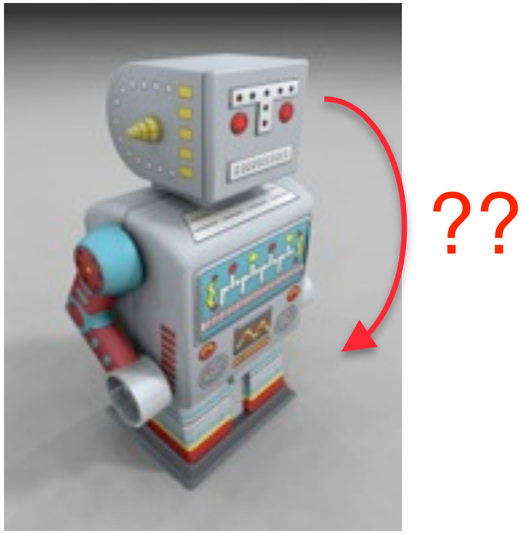
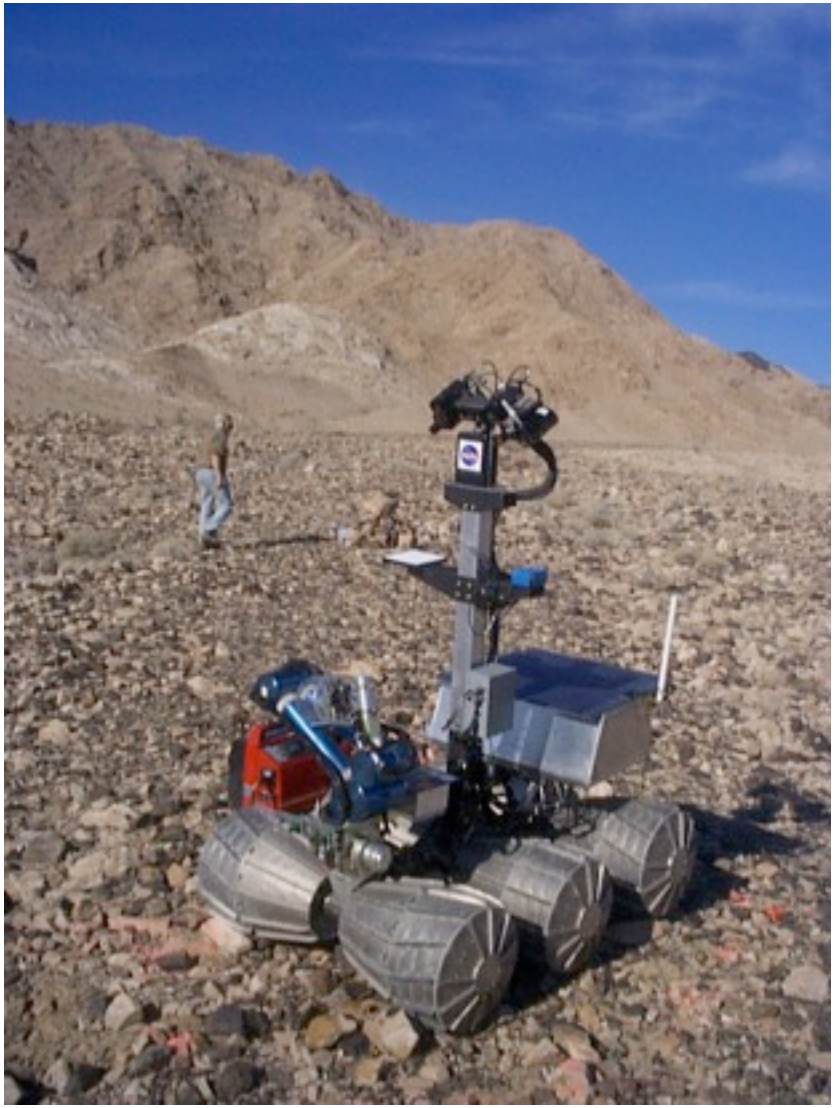
Ames Research Center

From Task to Motion Planning

David E. Smith
NASA Ames Research Center



1997-2000: Marsokhod



2001-2005: K9 rover

2007-2008: ATHLETE

2009-: A Different Kind of Rover

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Some Rover Peculiarities

- Hazardous environments
  - Slow rad-hardened processors (200 MHz)
  - Low power (125 Watts)
  - Limited memory (256 MB)
  - Limited storage (2 GB)
- Unstructured rough terrain
  - Navigation/localization difficult
- Limited autonomy
  - Local obstacle avoidance
  - Opportunistic pictures

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Some Rover Peculiarities

Ignore

- ~~Hazardous environments~~
  - ~~Slow rad-hardened processors (200 MHz)~~
  - ~~Low power (125 Watts)~~
  - ~~Limited memory (256 MB)~~
  - ~~Limited storage (2 GB)~~

- Unstructured rough terrain
  - Navigation/localization difficult

Ignore

- ~~Limited autonomy~~
  - ~~Local obstacle avoidance~~
  - ~~Opportunistic pictures~~





The Planning Problem

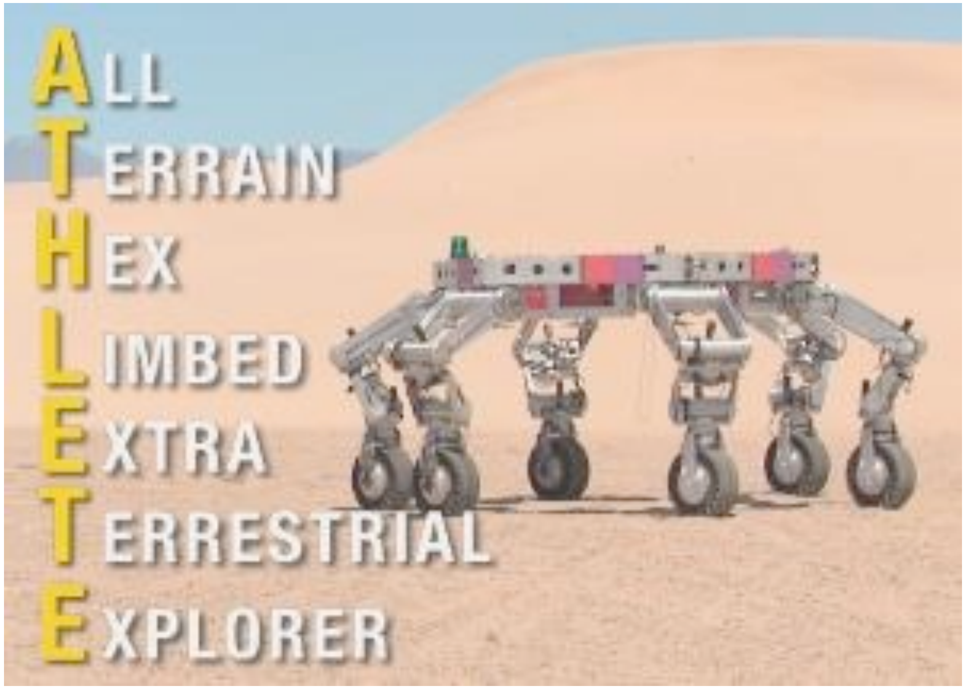
- Temporal
  - Action durations
  - Concurrency
- Time constraints
  - Communication windows
  - Illumination of targets
  - Temperature
- Uncertainty
  - Terrain & tracking
  - Duration of actions
  - Energy usage
  - Storage available
- Oversubscription
  - Many conflicting goals
  - Goal dependence

