

# Introduction to Space robotics

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## Objectives

1. Get familiar with Space robotics
2. Know main missions to Mars
3. Purpose of AI Planning in Space robotics

## Source

1. Special thanks to James Kurien's presentation
2. Yang Gao, and Steve Chien. Review on space robotics: Toward top-level science through space exploration. *Science Robotics* 28, Vol. 2, Issue 7, 2017.

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- Insight Lander
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- ExoMars

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## Space robotics

## Introduction

Space exploration is important to top-level science

- Formation of the universe
  - Origin of Earth
  - Evolution of life
  - Existence of life beyond Earth

## Space robotics plays a critical role

- Enable missions capable of surviving in the space
  - Perform exploration, assembly, construction, maintenance, or service tasks

2 attributes for space robotic (orbital or planetary)

- Locomotion (or mobility) to manipulate, grip, rove, drill, and/or sample
  - Autonomy

## Space robotics

## History (I)

## New exploration frontiers for mankind since the 1950s.

- Focused on sending humans into Earth's orbit
  - Result of space race between USA & URSS
  - Use of cheaper robotic proxies critical to understand space
  - Surveyor 3 lander (1967) 1st robotic locomotion system on the Moon  
(i.e., a manipulation cum sampling device)
  - Luna 17 (1970) 1st planetary rover (Lunokhod 1)

# Apollo 11 - 16th July 1969 (video 1) (video 2) (video 3) (First Man Movie) (Hidden Figures Movie)

## Space robotics

## History (II)

Table 1: Successfully flown robots on Earth's orbit, the Moon, Mars, and small bodies (I)

Launch	Mission	Country	Target	Rover	Arm	Samp.	Drill
1967	Surveyor 3	USA	Moon			x	
1970/72/76	Luna 16/20/24	URSS	Moon		x	x	x
1970/73	Luna 17/21	URSS	Moon	x			
1975	Viking	USA	Mars		x	x	
1981/01/08	Canadarm1/2	Canada	ISS		x		
1993	Rotex	Germany	Orbit		x		
1996	MPF	USA	Mars	x			
1997	ETS-VII	Japan	Orbit		x		
2003	Hayabusa	Japan	Asteroid			x	
2003	MERs	USA	Mars	x	x	x	
2004	ROKVISS	Germany	ISS		x		
2004	Rosetta	Europe	Comet		x	x	x
2007	Orbital Express	USA	Orbit		x		

# Space robotics

## History (III)

Table 2: Successfully flown robots on Earth's orbit, the Moon, Mars, and small bodies (II)

Launch	Mission	Country	Target	Rover	Arm	Sampler	Drill
2008	JEMRMS	Japan	ISS		x		
2008	Phoenix	USA	Mars		x	x	
2008	Dextre	Canada	ISS		x		
2012	Robonaut	USA	ISS		x		
2011	MSL	USA	Mars	x	x	x	
2013	Chang'E3	China	Moon	x			
2016	Aolong-1	China	Orbit		x		
2016 (2023)	OSIRIS-REx Sample Return	USA	NEA Bennu		x	x	
2018	Insight	USA	Mars		x	x	x
2018	Chang'E4	China	Moon	x			
2019	Chandrayaan'2	India	Moon	x			

## Space robotics

## Evolution: Mid-term on-orbit

N# On-orbit applications (2025-2035) require advanced robotics capabilities.

- Operators will range from national administrations to businesses
  - Focus:
    - Space debris removal
    - Rescue, planned orbit raising, inspection and support to deployment
    - Repair, refueling and orbit maintenance, etc
  - ISS opportunity to scientific experiments in space
  - China: own space station program

## Space robotics

## Evolution: Mid-term in robotic

Table 3: Medium-term space robotic missions in the pipeline

Launch	Mission	Country	Target	Rover	Arm	Sampler	Drill
2020	Chang'E5	China	Moon	x	x	x	x
2020	Mars2020	USA	Mars	x	x	x	x
2020	ExoMars	2020	Europe	Mars	x		x
2020	Chinese Space Station	China	Orbit		x		
2022	SLIM	Japan	Moon		x	x	x
2025	Phobos Sample	Europe & Russia	Phobos	x	x		

## Space robotics

## Evolution: Long-term (I)

Table 4: Long-term space robotic missions

Destination	Proposed mission concepts	Proposed robotic locomotion
Earth's orbit	Space debris removal, on-orbit servicing, and assembly	Arm, hand/gripper, harpoon
Moon	Sample return, ISRU, exploration of shaded craters, prepare for manned base	Rover, arm, sampler, drill
Mars	Sample return, ISRU, crewed base	Aeroshell, airplane, balloon, helicopter, hopper, swarms
Venus	Exploration	Balloon
Mercury	Exploration	Rover
Asteroid	Sample return, ISRU Sample return, ISRU	Rover, hopper, arm, harpoon

## Space robotics

## Evolution: Long-term (II)

Table 5: Long-term space robotic missions

<b>Destination</b>	<b>Proposed mission concepts</b>	<b>Proposed robotic locomotion</b>
Titan	Exploration	Aeroshell, aerobot, balloon, lake lander, submarine, ship, cooperative robots
Europa/ Enceladus	Exploration	Subsurface, submarine, hopper
Gas giants	Exploration	Balloon

# Why Mars?

## Introduction (I)

Mars is a lot like Earth

- About  $\frac{1}{2}$  size than Earth
  - Martian day slightly under 25 hours
  - Avg. temp  $-63^{\circ}$  ( $-140^{\circ}\text{C}$  to  $20^{\circ}\text{C}$ )

## Distant past

- Evidence of oceans and warm temperatures
  - It may have harbored life

Present

- Frozen water and a thin atmosphere of carbon dioxide remain
  - It is possible that it harbors life today
  - Earth is sending many robotic spacecraft to investigate

## Future

- Mars has all of the materials needed to support human civilization
  - Several nations interested in sending humans to Mars in the future

