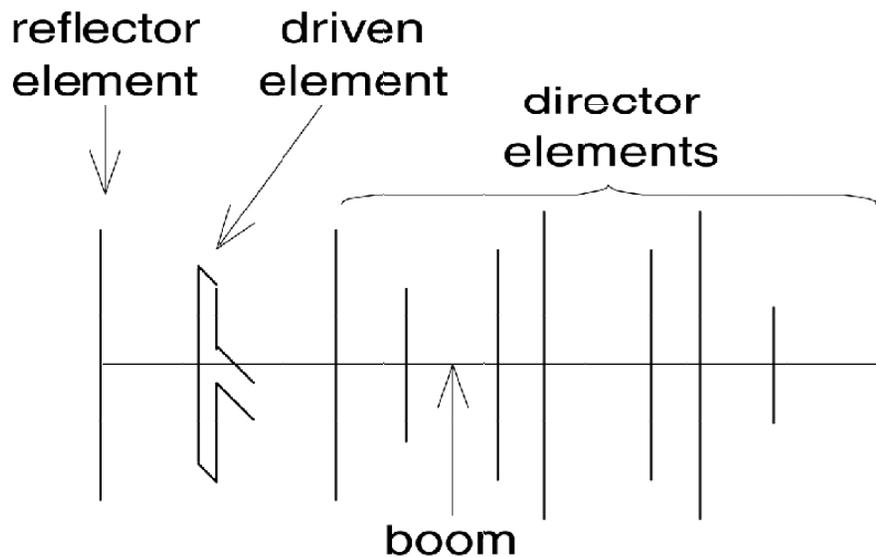
# Antenna Design



- Evolutionary design of antennas has recently garnered much attention
- NASA telcomm workhorse; problems: bulky, bandwidth limitations, directionality
- Real-world engineering domain
- Many challenging problems
- Spacecraft antennas:
  - Mars Odyssey UHF Antenna
  - Optimize e/m and physical dimensions, exploit surroundings
  - ST5 Mission

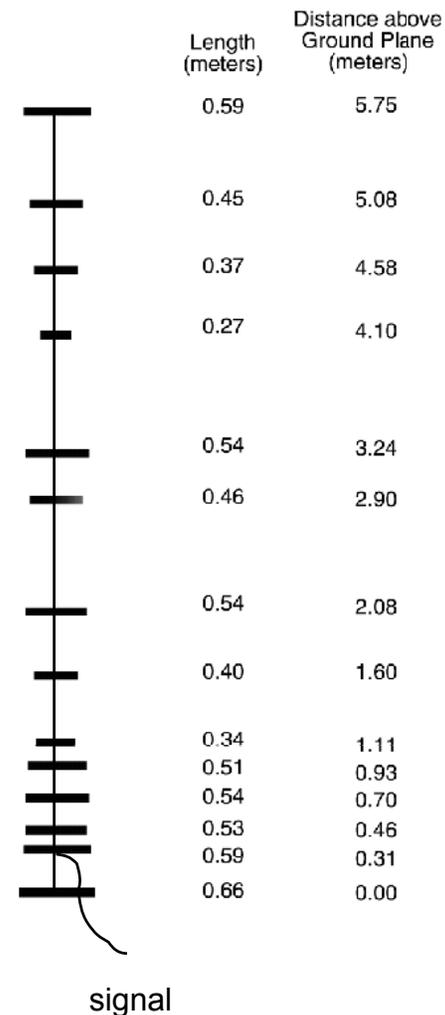
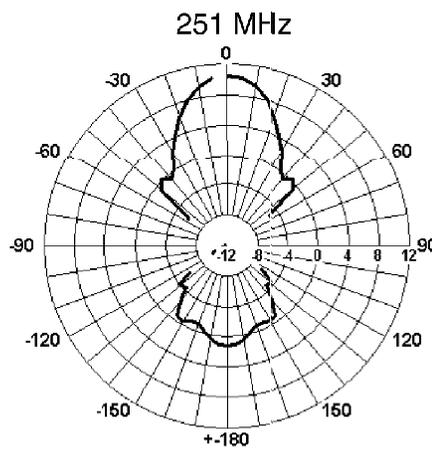
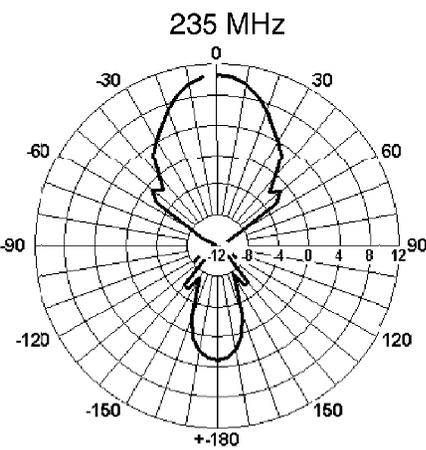
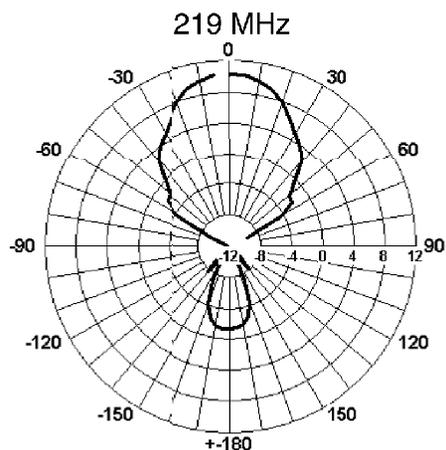
# Yagi-Uda Antenna

- Invented 1954, yet remains difficult to design/optimize:
  - numerous parasitics
  - complex interactions
  - sensitivity at high gain
- Comparison to previous work
- Representation

