Lecture 2: Examples of Poor Engineering

"Software Forensics" Case Studies

- Mars Pathfinder
- Mars Climate Observer
- Mars Polar Lander
- Deep Space 2

Some conclusions

- Reliable software has very little to do with writing good programs
- Humans make mistakes, but good engineering practice catches them!

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 Jan 1999	No data was ever retrieved
Mars Odyssey	7 Apr 2001	Arrived in orbit: Oct 23 2001	Still operating

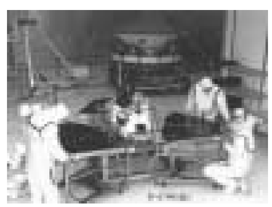
Mars Pathfinder

Mission

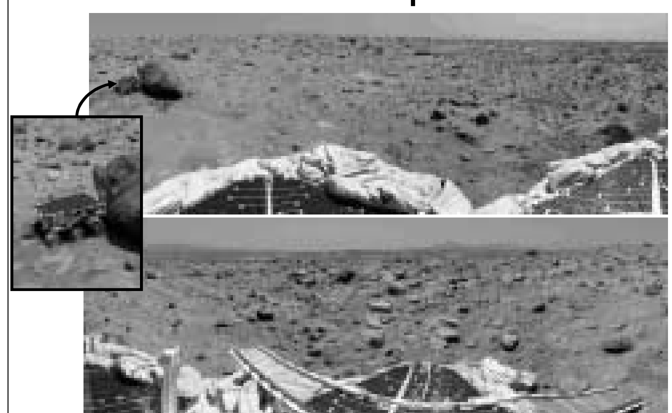
- Demonstrate new landing techniques
  - parachute and airbags
- Take pictures
- Analyze soil samples
- Demonstrate mobile robot technology
  - Sojourner

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!!!



Remember these pictures?



Pathfinder had Software Errors

Symptoms: software did total systems resents and some data was lost each time
- Symptoms noticed soon after Pathfinder started collecting meteorological data

Cause
- 3 Process threads, with bus access via mutual exclusion locks (mutexs):
  - High priority: Information Bus Manager
  - Medium priority: Communications Task
  - Low priority: Meteorological Data Gathering 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 and 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

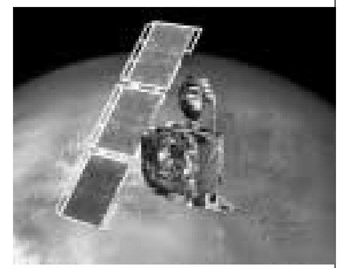
Mars Climate Orbiter

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



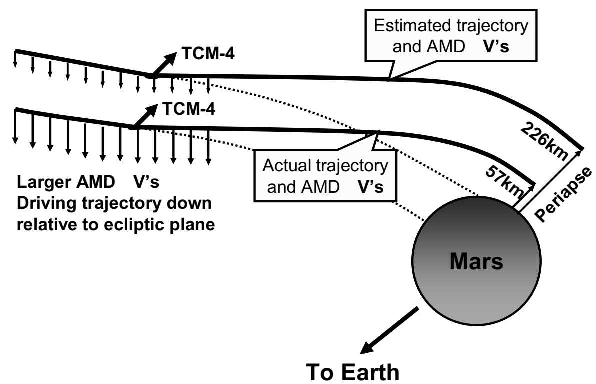
Small Forces…

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

MCO Navigation Error



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

Mars Polar Lander

Launched
- 3 Jan 1999

Mission
- Land near South Pole
- Dig for water ice with a robotic arm

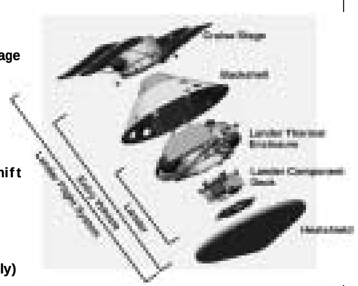
Fate:
- Arrived 3 Dec 1999
- No signal received after initial phase of descent

Cause:
- Several candidate causes
- Most likely is premature engine shutdown due to noise on leg sensors

What happened?

Lack of data hampers investigation
- 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)



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

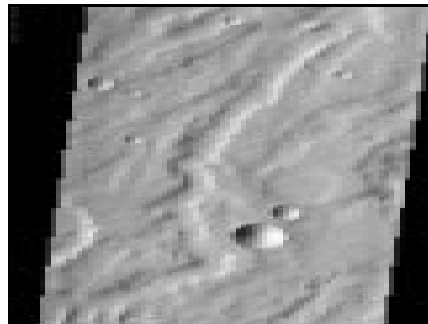
Deep Space 2

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)



Mars Odyssey Sept 12 and earlier

Original Caption Released with Image:
Color differences in this daytime infrared image ... represent differences in the mineral composition of the rocks, sediments and dust on the surface.

what went wrong?

	Challenger	Ariane	Pathfinder	Climate Orbiter	Polar Lander	Deep Space 2
design						
requirements not implemented		?		x	x	
reused code without checking assumptions		x				
redundant design not redundant	x	x				
testing						
didn't test to specifications		x		x	x	?
lack of expertise at inspections		x		x	x	
no regression test					x	
lack of integration test		x		x		x
insufficient test data	x	x			x	x
tested "wrong" system					x	

	Challenger	Ariane	Pathfinder	Climate Orbiter	Polar Lander	Deep Space 2
problem tracking						
didn't investigate anomalies	x		x	x		
didn't use problem reporting system	x		x	x	x	?
didn't track problems properly	x	x	x	x	x	?
operation						
software used before ready				?	?	x
system changed after testing					x	?
lack of diagnostic data during operation			x	x	x	x
different team maintains software				x	x	
management						
poor communication between teams	x	x	x	x	x	?
inexperienced managers	?			x	x	x
failure to adjust budget and schedule	x			x	x	x
insufficient staffing	x			x	x	x
commercial pressure took priorities	x	x		x	x	x

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

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/