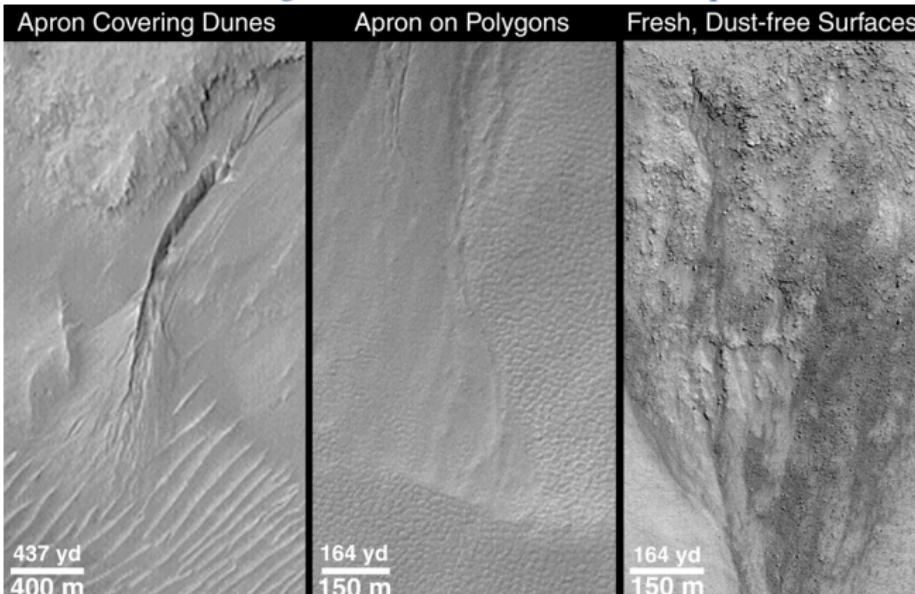


(Source:

# Why Mars?

## Introduction (II)

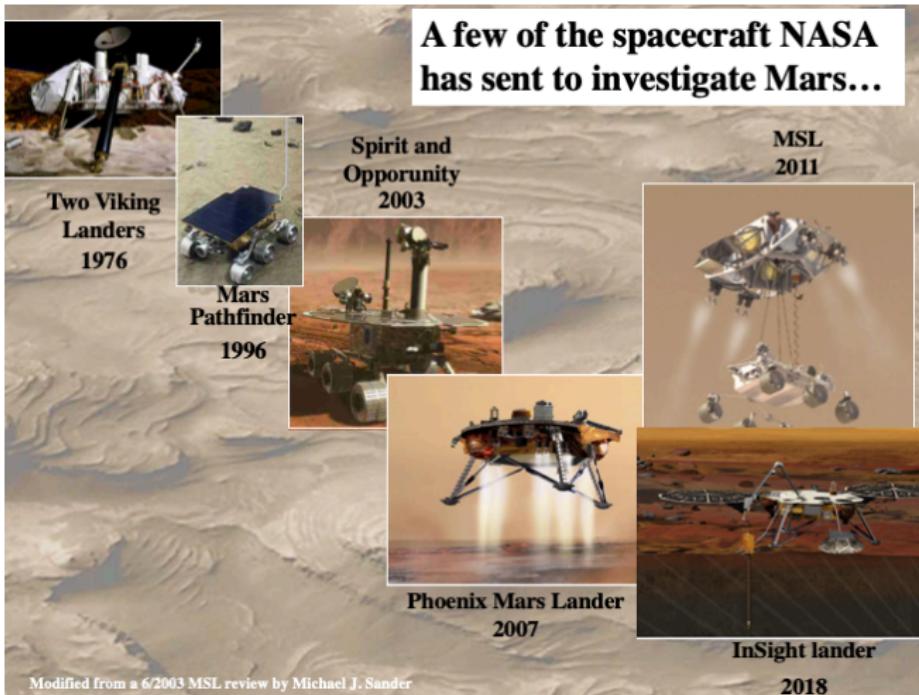
### Strong evidence of recent water activity



(Source)

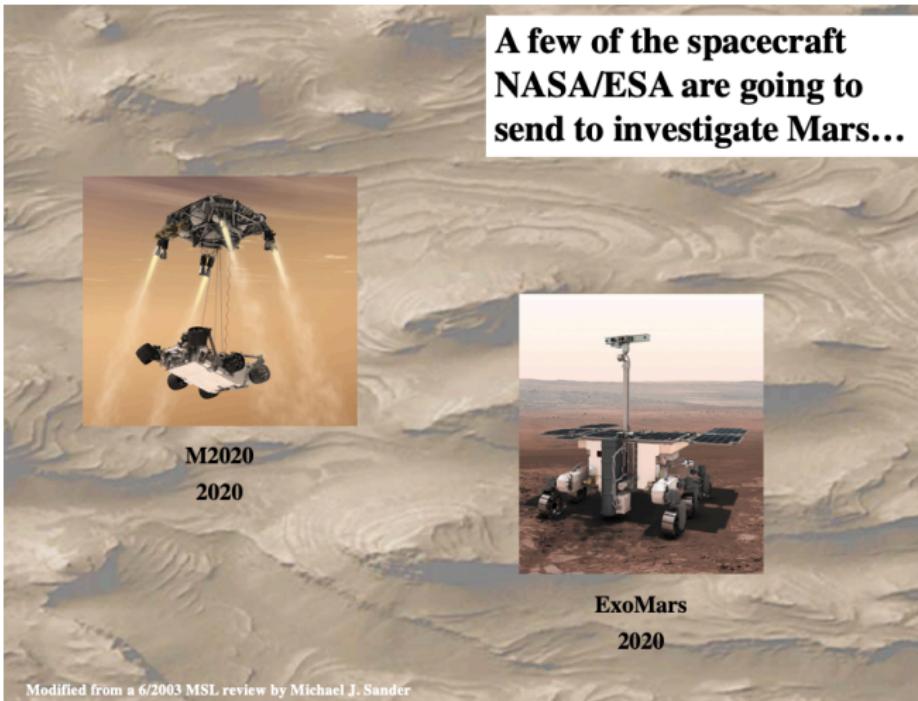
## Why Mars?