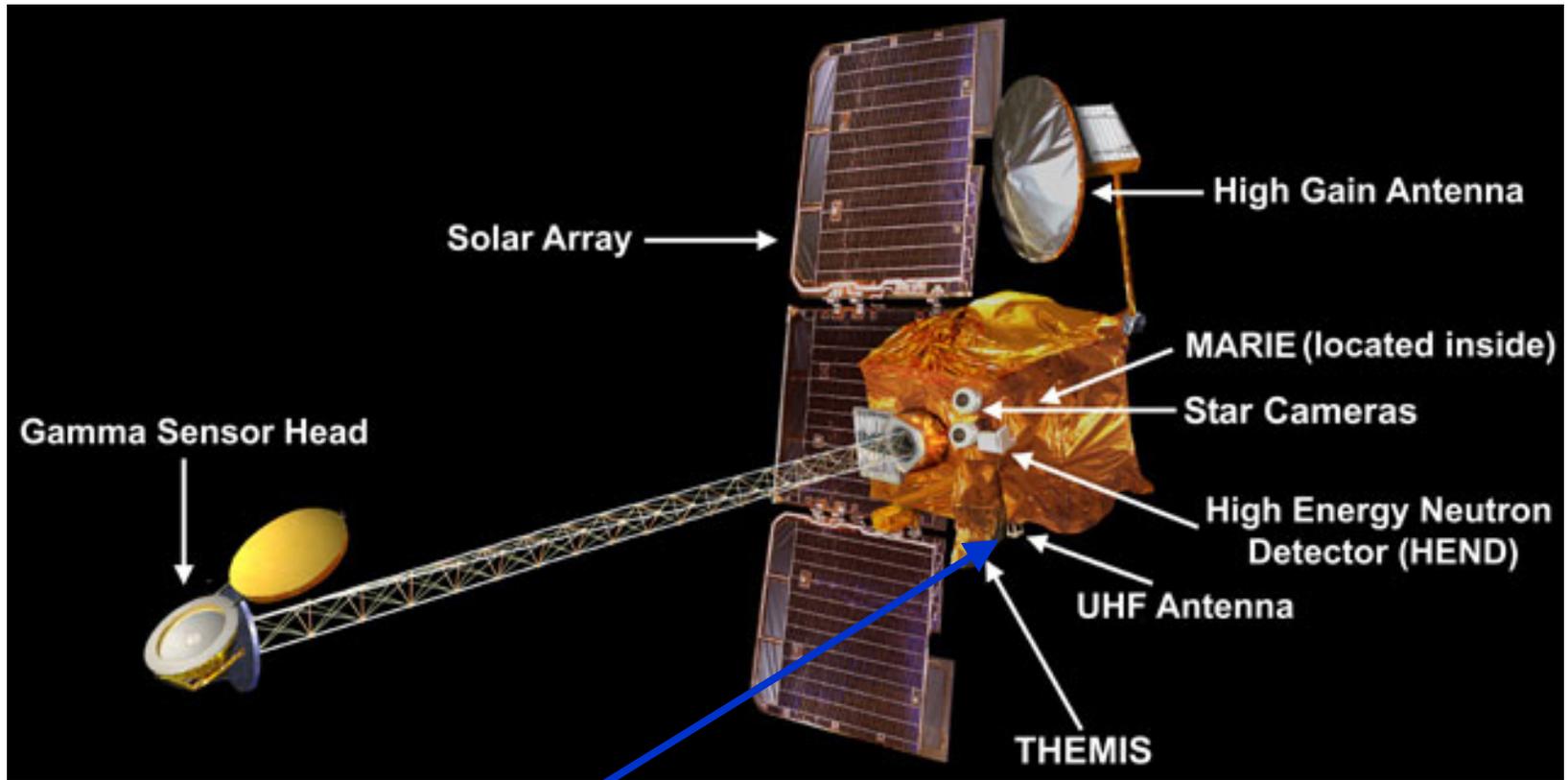


# Yagi-Uda Results

- Results: high-performance Yagi-Uda antenna
- 7.8% performance improvement in mainlobe gain
- Achieves 13.6% bandwidth while maintaining high gain (> 11 dB)
- Very good impedance characteristics
- Small back/sidelobes



