Lecture 2: Examples of Poor Engineering

- "Software Forensics" Case Studies:
  - Mars Pathfinder
  - Mars Climate Observer
  - Mars Polar Lander
  - Deep Space 2
- Some conclusions
  - e.g. Reliable software has very little to do with writing good programs
  - e.g. Humans make mistakes, but good engineering practice catches them!

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NASA JPL's Mars Program

Mission	Launch Date	Arrival Date	Outcome
Viking I Viking II	20 Aug 1975 9 Sept 1975	Landed 20 Jul 1976 Landed 3 Sept 1976	Operated until 1982 Operated until 1980
Mars Observer	25 Sept 1992	Last contact: 22 Aug 1993	Contact lost just before orbit insertion
Pathfinder	4 Dec 1996	Landed 4 July 1997	Operated until 27 Sept 1997
Global Surveyor	7 Nov 1996	Orbit attained 12 Sept 1997	Still operational
Climate Orbiter	11 Dec 1998	Last contact: 23 Sept 1999	Contact lost just before orbit insertion
Polar Lander	3 Jan 1999	Last contact: 3 Dec 1999	Contact lost before descent
Deep Space 2	3 Jan 1999	Last contact: 3 Dec 1999	No data was ever retrieved
Mars Odyssey	7 Apr 2001	Expected: October 24, 2001	

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Mars Pathfinder

- Mission
  - Demonstrate new landing techniques
    - parachute and airbags
  - Take pictures
  - Analyze soil samples
  - Demonstrate mobile robot technology
    - Sojourner
- Major success on all fronts
  - Returned 2.3 billion bits of information
  - 16,500 images from the Lander
  - 550 images from the Rover
  - 15 chemical analyses of rocks & soil
  - Lots of weather data
  - Both Lander and Rover outlived their design life
  - Broke all records for number of hits on a website!!!

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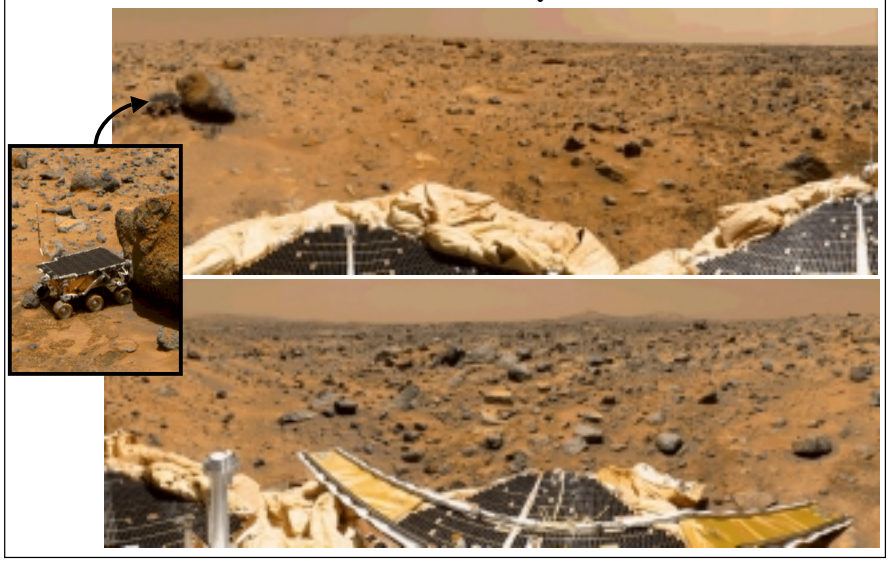
Remember these pictures?



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Pathfinder had Software Errors

- **Symptoms**
  - Software did total system resets
    - Symptoms noticed soon after Pathfinder started collecting meteorological data
    - Some data lost each time
- **Cause**
  - 3 Process threads, with bus access via mutual exclusion locks (mutexs):
    - High priority: Information Bus Manager
    - Low priority: Meteorological Data Gathering Task
    - Medium priority: Communications Task
  - Priority Inversion:
    - Low priority task gets mutex to transfer data to the bus
    - High priority task blocked until mutex is released
    - Medium priority task pre-empts low priority task
    - Eventually a watchdog timer notices Bus Manager hasn't run for some time…
- **Factors**
  - Very hard to diagnose:
    - Hard to reproduce
    - Need full tracing switched on to analyze what happened
  - Was experienced a couple of times in pre-flight testing
    - Never reproduced or explained
    - Hence testers assumed it was a hardware glitch

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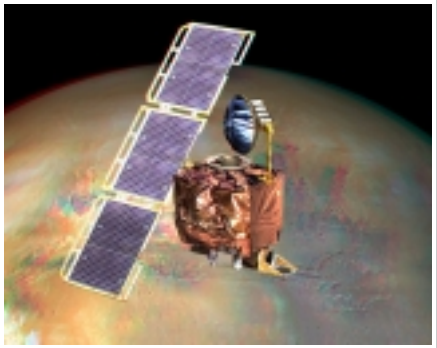
Mars Climate Orbiter

- **Launched**
  - 11 Dec 1998
- **Mission**
  - interplanetary weather satellite
  - communications relay for Mars Polar Lander
- **Fate:**
  - Arrived 23 Sept 1999
  - No signal received after initial orbit insertion
- **Cause:**
  - Faulty navigation data caused by failure to convert imperial to metric units



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Small Forces...