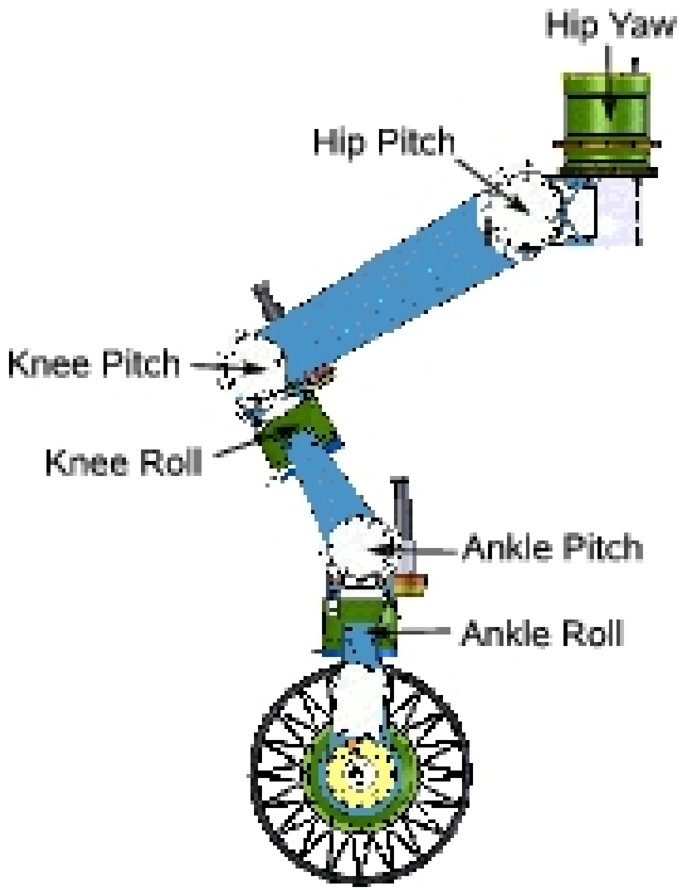




ATHLETE

- 6 legs, 36 degrees of freedom
- Feet are wheels (walk and roll)
- Tool takeoff on each wheel

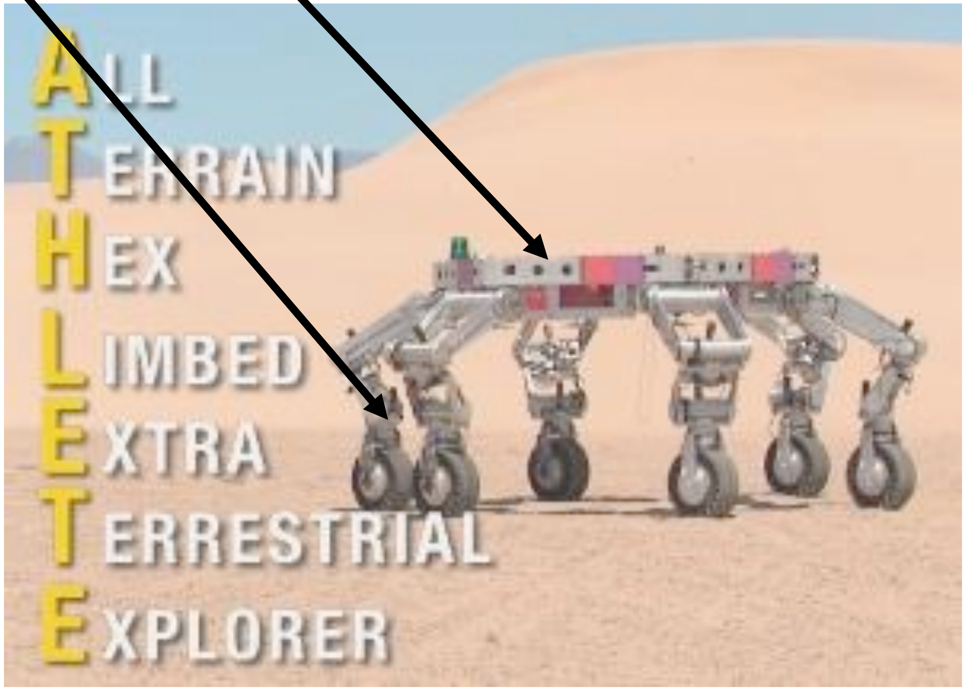




ATHLETE

- 6 stereo camera pairs outward
- 3 stereo camera pairs inward
- 1 stereo pair on each foot
- 2.75m chassis
- 850 kg

1/2 scale



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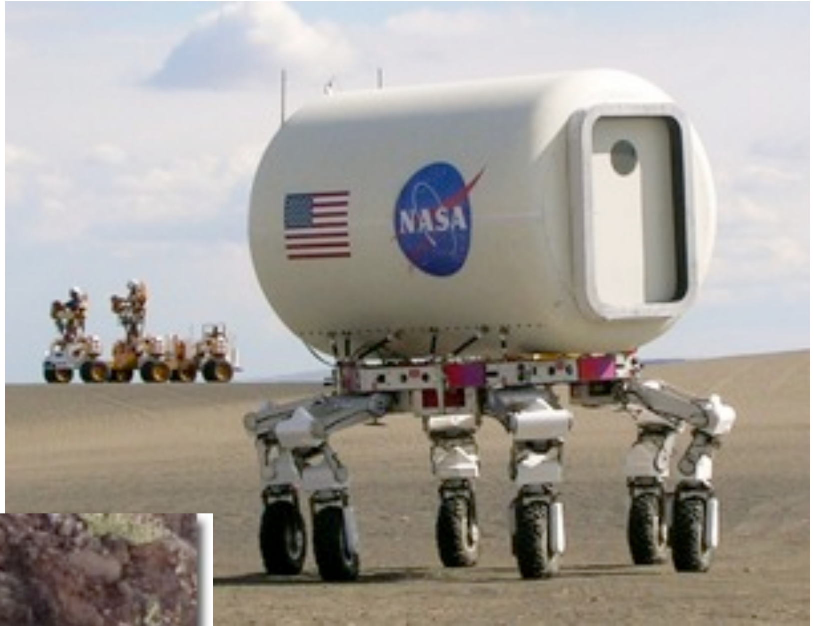
ATHLETE Capabilities



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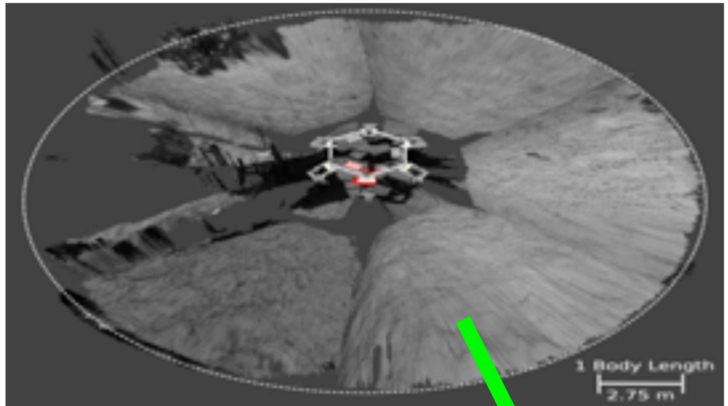
ATHLETE in action