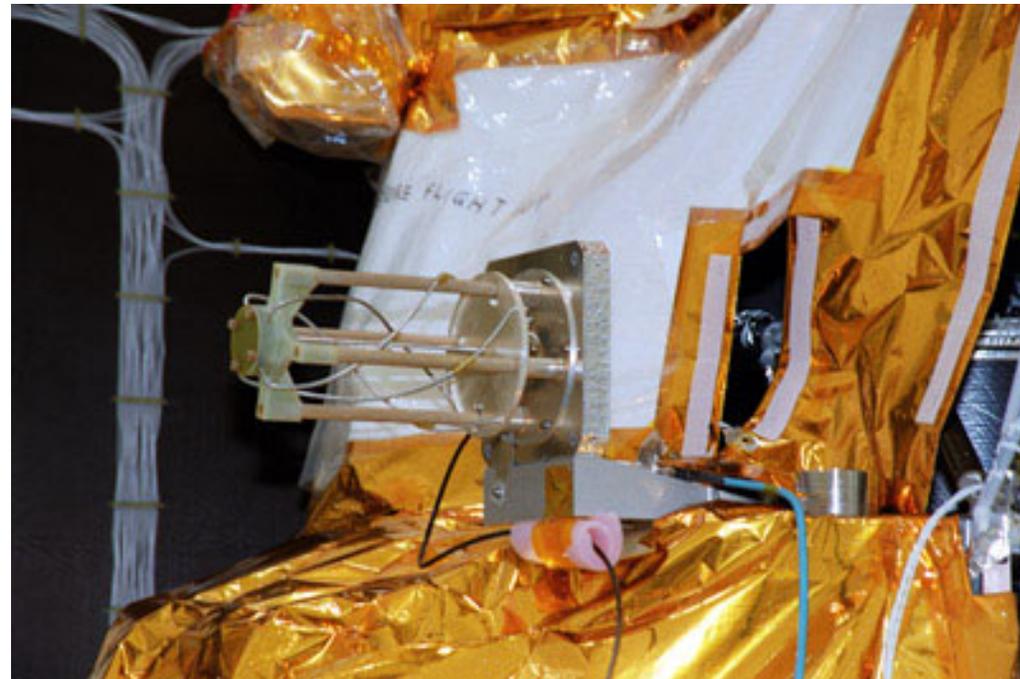
# Mars Odyssey UHF Antenna



- UHF Antenna
- Currently orbiting Mars

# Mars Odyssey UHF Antenna

- Primary, full-duplex, data link between spacecraft and landed assets
- Deployed antenna: graphite/epoxy Quadrifilar Helix with small ground plane
- Not designed with surrounding structures in mind
- Solar panels sometimes moved to optimize antenna performance

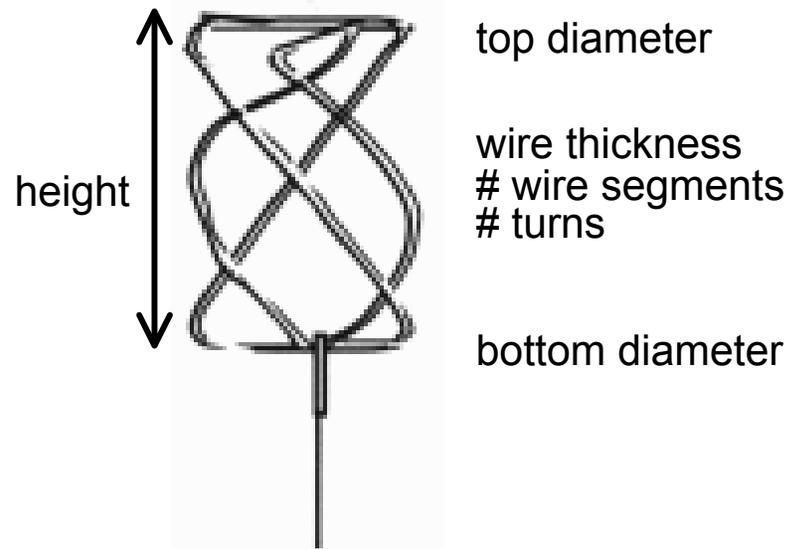


	Requirement	Value
a	Frequencies of Operation	401.5275 MHz, 437.1 MHz
b	Power Handling	12 Watts RF continuous
c	Channel Bandwidth	500 kHz
d	Pattern Requirement	Figure 2
e	Polarization	RHCP
f	VSWR	2:1 Maximum
g	Envelope	Height: 12.2 inches (maximum) Base: 9 inches (maximum) Top: 6.25 inches (maximum)
h	Mass	1.3 kg (maximum)
i	Axial Ratio	5 dB (maximum)

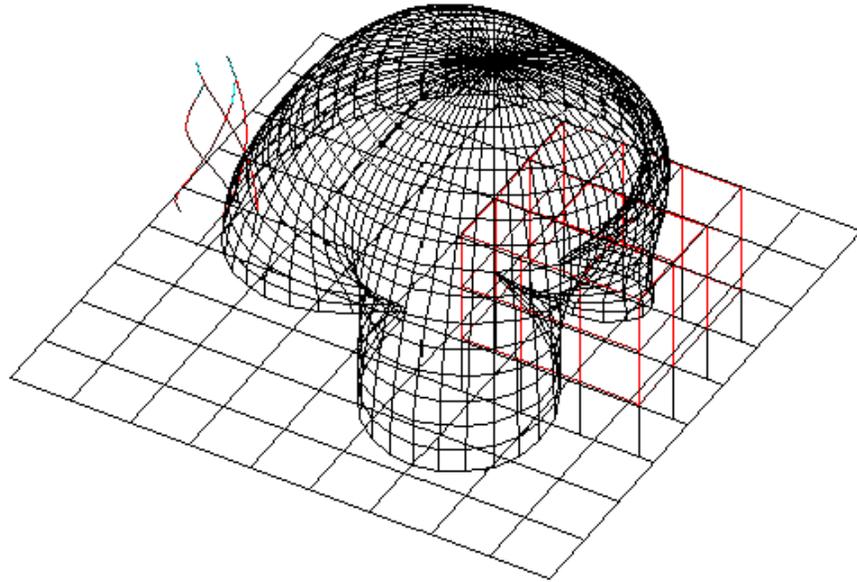
# Optimizing a Quadrifilar Helical Antenna



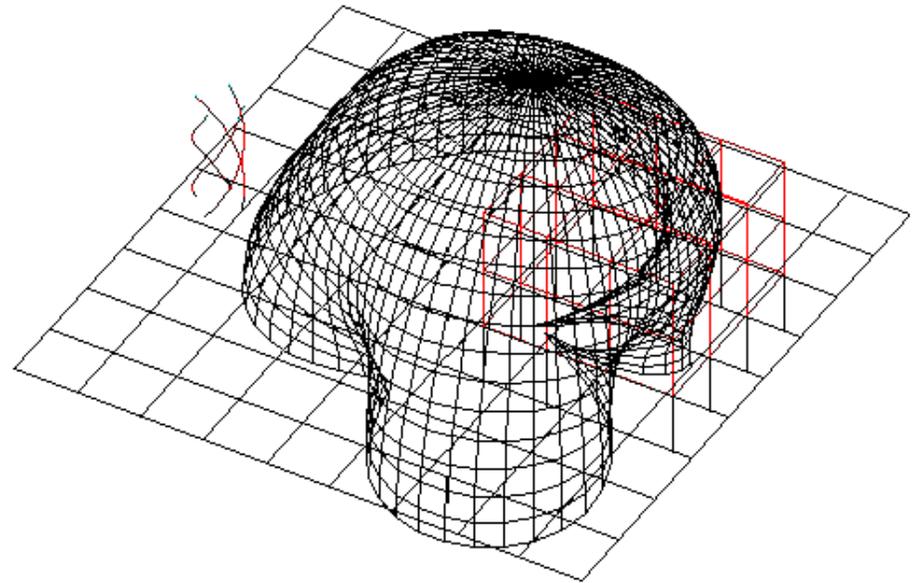
- Using the coevolutionary algorithm, we optimized the design parameters for a quadrifilar helical antenna:



# wire segments	# turns	wire thickness	bottom diameter	top diameter	height
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MARS ODYSSEY QHA  
UHF



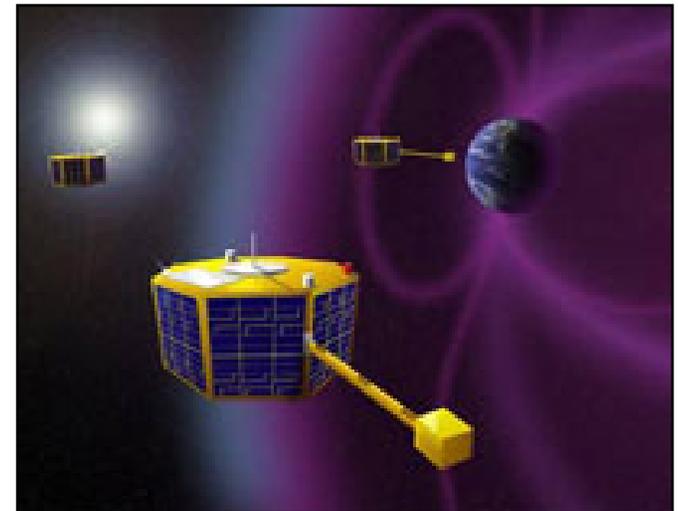
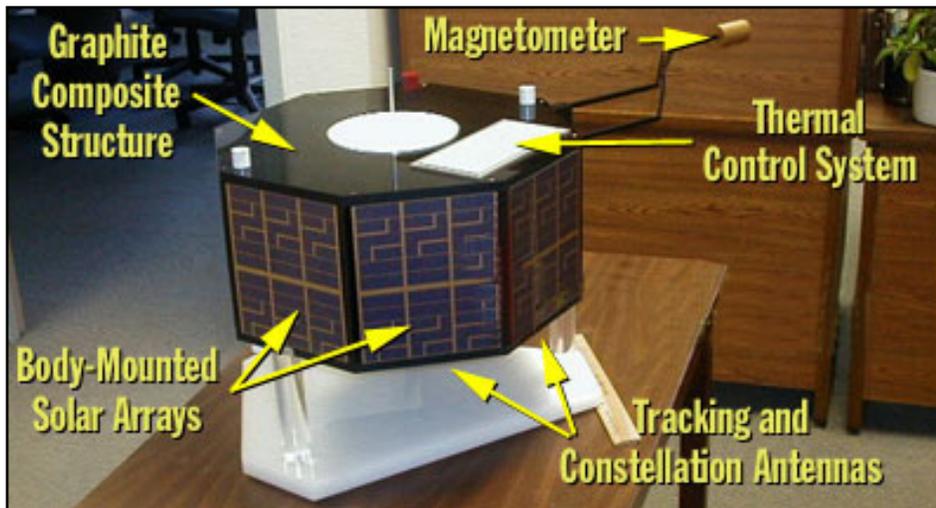
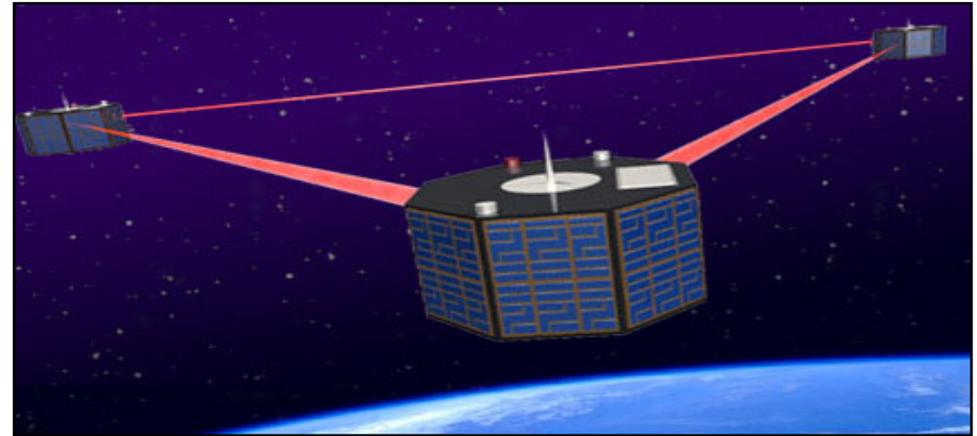
COEVOLVED QHA UHF

- Coevolved antenna is  $\frac{1}{4}$  the size (volume)