## Evolution of Mars landers (I)

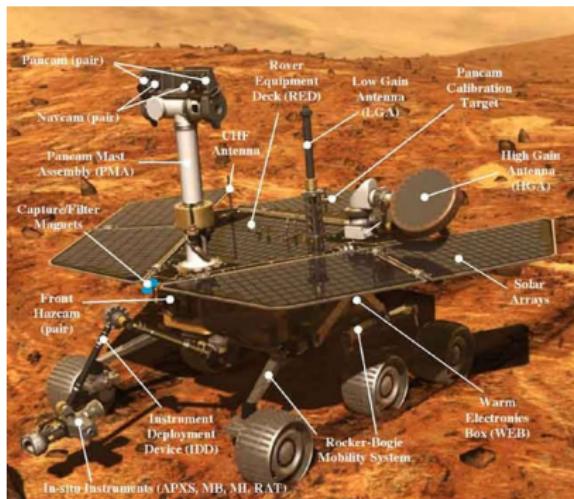


# Why Mars?

## Evolution of Mars landers (II)



## Main missions to Mars



## Launch:

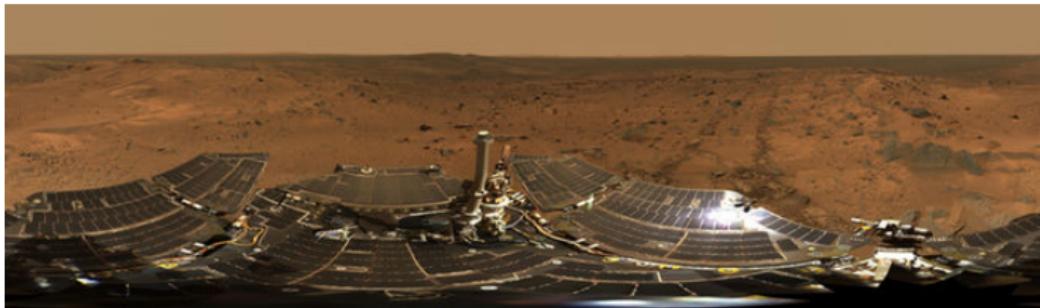
- Jun 10, 2003 (Spirit)
  - July 7, 2003 (Opportunity)

Landed:

- Jan 4, 2004 (Spirit RIP - March 22, 2010)
  - Jan 25, 2004 (Opportunity)

## Main missions to Mars

### Spirit and Opportunity (II)

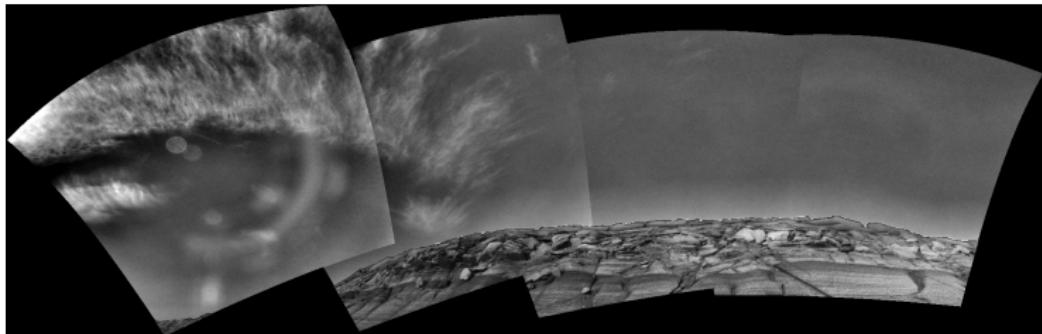


- Some Mars rocks contain minerals that only form in water
  - Some sediment layers were formed in standing water
  - Mars was covered with standing water in the past
  - Mars used to be much warmer and wetter

## Main missions to Mars

## Spirit and Opportunity (III)

## Clouds of water vapor on Mars



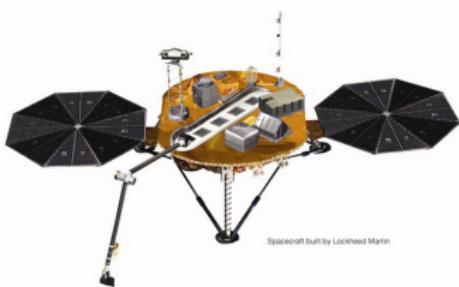
(Video Sunset) (Video MER by Steve Squyres)

## Main missions to Mars

## Phoenix Mars Lander (I)

## Features

- Launch: August 27, 2007
  - Landed: May 25, 2008
  - Operated until November 2008



## Goals

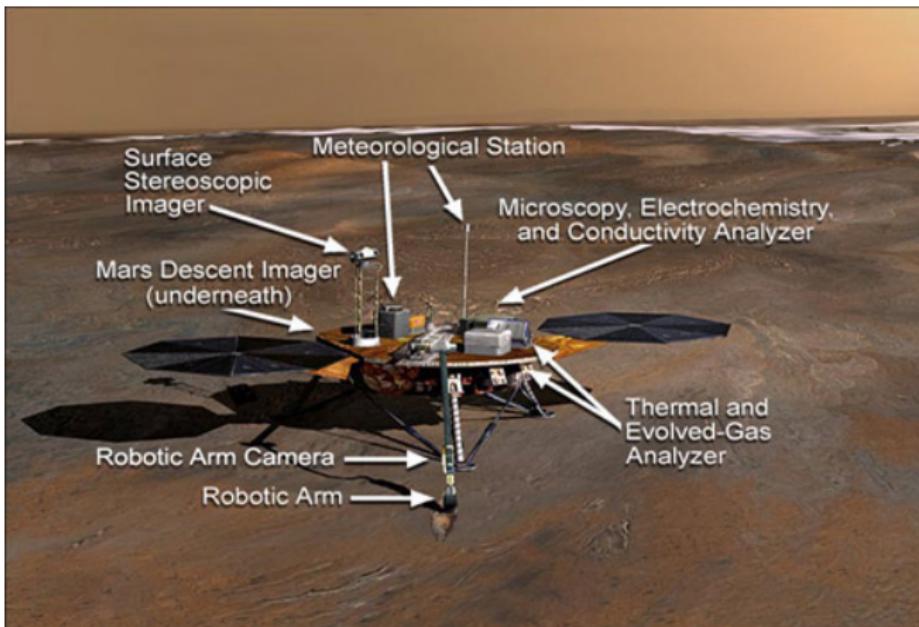
- Study the history of water in the Martian arctic
  - Search for evidence of a habitable zone and assess biological potential

## How?

- Land in the Martian Arctic
  - Dig through regolith to water ice
  - Analyze ice samples in on-board

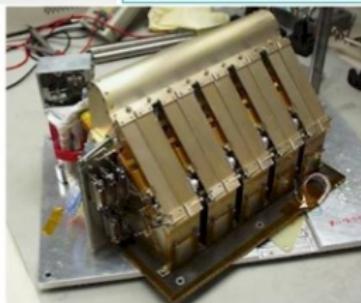
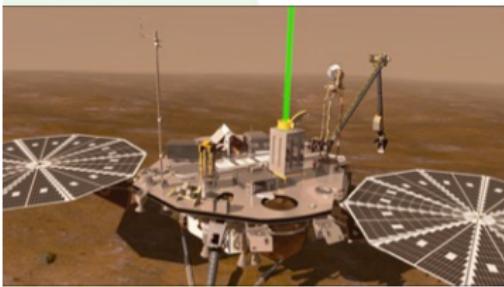
# Main missions to Mars