Current Operation

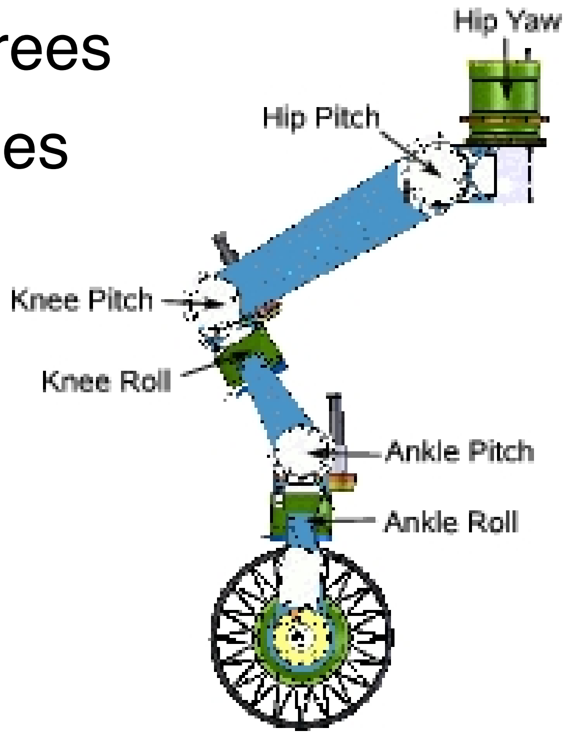
- Remotely operated
- Rolling: ok
- Walking: slow



command center

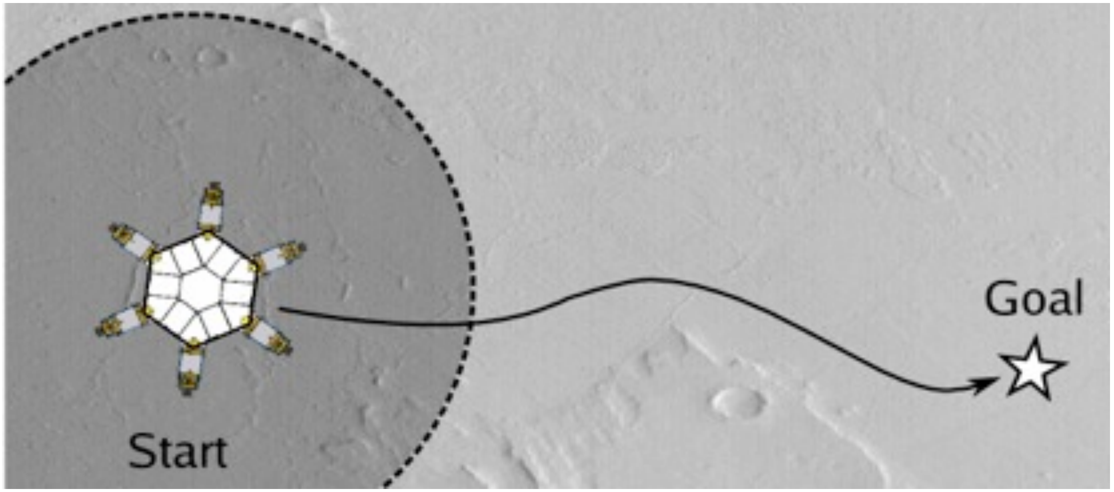
Walking

- Raise foot 10 cm
- Raise foot 40 cm
- Rotate hip 60 degrees
- Pitch knee 40 degrees
- Pitch ankle -40 degrees
- Rotate hip 10 degrees
- Lower foot 40 cm
- Lower foot 10 cm



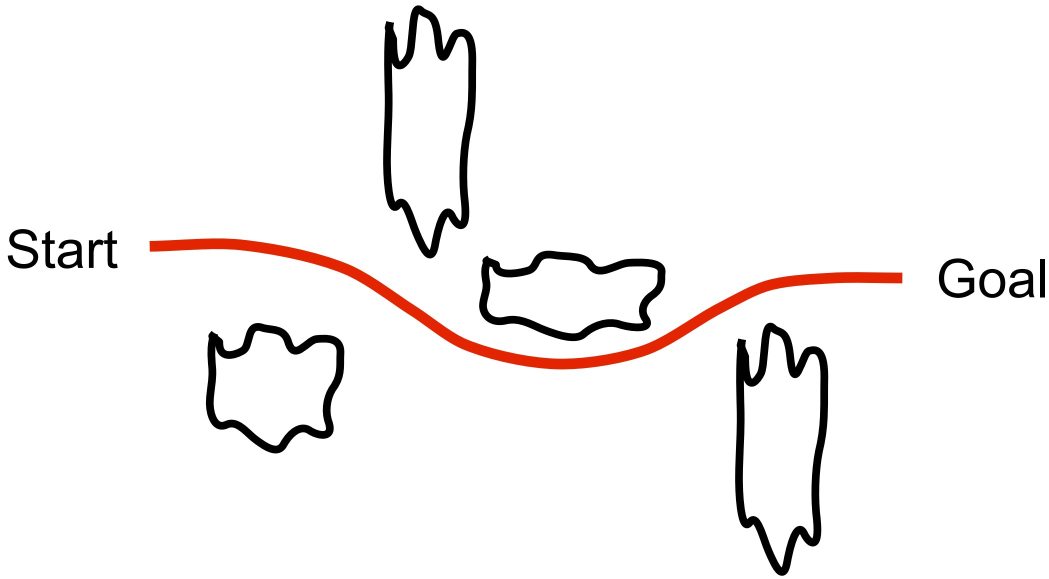
Simple Planning Problem

- Given:
  - simple goal point
  - terrain map with varying resolution
    - detailed ≤ 5 meters
    - satellite > 5 meters
- Find:
  - command sequence
  - prefer rolling to stepping



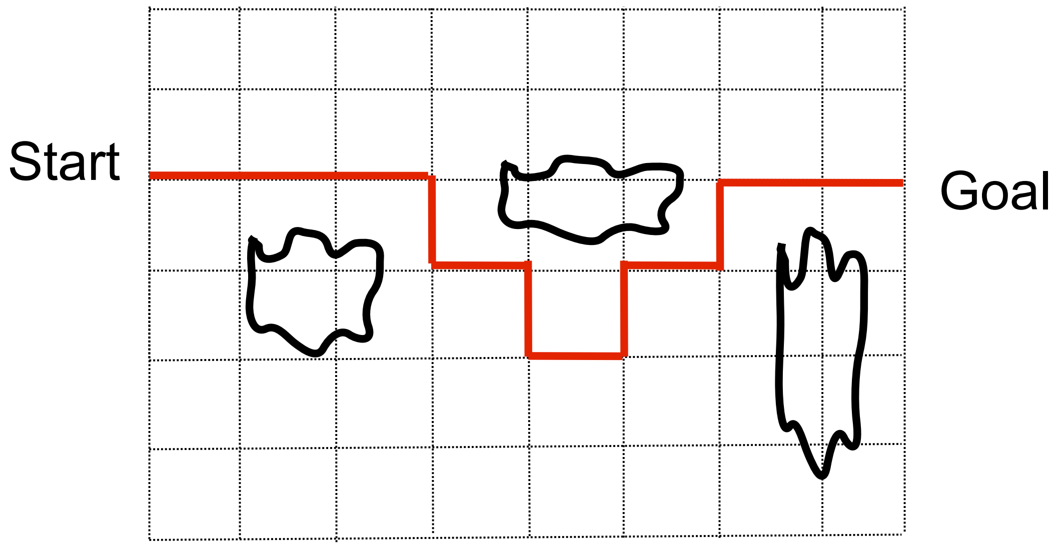
Path Planning

Cartesian Space:



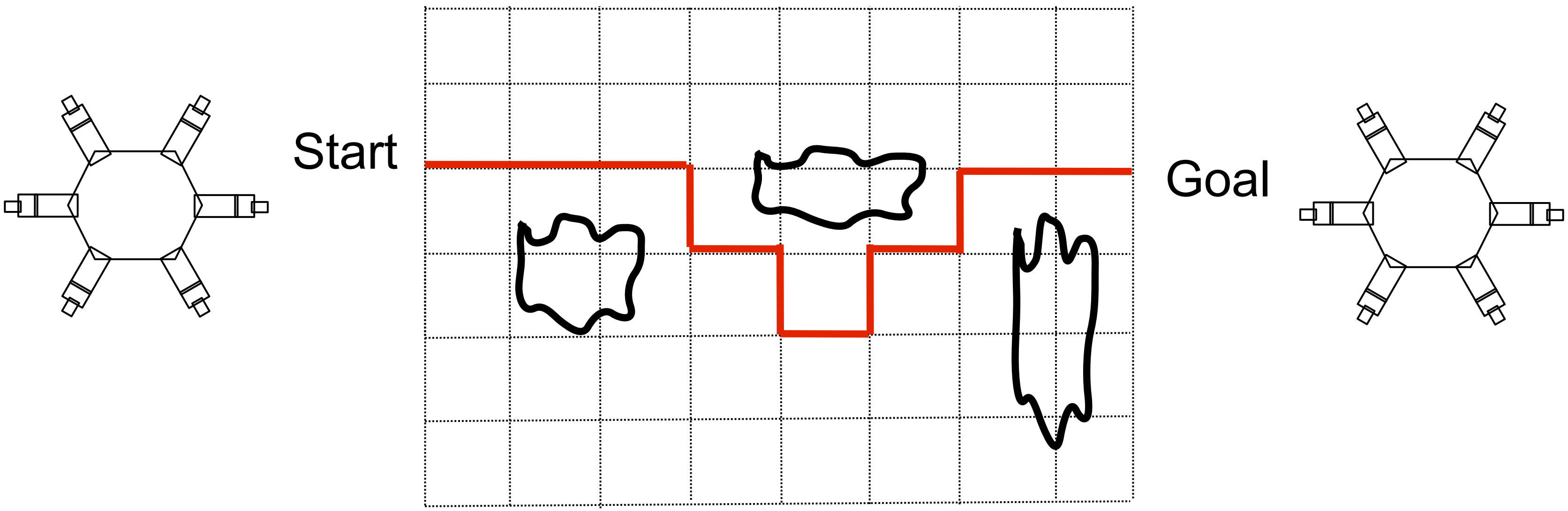
Discretization

Cartesian Space:



Discretization

Cartesian Space:

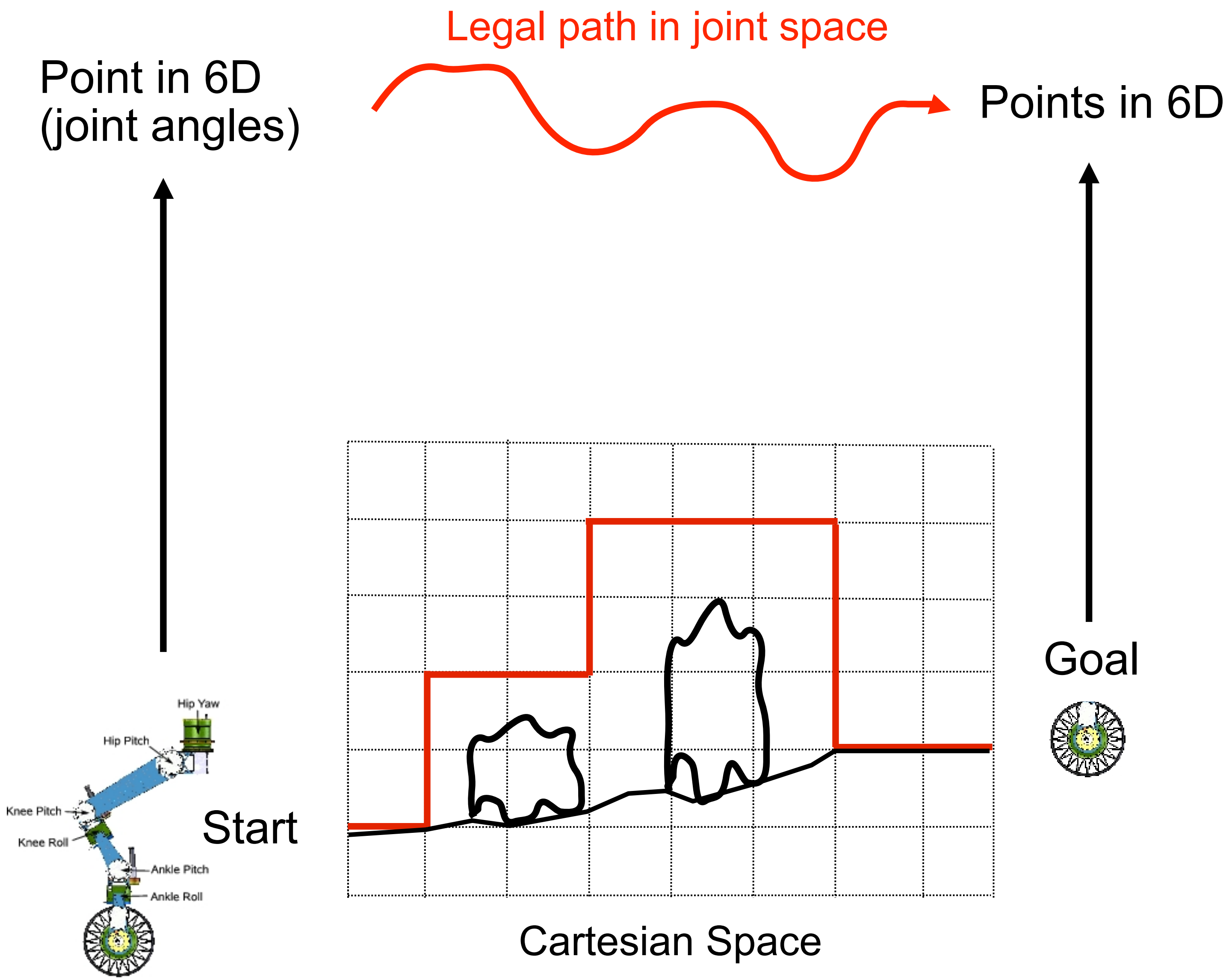


Discretization

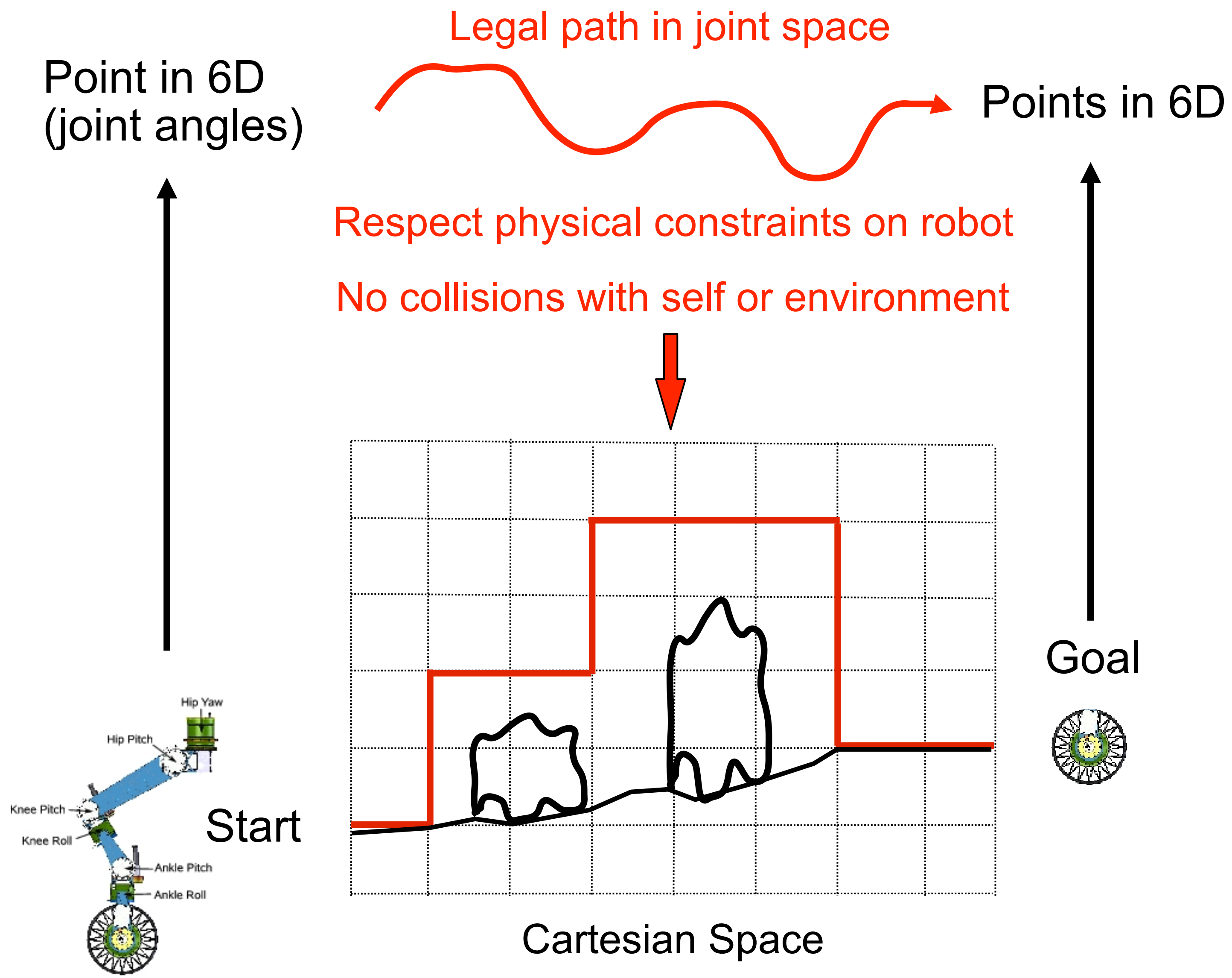
Cartesian Space: ????