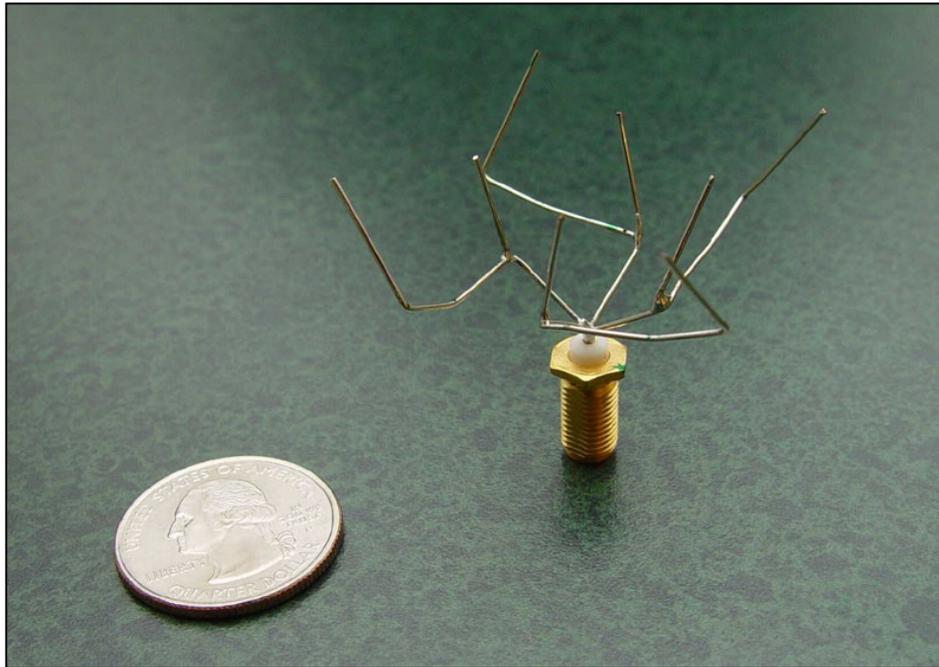
# ST5 Mission



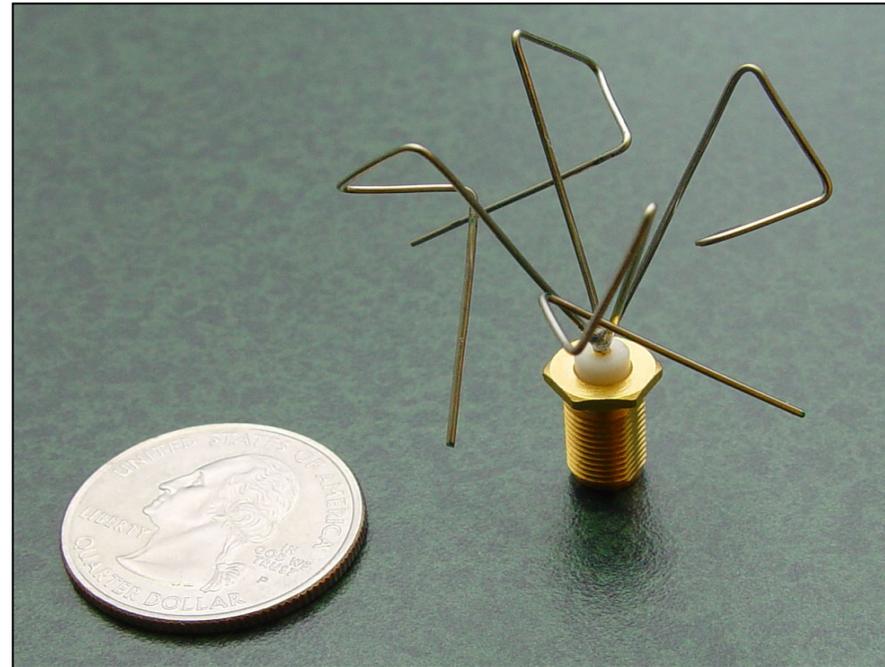
- New Millennium Program mission
- Three nanosats
- Measure effect of solar activity on the Earth's magnetosphere



# Prototyped Evolved Antennas



**ST5-3-10**



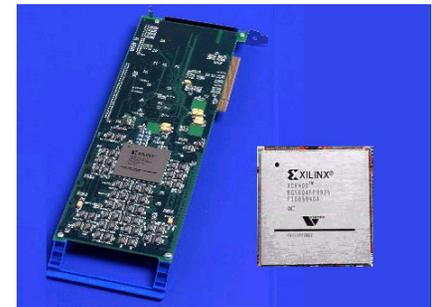
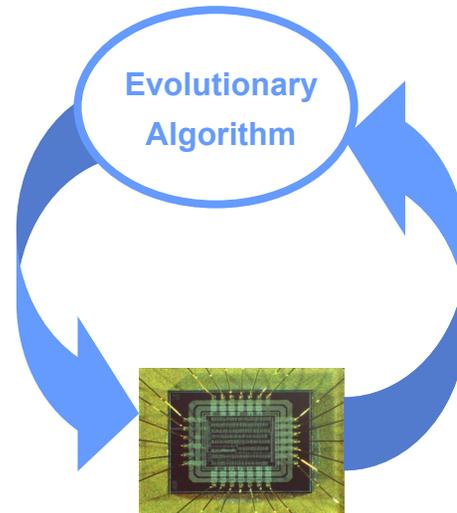
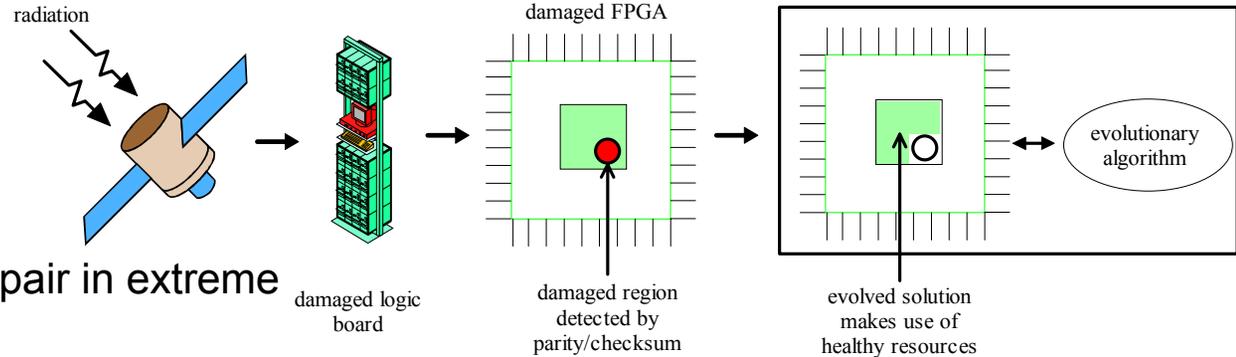
**ST5-4W-03**