## Phoenix Mars Lander (II)



## Main missions to Mars

## Phoenix Mars Lander (III)

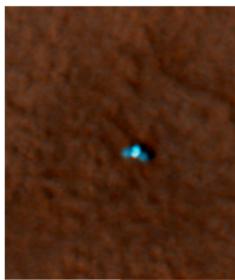


# Main missions to Mars

## Phoenix Mars Lander (IV)



## Phoenix Mars Lander (V)



# Main missions to Mars

## Phoenix Mars Lander (VI)

Phoenix achievements



- Observed and sampled water ice in the Martian arctic
- Studied the water cycle
  - Sublimation of ice, precipitation of ice crystals (snow)
  - Evidence that a liquid water film can form in the soil
- Studied chemical makeup of the soil
  - Salts that typically form in presence of liquid water
  - Perchlorates that could be an energy source for life

# Main missions to Mars

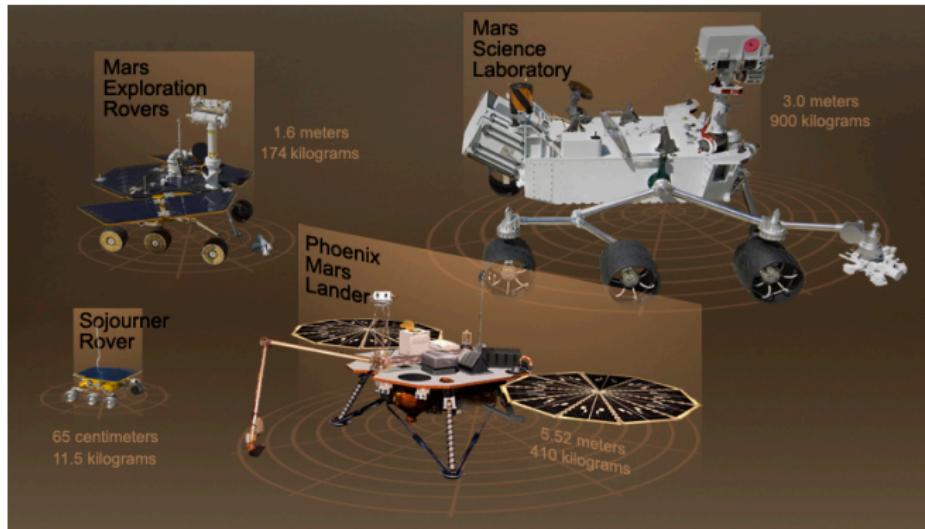
## Phoenix Mars Lander (VII)



[\(Video\)](#)

# Main missions to Mars

## MSL (I)



# Main missions to Mars

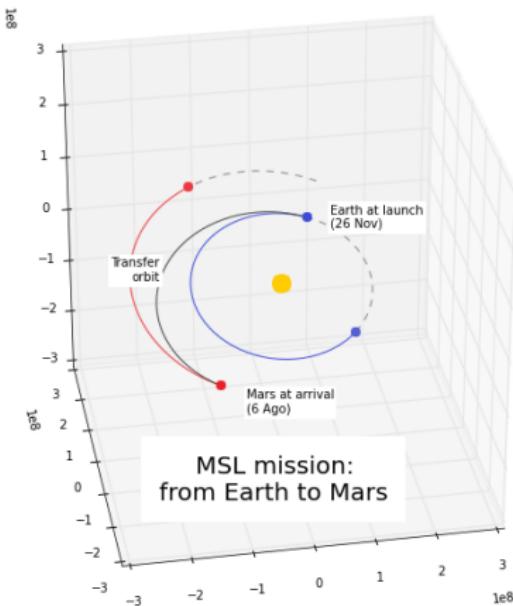
## MSL (II)



- Launch: Nov. 26, 2011
- Landed: August 5, 2012

# Main missions to Mars

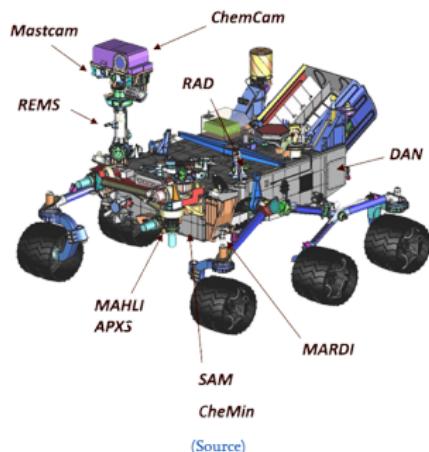
## MSL (III)



(Source)

# Main missions to Mars

## MSL (IV)



- Mast Camera (Mastcam)
- Chemistry & Camera (ChemCam)
- Alpha Particle X-ray Spectrometer (APXS)
- Mars Hand Lens Imager (MAHLI)
- Chemistry & Mineralogy (CheMin)
- Sample Analysis at Mars (SAM)
- Radiation Assessment Detector (RAD)
- Rover Environmental Monitoring Station (REMS)
- Dynamic Albedo of Neutrons (DAN)
- Mars Descent Imager (MARDI)

# Main missions to Mars

## MSL (V)

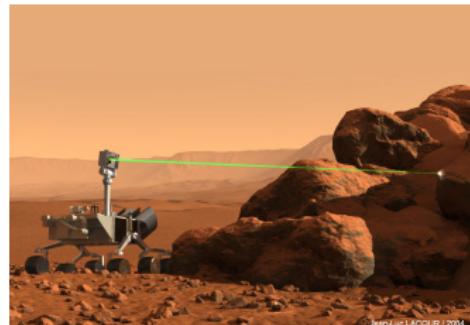
MSL goals (Primary mission 687 days)

- Assess potential habitat for life, past or present
- Assess biological potential...
- Characterize the geology of the landing region ...
- Investigate processes relevant to past habitability...
- Characterize surface radiation...