- Collisions of the entire leg
- Not every Cartesian path can be followed
- Not a 1-1 mapping

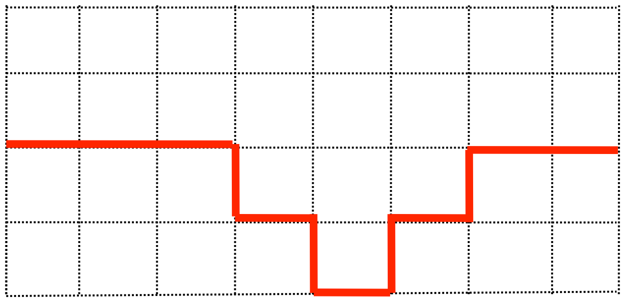
Configuration Space



Configuration Space

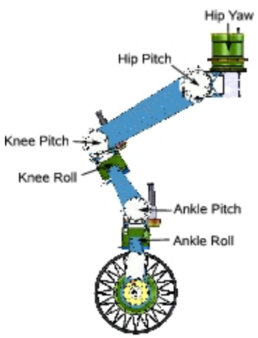


Planning in Configuration Space

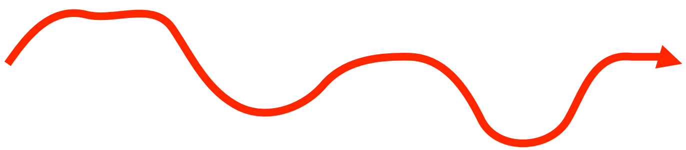


A*

Discretize



Point in 6D
(joint angles)



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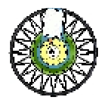
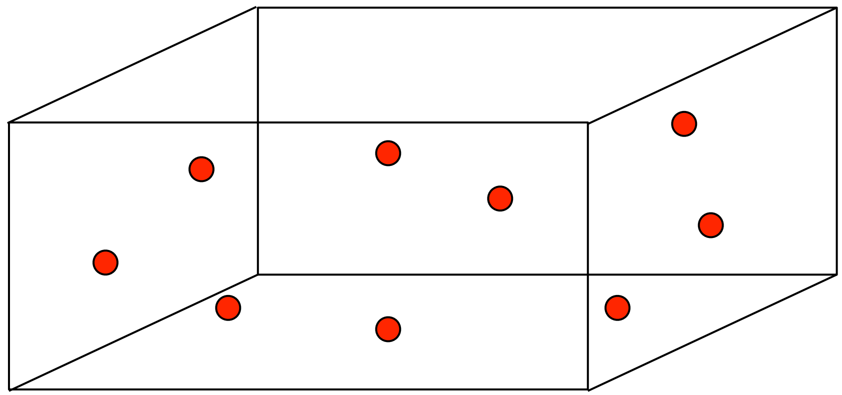
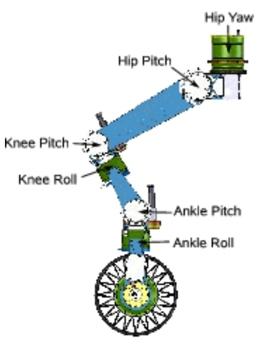


Legal path in joint space

Planning in Configuration Space



Probabilistic Methods



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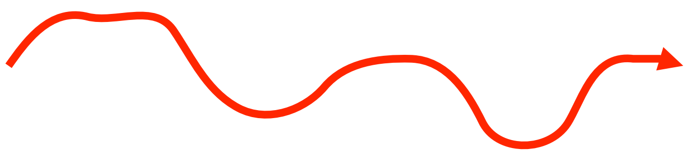
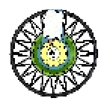


Points in 6D



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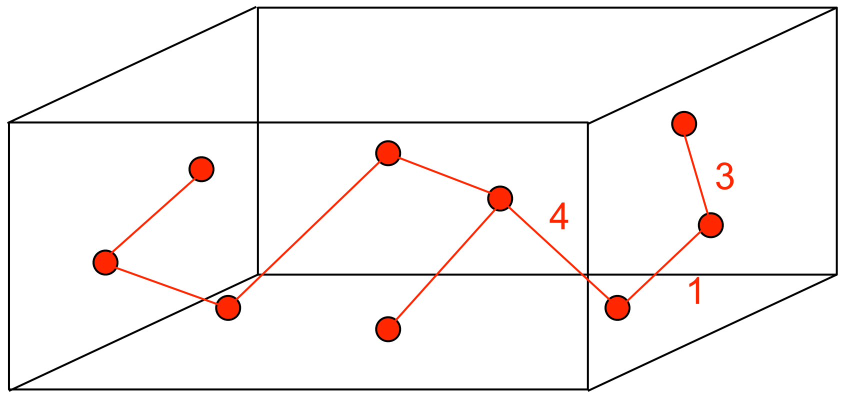
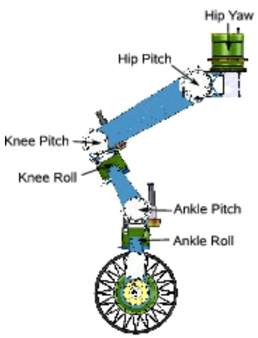
Planning in Configuration Space



PRMs
A*

Probabilistic Methods



Point in 6D
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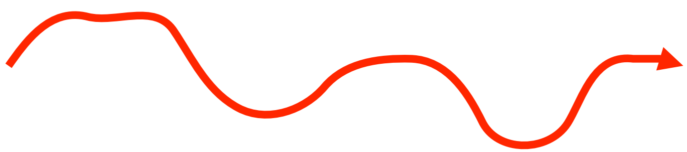
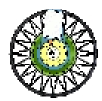
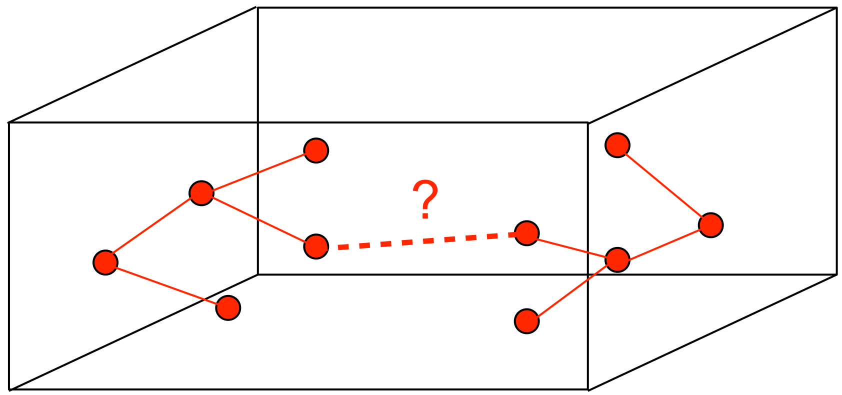