# Evolutionary Fault-Recovery

# Fault Recovery

## Dynamic Evolution for Fault Tolerance

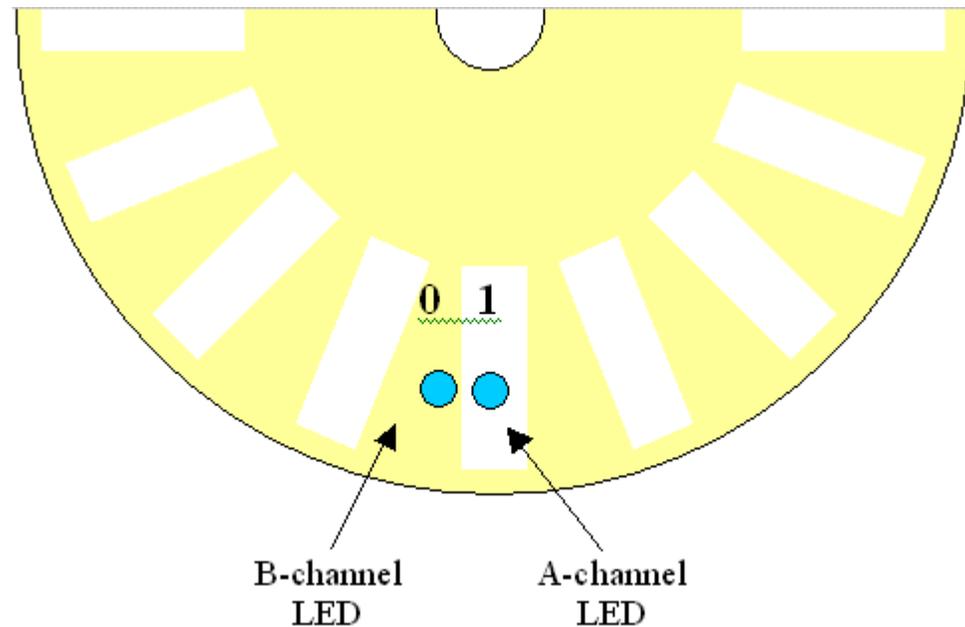
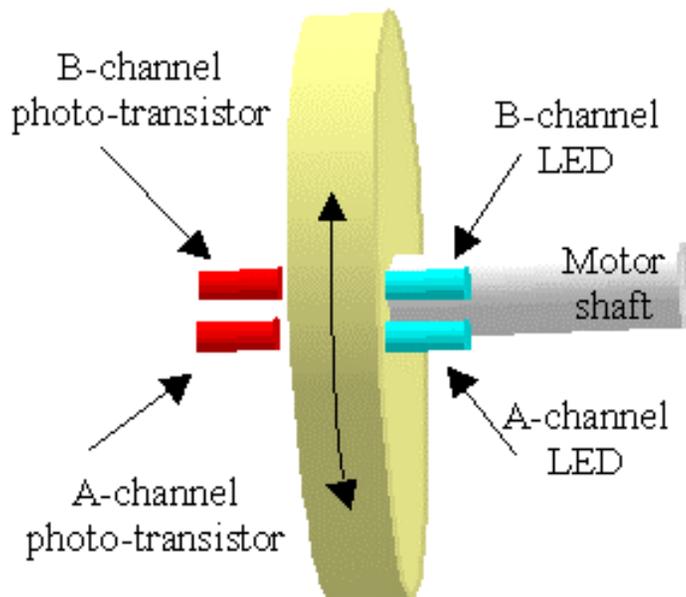
- Description:
  - Fault tolerance / self-repair in extreme environments
    - High temperature
    - High radiation
- Output: adaptive algorithms for autonomous self-repair of re-programmable logic chips
- Target Customer: Aerospace Technology, Space Science, Earth Science Enterprises
- Impact: increased safety, autonomy
- Schedule: FY04