Instruments include

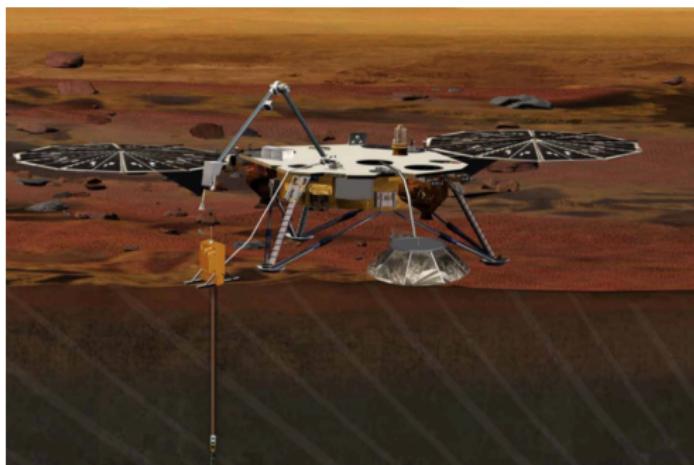
- Chemcam
- Variety of spectrometers
- Subsurface water detection

(Landing Process MSL video)



# Main missions to Mars

## Insight Lander (I)



- Launch: 5 May 2018
- Landing: 26 Nov. 2018

# Main missions to Mars

## Insight Lander (II)

- Same concepts as Phoenix lander mission
- Different instruments to study the Martian interior
- The Instrument Deployment Arm & Camera will deploy 2 instruments:
  - Seismic Experiment for Interior Structure (French space agency): a seismographic instrument used to study the Martian interior and seismic activity
  - Heat Flow and Physical Properties Probe (German space agency): a self-burrowing mole that penetrates up to 5 m to measure heat escaping from interior

(Insight video)

# Main missions to Mars

## M2020 (I)



- Launch: Summer 2020
- Landing: February 2021

# Main missions to Mars

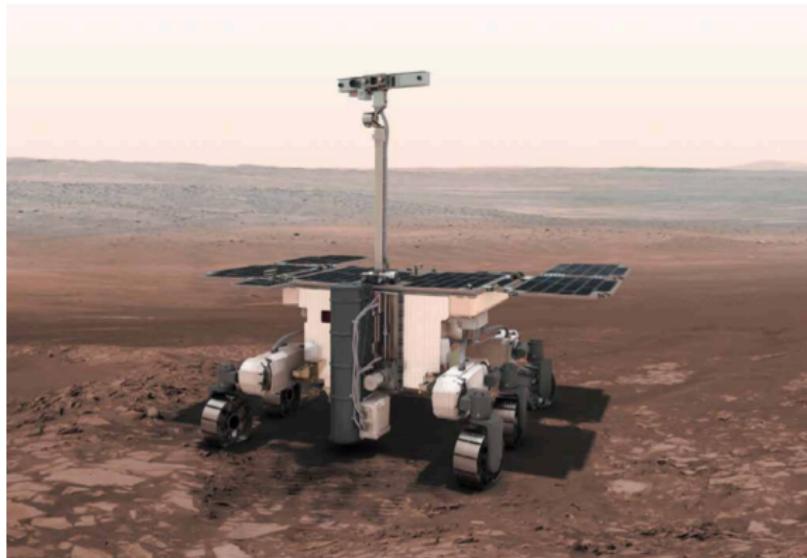
## M2020 (II)

- Shares heritage with the MSL rover with entirely new instruments
  - Use the Skycrane deployment method: rocket-powered hovering carrier to lower the rover to the surface of Mars with a tether
  - Delivery method is enhanced with Terrain Relative Navigation to enable the system to avoid hazardous terrain in selecting a location to lower the rover.
  - A drill capable of coring and caching samples for potential future retrieval to return to Earth
- More autonomous
  - An onboard scheduler to better use available time, energy, and data volume
  - Ability to autonomously target instruments based on scientist-provided criteria (SUPERCAM)

(Building M2020 video)

# Main missions to Mars

## ExoMars (I)



- Launch: 2020
- Landing: 2021

# Main missions to Mars

## ExoMars (II)

- First European funded mission: autonomous rover, automated exobiology laboratory & robotic drilling system
- Complement the ExoMars Phase 1 launched in March 2016 (Video)
- Instruments for:
  - Accurate visual and spectral characterization of the surface for molecular identification of organic compounds
  - Electromagnetic and neutron subsurface investigations to understand depositional environment (e.g. sedimentary, volcanic, and Aeolian)
- Unique contribution on exobiology to search past/present traces of life

(ExoMars Rover video)

# Planners in space missions

## Legacy planners

- NONLIN+ (Tate y Whiter, 1984): general planning architecture, precursor of current planners
- SIPE (Wilkins 1988): independent domain planner and 1st in managing consumable and producible resources and managing conflicts. Used in air and military campaigns
- DEVISER (Vere 1983): based on NONLIN, was used in Voyager to photograph Jupiter, Saturn and its satellites in 1979, 1980 and 1981

# Planners in space missions

## New approaches

- HSTS (Muscettola 1994): integrates P& S, applied to the problem of planning observations in the Hubble Space Telescope
- O-PLAN2 (Tate et al., 1994): based on NONLIN and Blackboard techniques.  
Applications: rescue coordination, military operations, space missions
- NMRA (Muscettola and Smith, 1997): New Millennium Remote Agent was the first time that an AI agent controls a spacecraft for 6 days: the Deep Space One (DS-1)
- ASPEN (Rabideau et al. 1999): JPL-NASA P&S system
  - Earth Orbiting (EO-1): controllable by a small group
  - Citizen Explorer: small mission with teaching purposes
  - Antarctic Mapping Missions: Mars-or Marie Curie rover
- EUROPA (Frank, Jónsson and Morris 2000): MSL or Phoenix

# Planners in space missions

## Summary

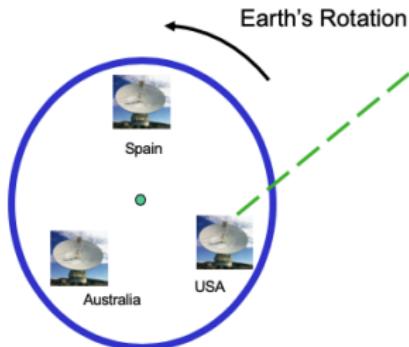
System	Mission	Year	Used	Techniques
DEVISER	Voyager	1977	On-ground	POP
PLANIT-II	Galileo	1995	On-ground	Used by AI experts who provide specific Scheduling algorithms
	Mars Pathfinder	1997	On-ground	
	Spitzer Space Telescope	2003	On-ground	
HSTS	DS-1	1998	On-board	HTN & SAT & Refinement CS
ASPEN	AMM-2	2000	On-ground	Repair CS
PROBA	Proba	2001	On-board	OR
ASPEN & CASPER	EO-1	2003	On-board	Repair CS
MPS	Smart-1	2003	On-ground	OR
EUROPA/ MAPGEN	MER	2003	On-ground	HSTS descendent
MEXAR-2	Mars Express	2005	On-ground	Refinement CS
EUROPA2/ ENSEMBLE	Phoenix	2007	On-ground	HSTS descendent
	MSL	2009	On-ground	

# Introduction

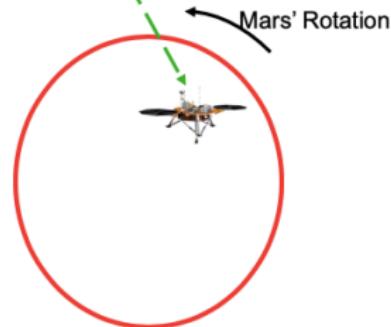
## How we communicate?