Legal path in joint space

Points in 6D

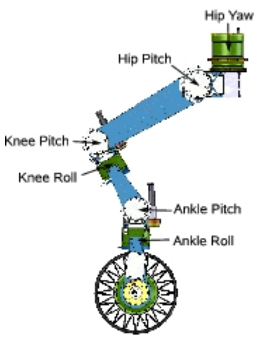


Planning in Configuration Space



Grow trees
(RRT)

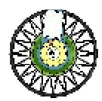
Probabilistic Methods



Point in 6D
(joint angles)

Legal path in joint space

Points in 6D



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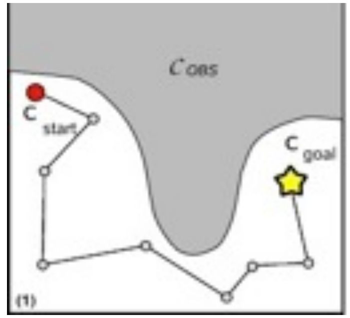
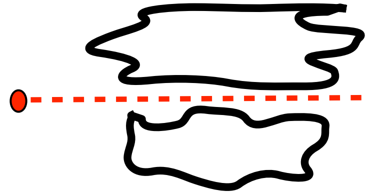
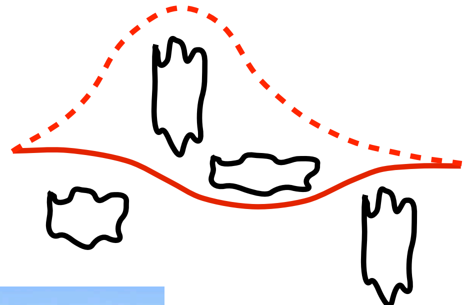
Problems with Prob. Methods

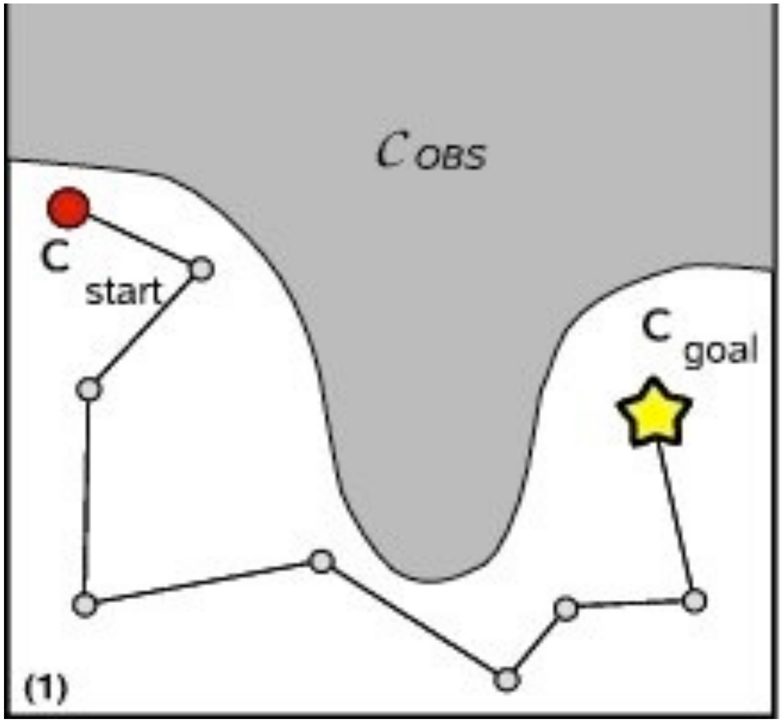
- Optimality
- Awkward paths
- Narrow channels
- Non-repeatability
- Active compliance







Path Smoothing



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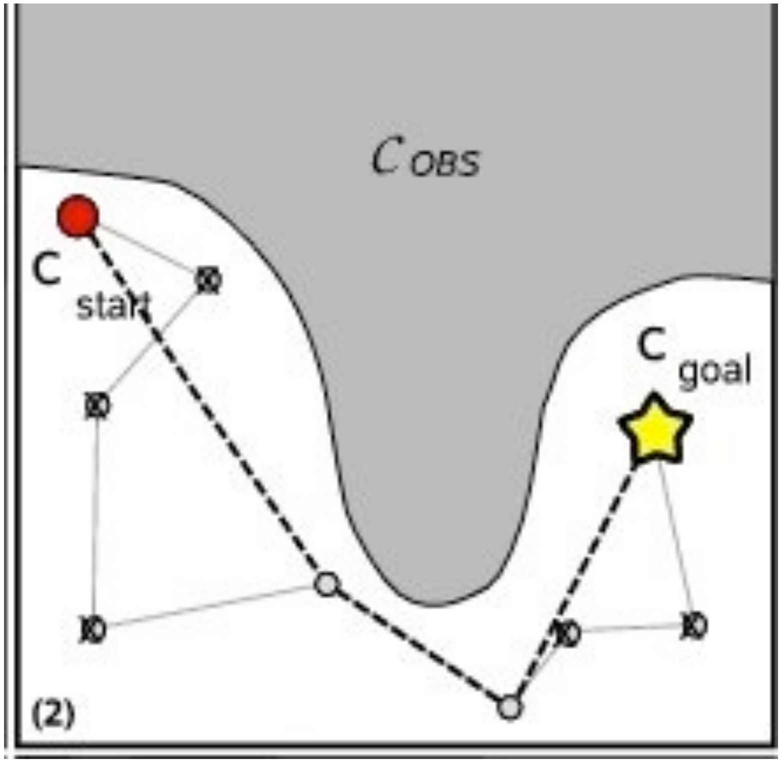

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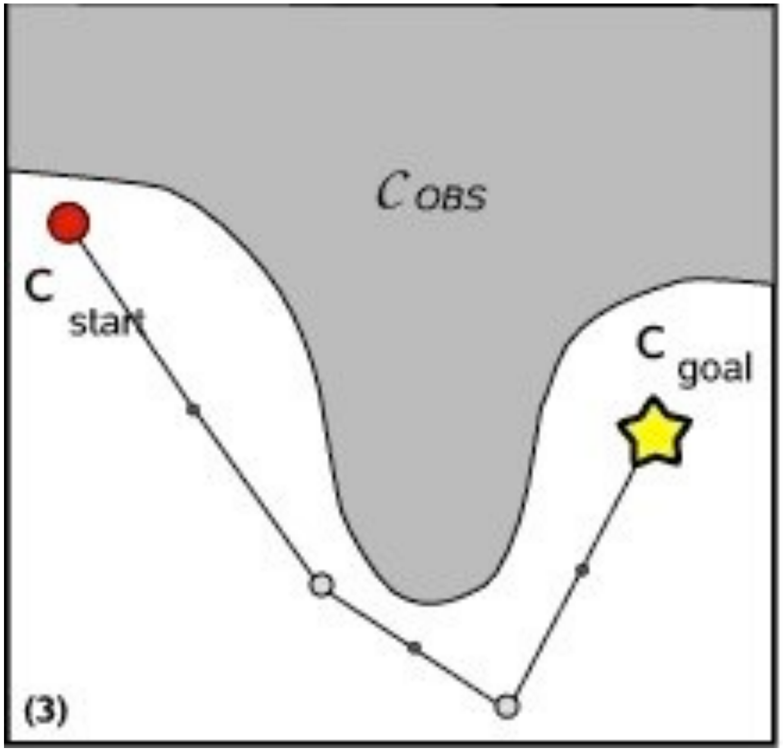