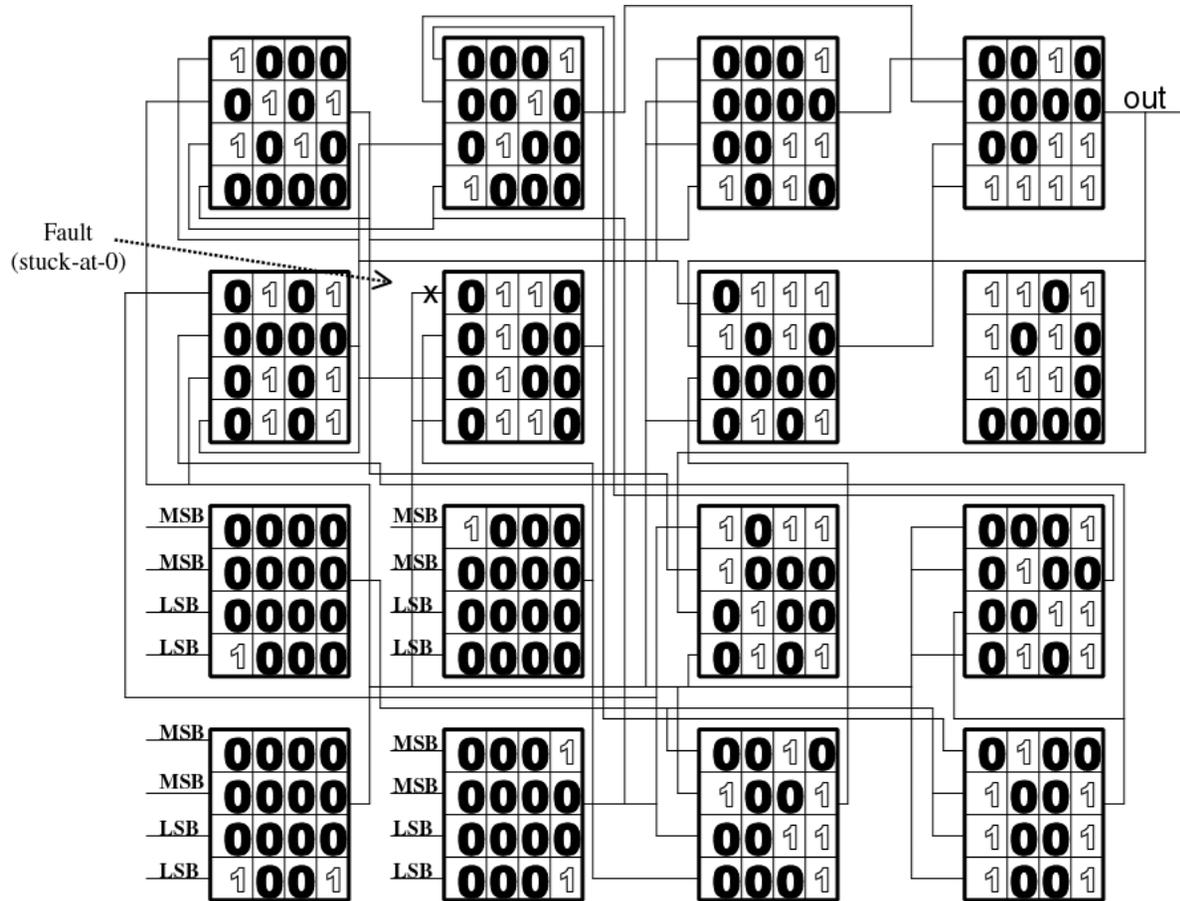
chip reprogrammed by algorithm

# Quadrature Decoder

- Applications requiring determination of angular translation (or speed)
- Example: DC-motor to drive system for a mobile robot we may wish to move forward (or reverse) by a fixed distance
- Decoder determines rotation direction