Deep Space Network  
70 meter (210 foot) antenna



Mars Orbiter



# Introduction

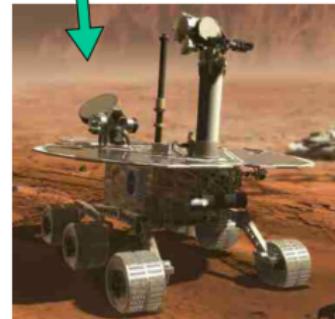
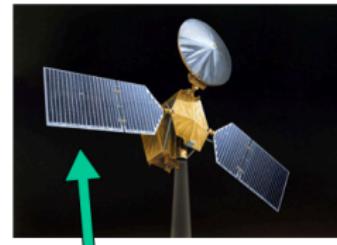
## Types of Data Exchanged

Data that is received from a rover

- Images
- Other scientific data
- Engineering data
  - Battery level
  - Temperatures onboard the lander
  - Amount of storage space available

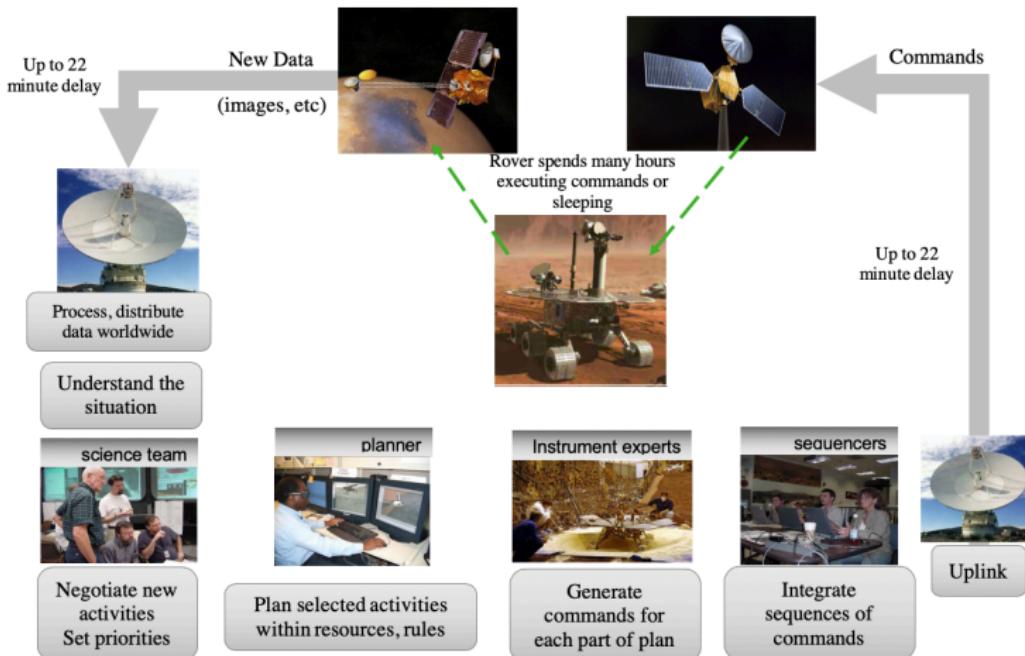
Data that is sent to a rover

- Sequences of commands to be executed  
Take a picture, point the camera, move the arm
- Complex behaviors to perform  
Drive to a target while avoiding rocks
- When to communicate with the orbiters
- Changes to heating or other parameters



# Introduction

## Daily Science Operations



# Introduction

## Controlling a rover

Communication is limited

- Commands take up to 22 minutes to reach Mars via radio
- Commands sent to the rover once per day (typically)
- Images and other data received once a day, sometimes at 4am

Resources are limited

- Runs on a battery supplied by solar panels or radio-thermal generator
- Some experiments can only be run a few times
- We don't have an unlimited ability to transmit data

Coordination

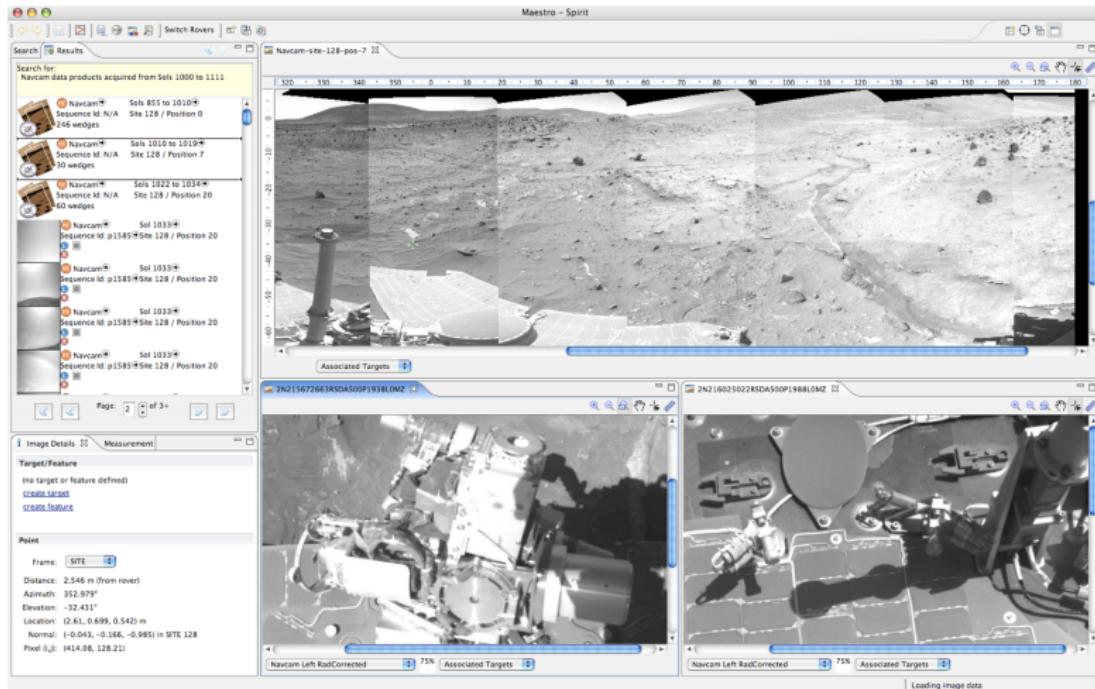
- Many scientists want to command the rover at once
- We want to respond to whatever the rover's last actions revealed
- We must come up with a plan quickly, in time to send it to the rover
- There are many safety constraints our commands must obey