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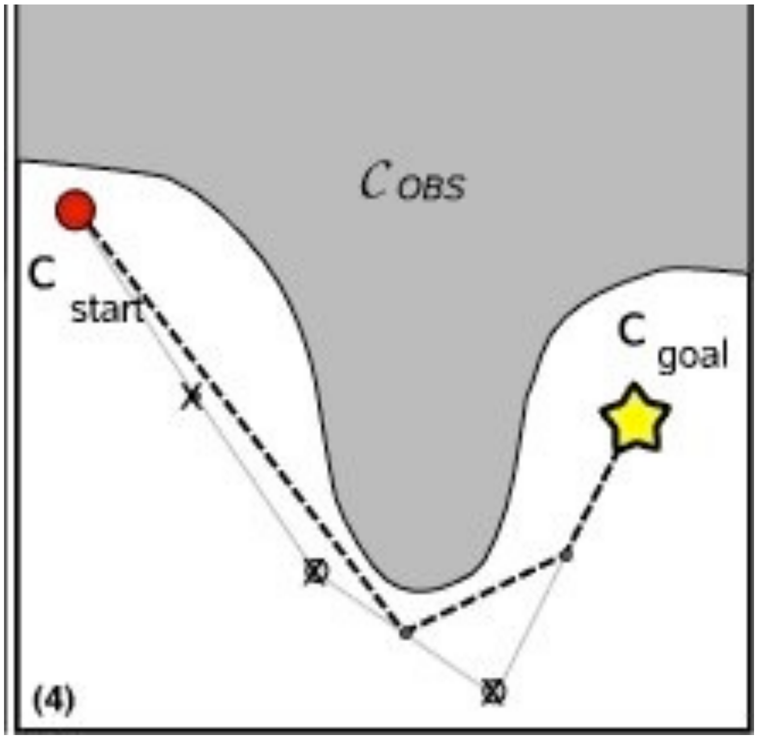
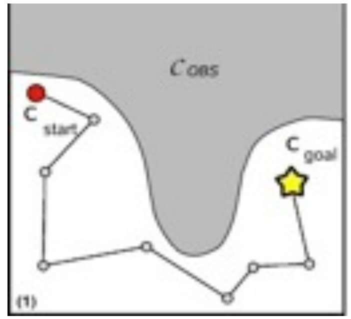
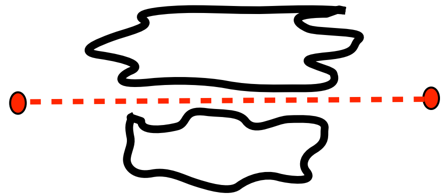


Problems with Prob. Methods

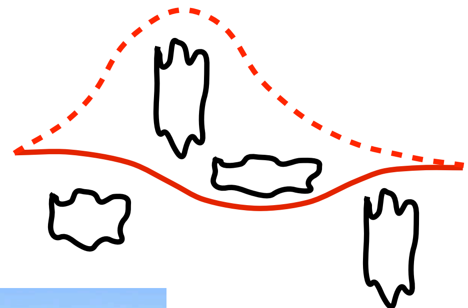
- Optimality
  - enough points, A*, smoothing



- Awkward paths
  - smoothing
- Narrow channels
  - smarter points



- Non-repeatability
  - roadmap retention



- Active compliance
  - sequencing

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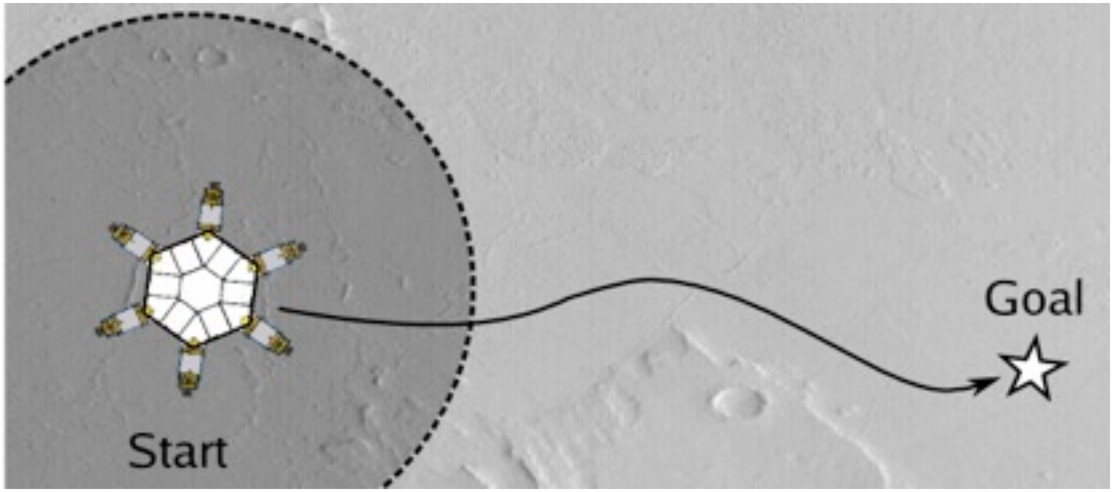
Simple Planning Problem

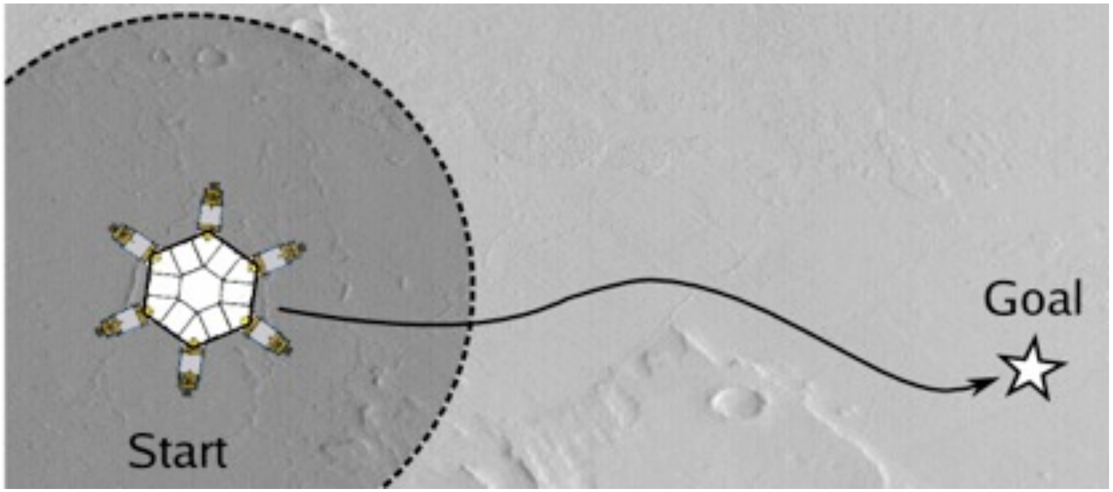
- Given:
  - simple goal point
  - terrain map with varying resolution
    - detailed ≤ 5 meters
    - satellite > 5 meters
- Find:
  - command sequence
  - prefer rolling to stepping