# Results



Evolved Quad Decoder Configuration

# Hardware Demo



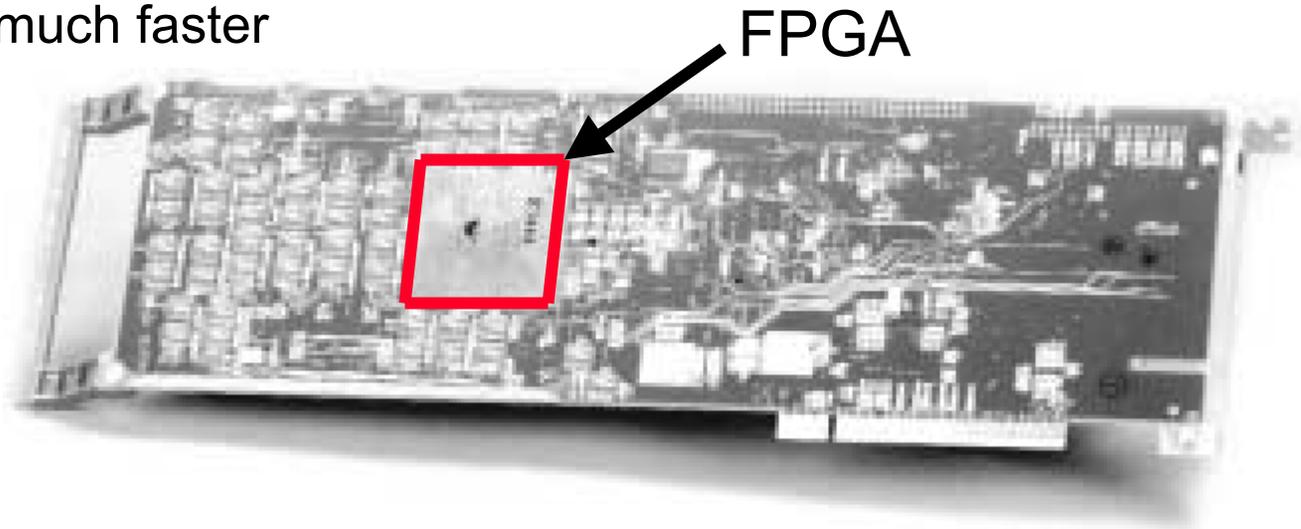
## Virtex FPGAs

- are relatively new
- will be used on 2003 MER mission

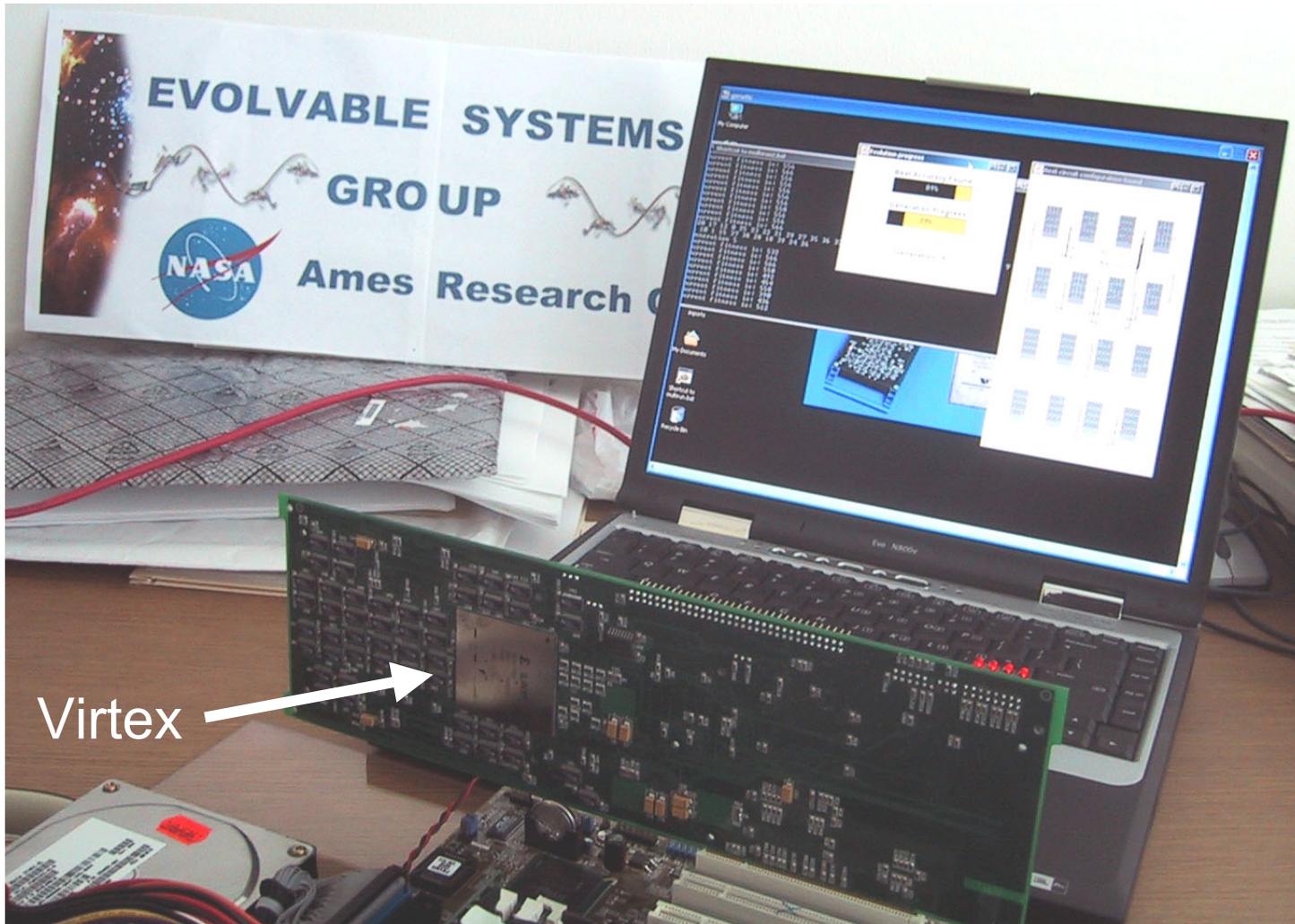


## Demo

- 20 random latchup faults are simulated
- Quad decoder is repaired automatically in minutes
- FPGA chip is reprogrammed about 5 times per second – we will soon go much faster



# Hardware Demo



Virtex →

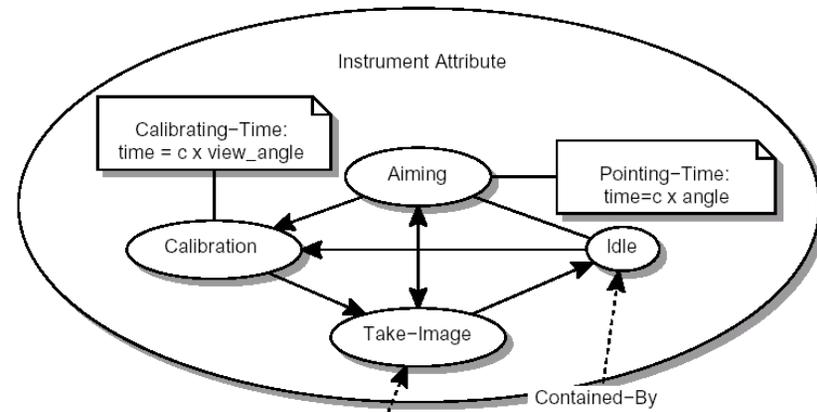
# Evolutionary Scheduling

# Evolutionary Scheduling

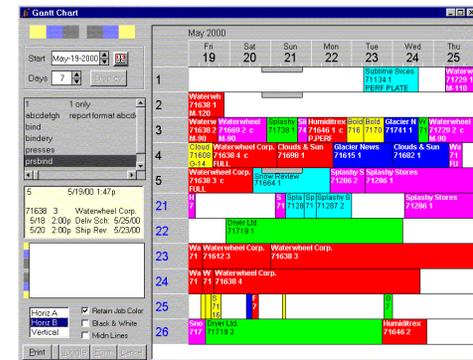


## Evolutionary Algorithms For Scheduling

- Description:
- Inspired by commercial successes of evolutionary scheduling, this task seeks to apply evolutionary methods to satellite fleet scheduling problems:
  - Multi-satellite, multi-instrument
  - Constraints: image locations, imager slew and duty cycle, memory, downlink locations
  - Constraints are complex and poorly understood: prime target for an EA
- Impact: automated fleet scheduling → new capability; improved satellite utilization: more science data, less expense



Simplified Satellite Instrument States Showing Constraints



Genetic Gantt Chart Encoding

# Conclusion

- **Evolvable Systems** research has promising potential in NASA applications:
  - Antenna design
  - Circuit design
  - Fault recovery
  - Satellite Scheduling
- **Evolutionary Algorithms:**
  - are based on biological metaphors
  - have great practical potential
  - are getting popular in many fields
  - yield powerful, diverse applications
  - inherently parallel
  - frequently give high performance against low costs on a wide range of problems