Uncertainty

- The environment is complex (rocks, shadows, varying temperature)
- The rover may not succeed in performing the commands
- It takes time to understand what is going on around the rover

# Introduction

## Data Browsing, Image Analysis & Targeting





# Introduction

## Activity Planning & Analysis

**Phoenix Science Interface (psifx)**

File Edit Plan Window Help

characterization\_sol4\_tact\_tokened\_v1.4-5 (Re) characterization\_sol3\_asrun\_v1.3-4 (Read Only)

Sol 3 11:51:31 5 overlapping Sol 3 12:16:11 25 min 20 sec

LPEB Preheat - RA  
RA cold characterization  
sol 3 AM data xfer and restart  
Command History  
LPEB Preheat - TEGA  
TEGA checkout 2: puncture foils and atm  
TEGA checkout 2: puncture foils and atm  
sol 3 AM WCL PT monitor  
sol 3 noon LIDAR  
sol 3 noon SSI regular ATIM  
SSI Fiducials  
SSI doc OM tongue  
SSI One-color 360 pan 3/3  
Command History  
sol 3 TECP wind (no RA move)  
WCL checkout  
RA hot characterization  
RAC doc blind spot  
RAC doc OM tongue  
KIN/PTM ->Sol 4 00:00 move  
Merge Timeline

Activity Dictionary Resources Campaigns

Conditions Control Lander MECA MET\_LIDAR MET\_PT OrbitalEvents

activity type Europa APcore JMS

Phoenix Science Interface (psifx)

characterization\_sol4\_tact\_tokened\_v1.4-5

Name	Scheduled	start (SFODateFormat)	Start Time
RAC doc TEGA cover 4	2008-150712:16:06	Sol 4 13:24:19	
RAC doc OM slot	2008-150712:20:36	Sol 4 13:28:41	
RAC doc footpad -Y	2008-150712:22:45	Sol 4 13:30:47	
RAC doc footpad -X, +Y	2008-150712:22:55	Sol 4 13:32:58	
Image RA at TEGA teach point and def po	2008-150712:30:35	Sol 4 13:38:25	
SSI Fiducials	2008-150712:37:33	Sol 4 13:45:11	
SSI Image footpad	2008-150712:38:13	Sol 4 13:48:46	
SSI Image TEGA cover 5 (retracted)	2008-151107:02:33	Sol 4 14:30:00	
RAC doc TEGA cover 5 (retracted)	2008-151107:02:33	Sol 4 14:30:00	
Sol 4 Optical Depth	2008-151107:01:22	Sol 4 15:12:49	
FINCON pre PM pass	2008-151106:46:10	Sol 4 14:52:04	
FINCON post PM pass	2008-151106:46:22	Sol 4 15:06:46	
INCON from telemetry	2008-151107:01:36	Sol 4 15:47:32	
FINCON at Science Master shutdowns	2008-151107:14:29	Sol 4 15:38:51	
p#f001_07	2008-151107:06:59	Sol 4 16:30:49	
p#f004_08	2008-151107:04:38	Sol 4 16:18:48	
p#f004_09	2008-151106:32:24	Sol 4 26:10:27	
p#f004_10	2008-151106:09:01	Sol 4 22:02:58	
p#f004_11	2008-151106:04:31	Sol 4 23:55:02	
p#f005_01	2008-151121:12:13	Sol 5 01:58:38	
p#f005_02	2008-151121:13:06	Sol 5 03:49:46	
FINCON pre-AM pass ***SP1***	2008-151121:13:11	Sol 5 03:52:46	
p#f005_03	2008-151121:15:42:58	Sol 5 05:24:39	
FINCON post-AM pass	2008-151121:16:13:31	Sol 5 05:54:39	

Subtotal: - - Total: 2008-150709:29:41 Sol 4 00:00:00 32:3

Merge Timeline

Plan Advisor Constraints

Fix selected Fix violations

Europa + APcore

The constraints are satisfiable.

1 temporal violation.

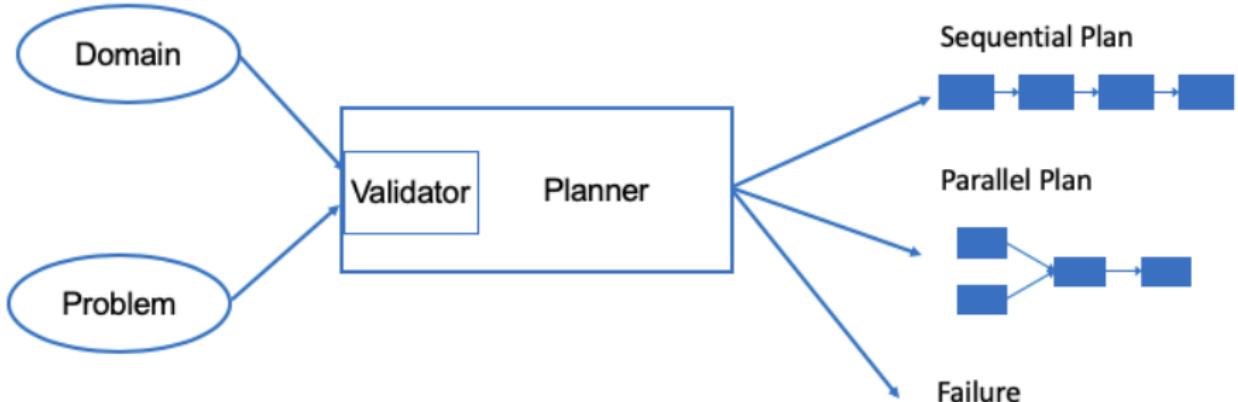
The start of **SCT\_INCON\_SOL003 PM** is Sol 3 15:27:00. It should be Sol 3 15:41:02.

No flight rule violations, or no flight rules.

10 elements require freezing.