- **Locus of error**
  - Ground software file called "Small Forces" gives thruster performance data
  - This data used to process telemetry from the spacecraft
    - Spacecraft signals each Angular Momentum Desaturation (AMD) maneuver
    - Small Forces data used to compute effect on trajectory
    - Software underestimated effect by factor of 4.45
- **Cause of error**
  - Small Forces Data given in Pounds-seconds (lbf-s)
  - The specification called for Newton-seconds (N-s)
- **Result of error**
  - As spacecraft approaches orbit insertion, trajectory is corrected
    - Aimed for periapse of 226km on first orbit
  - Estimates were adjusted as the spacecraft approached orbit insertion:
    - 1 week prior: first periapse estimated at 150-170km
    - 1 hour prior: this was down to 110km
    - Minimum periapse considered survivable is 80km
  - MCO entered Mars occultation 49 seconds earlier than predicted
    - Signal was never regained after the predicted 21 minute occultation
    - Subsequent analysis estimates first periapse of 57km

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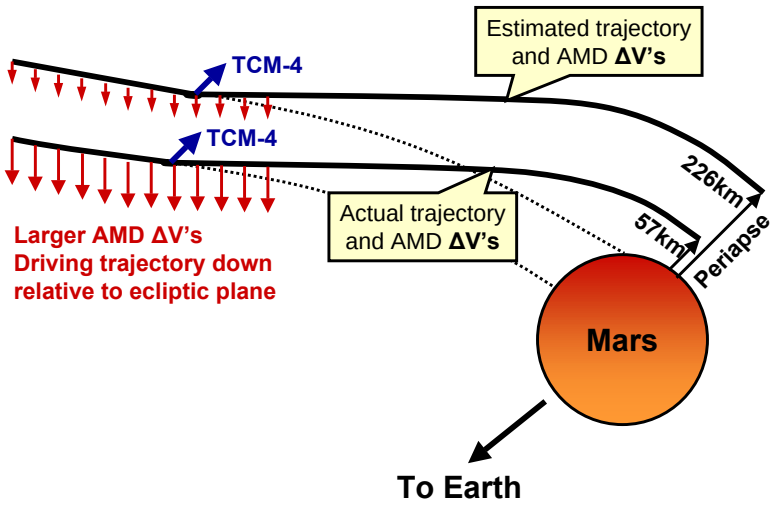
MCO Navigation Error



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Contributing Factors

- For 4 months, AMD data not used due to file format errors
  - Navigators calculated data by hand
  - File format fixed by April 1999
  - Anomalies in trajectory became apparent almost immediately
- Limited ability to investigate:
  - Thrust effects measured along line of sight using doppler shift
  - AMD thrusts are mainly perpendicular to Earth-spacecraft line of sight
- Poor communication between teams:
  - E.g. Issue tracking system not properly used by navigation team
    - Anomalies not properly investigated
- Inadequate staffing
  - Operations team monitoring three missions simultaneously (MGS, MCO and MPL)
- Operations Navigation team unfamiliar with spacecraft
  - Different team from development & test
  - Did not fully understand the significance of the anomalies
  - Familiarity with previous mission (MGS) assumed sufficient:
    - but AMD was performed 10-14 times more often on MCO as it has asymmetric solar panels.
- Inadequate Testing
  - Software Interface Spec not used during unit testing of small forces s/w
  - End-to-end test of ground software never completed
  - Ground software was not considered "mission critical" so less rigorous V&V
- Inadequate Reviews
  - Key personnel missing from critical design reviews

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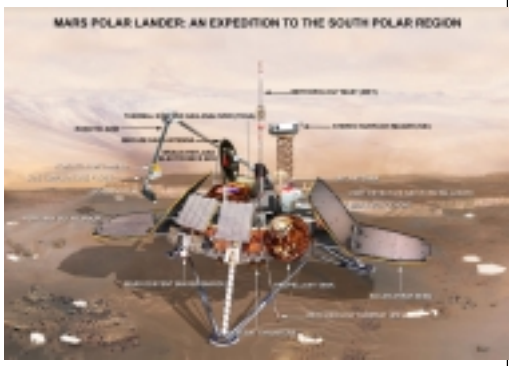
Mars Polar Lander

- Launched
  - 3 Jan 1999
- Mission
  - Land near South Pole
  - Dig for water ice with a robotic arm
- Fate:
  - Arrived 3 Dec 1999
  - No signal received after initial phase of descent
- Cause:
  - Several candidate causes
  - Most likely is premature engine shutdown due to noise on leg sensors



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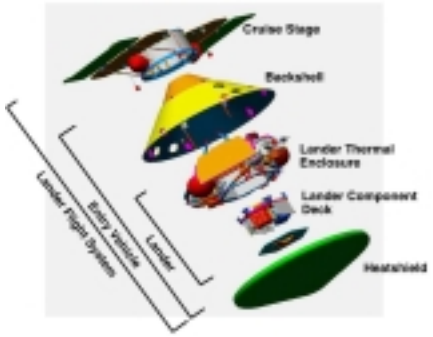
What happened?