# How we use AI planning?

## Inputs & Outputs



# How we use AI planning?

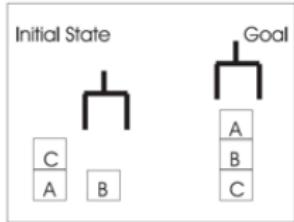
## Blocksworld

### Domain

```
(:action pick-up
  :parameters (?x)
  :precondition (and (clear ?x)
                      (ontable ?x)
                      (handempty))
  :effect(and (not (ontable ?x))
              (not (clear ?x))
              (not (handempty))
              (holding ?x)))
```

...

### Problem



### Plan

1. pick-up C
2. put-down C
3. pick up B
4. stack B,C
5. pick-up A
6. stack A,B

Planner

# How we use AI planning?

## Problems?! (I)

### Very Simplified Rover Domain

```
action take-picture
:precondition not vibrating
:duration 10 minutes

action communicate
:precondition not vibrating
:duration variable

action drive
:effect vibrating
:duration 60 minutes
```

### Problem

#### Scientist 1 Goals

- Take picture of rock 1
- Drive to rock 2
- Take a picture of rock 2

#### Scientist 2 Goals

- Drive to rock 3
- Take a picture of rock 3

#### Engineering Goals:

- Communicate from 4-6pm



- Planner must explain which goals are in conflict and why
- We need to explore plans that violate the domain to understand how to change them
- Users need to negotiate which goals to delete or modify
- Example: Can we modify comm to be 4:30 - 6?  
skip one of the pictures?

# How we use AI planning?

## Problems?! (II)

### Very Simplified Rover Domain

```
action take-picture
:precondition not vibrating
:duration 10 minutes

action communicate
:precondition not vibrating
:duration variable

action drive
:effect vibrating
:duration 60 minutes
```

### Problem

```
Scientist 1 Goals
• Take picture of rock 1
• Drive to rock 2
• Take a picture of rock 2

Scientist 2 Goals
• Drive to rock 3
• Take a picture of rock 3

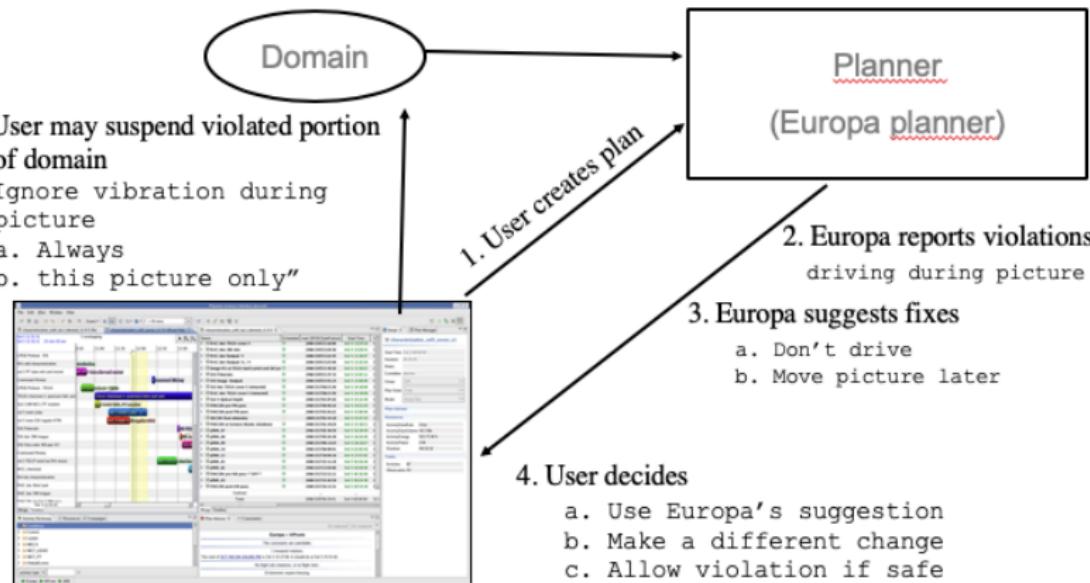
Engineering Goals:
• Communicate from 4-6pm
```



- 99.9% of the time we should not take a picture while driving
- We need the planner to report the conflict involving vibration
- We need to temporarily turn it off without re-writing the model

# How we use AI planning?

## How it is done?





# How we use AI planning?

## How the planner appears to the user

Summary of violations for entire plan

The screenshot shows the 'Plan Advisor' window with the title 'Plan Rules'. It displays a table of 'Violations' with columns: Violations, Participants, Time, Description, Advisor, Type, Status, and Context. There are 10 unverified violations listed, all related to 'Chemcan\_LBS\_RME 1'. A context menu is open over the last violation, listing options: 'Move the end of Chemcan LBS RME 1 to Sol 139 11:47:07', 'Remove the constraint', 'Delete: Chemcan LBS RME 1', and 'Delete: Chemcan Safety 1'.

Violations	Participants	Time	Description	Advisor	Type	Status	Context
Plan Rule (9/9)							
SC_CPU_On	Chemcan_LBS_RME 1	Sol 139 10:44:40	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_ASM_State_Stationary	Chemcan_LBS_RME 1	Sol 139 10:44:40	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_Chem_Can_Mast_Unit_Telescope_Focusing	Chemcan_LBS_RME 1	Sol 139 10:44:40	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_Chem_Can_Mast_Unit_Telescope_Focusing	Chemcan_LBS_RME 1	Sol 139 10:44:40	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_CPU_On	Chemcan_Safety 1	Sol 139 12:32:07	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_ASM_State_Stationary	Chemcan_Safety 1	Sol 139 12:32:07	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_Chem_Can_Body_Unit_Telescope_Focusing	Chemcan_Safety 1, ...	Sol 139 12:32:07	Oversubscribed by 2.0	Europa	Plan Rule	true	Activity Gr...
SC_Chem_Can_Mast_Unit_Laser_Warmup_20_j	Chemcan_Safety 1	Sol 139 12:32:07	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
SC_Chem_Can_Mast_Unit_Telescope_Focusing	Chemcan_Safety 1	Sol 139 12:32:07	Oversubscribed by 1.0	Europa	Plan Rule	true	Activity Gr...
Temporal (1/1)							
Distance	Chemcan_LBS_RME ...	Sol 139 11:47:07	In-odd separation.				

The start of [Chemcan Safety 1](#) should be no earlier than the [end of Chemcan LBS RME 1](#).

Full description of selected violation

Push button to request that the planning software resolve all problems

Suggestions for resolving a single problem manually