- Investigation hampered by lack of data
  - spacecraft not designed to send telemetry during descent
  - This decision severely criticized by review boards
- Possible causes:
  - Lander failed to separate from cruise stage (plausible but unlikely)
  - Landing site was too steep (plausible)
  - Heatshield failed (plausible)
  - Loss of control due to dynamic effects (plausible)
  - Loss of control due to center-of-mass shift (plausible)
  - Premature Shutdown of Descent Engines (most likely!)
  - Parachute drapes over lander (plausible)
  - Backshell hits lander (plausible but unlikely)



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Premature Shutdown Scenario

- Cause of error
  - Magnetic sensor on each leg senses touchdown
  - Legs unfold at 1500m above surface
    - transient signals on touchdown sensors during unfolding
    - software accepts touchdown signals if they persist for 2 timeframes
    - transient signals likely to be long enough on at least one leg
- Factors
  - *System* requirement to ignore the transient signals
    - But the *software* requirements did not describe the effect
    - s/w designers didn't understand the effect, so didn't implement the requirement
  - Engineers present at code inspection didn't understand the effect
  - Not caught in testing because:
    - Unit testing didn't include the transients
    - Sensors improperly wired during integration tests (no touchdown detected!)
    - Full test not repeated after re-wiring
- Result of error
  - Engines shut down before spacecraft has landed
    - When engine shutdown s/w enabled, flags indicated touchdown already occurred
    - estimated at 40m above surface, travelling at 13 m/s
    - estimated impact velocity 22m/s (spacecraft would not survive this)
    - nominal touchdown velocity 2.4m/s

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Deep Space 2

- Launched
  - 3 Jan 1999
- Mission
  - 2 small probes piggybacked on Mars Polar Lander
  - Demonstration of new technology
  - Separate from MPL 5 minutes before atmosphere entry
  - Bury themselves in Martian Soil
  - Return data on soil analysis and look for water
- Fate:
  - No signals were received after launch
- Cause:
  - Unknown
  - (System was not ready for launch)

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Factor	STS 51L	Ariane 501	Path-finder	MCO	MPL	DS-2
Didn't test to spec		●		●	●	?
Insufficient test data	●	●			●	●
Tested "wrong" system					●	
No regression test					●	
Lack of integration testing		●		●		●
Lack of expertise at inspections		●		●	●	
System changed after testing					●	?
Reqt not implemented		?		●	●	
Lack of diagnostic data during ops			●	●	●	●
S/W used before ready				?	?	●
Different team maintains S/W				●	●	
Didn't use problem reporting system	●		●	●	●	?
Didn't track problems properly	●	●	●	●	●	?
Didn't investigate anomalies	●		●	●		
Poor communication between teams	●	●	●	●	●	?
Insufficient staffing	●			●	●	●
Failure to adjust budget and schedule	●			●	●	●
Inexperienced managers	?			●	●	●
Commercial pressures took priority	●	●		●	●	●
reused code w/o checking assumptions		●				
'Redundant' design not redundant	●	●				

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Summary

- Failures can usually be traced to a single root cause
  - But good engineering practice should prevent these causing system failure
  - The real problems are failures of:
    - testing and inspection process
    - problem reporting and tracking
    - lack of expertise
    - inadequate resources
    - etc…
  - In most cases, it takes a failure of both engineering practice and of management
- Reliable software depends not on flawless programs but on how good we are at:
  - Communication (sharing information between teams)
  - Management (of Resources and Risk)
  - Verification and Validation
  - Risk Identification and tracking
  - Questioning assumptions

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Resource List

- Mars Observer
  - Project summary
    - http://www.msss.com/mars/observer/project/mo_loss/moloss.html
  - Brief summary of possible causes
    - http://catless.ncl.ac.uk/Risks/14.89.html#subj1
- Mars Pathfinder
  - Project info:
    - http://mars.jpl.nasa.gov/MPF/index1.html
  - Report on the priority inversion problem:
    - http://catless.ncl.ac.uk/Risks/19.49.html#subj1
- Mars Climate Orbiter
  - Project Info:
    - http://mars.jpl.nasa.gov/msp98/orbiter/
  - Investigation Report:
    - ftp://ftp.hq.nasa.gov/pub/pao/reports/2000/MCO_MIB_Report.pdf
- Mars Polar Lander & Deep Space 2
  - Project info:
    - http://mars.jpl.nasa.gov/msp98/lander/
    - http://mars.jpl.nasa.gov/msp98/ds2/
  - Investigation Reports:
    - http://www.nasa.gov/newsinfo/marsreports.html
- General Resources
  - JPL's list of missions (past, present and future)
    - http://www.jpl.nasa.gov/missions/missions_index.html
  - Basics of Space Flight:
    - http://www.jpl.nasa.gov/basics/

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