Dumb Idea #1

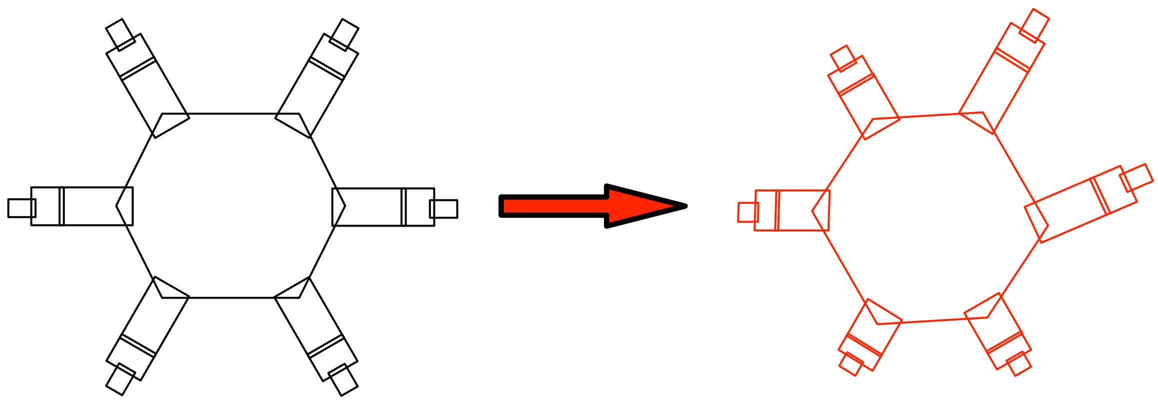
Joint space planning for entire robot

– (all 6 legs + shifting + rolling)



Almost as Dumb Idea #2

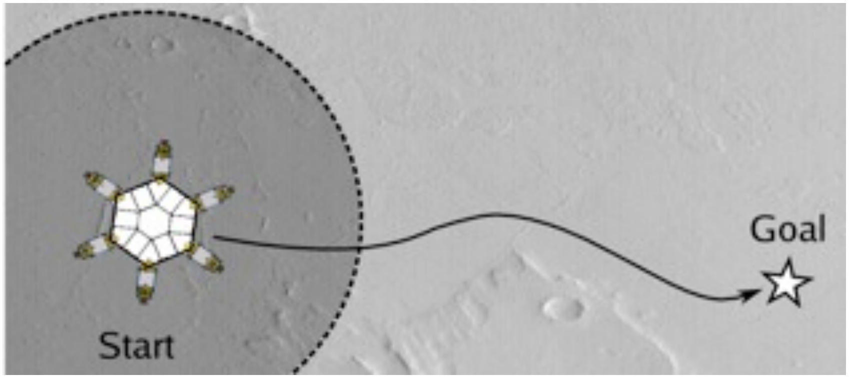
Joint space planning for all six legs



- 16 minutes on flat terrain
- 27 minutes on rough terrain

Decomposition

- Sequence of locations
- Rolling, Rotating, Shifting, Stepping
- Footfalls
- Joint planning for Steps



  - Computational
  - Data quality degrades quickly over distance
  - Uncertainty regarding future configurations

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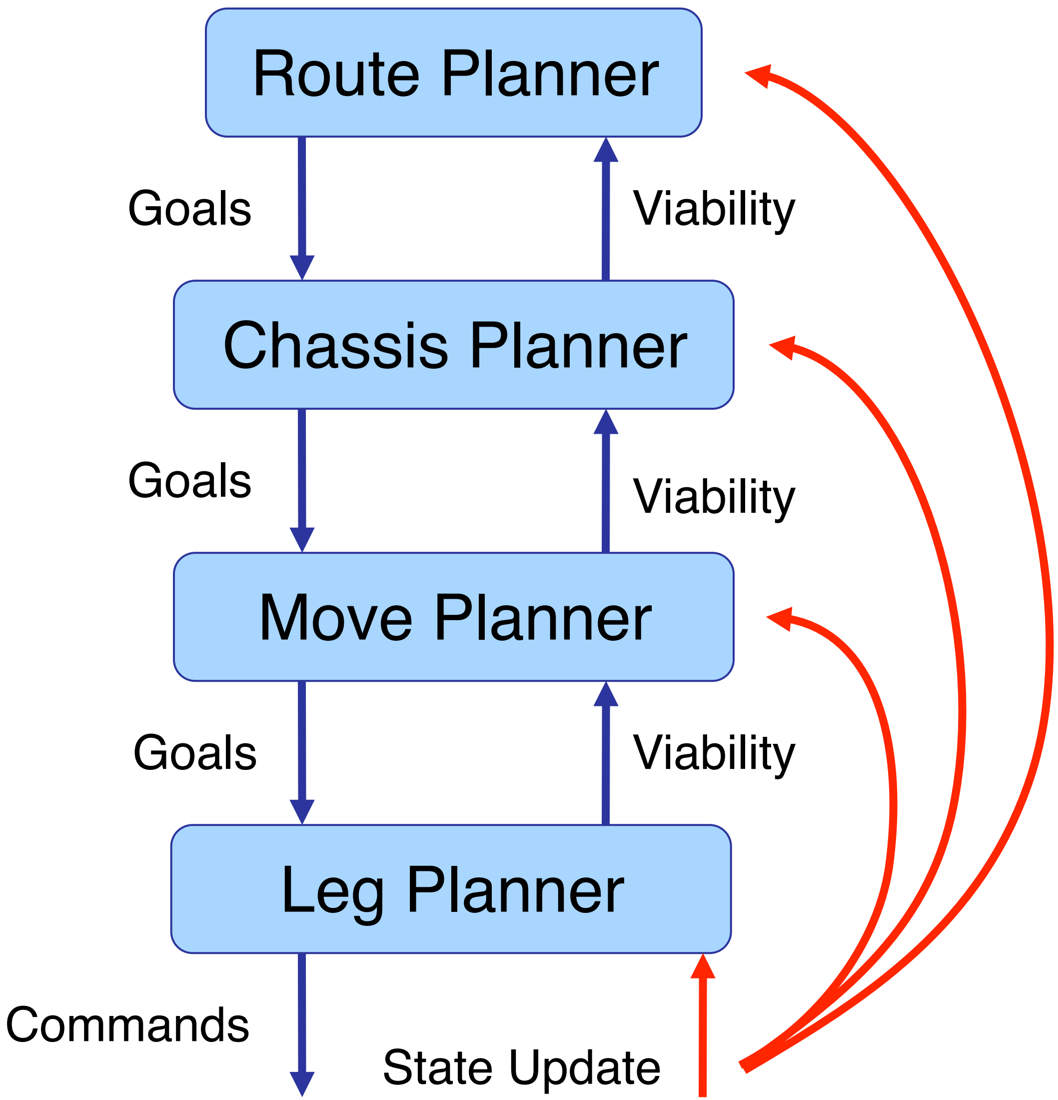
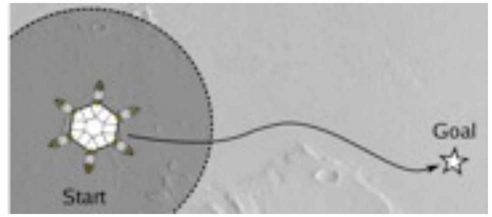
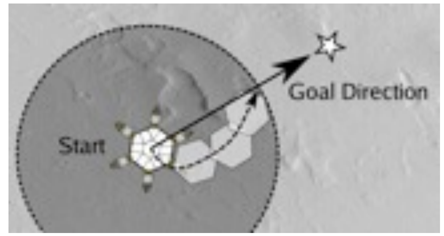
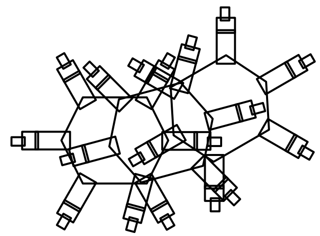
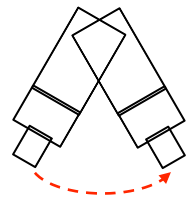
Decomposing the problem





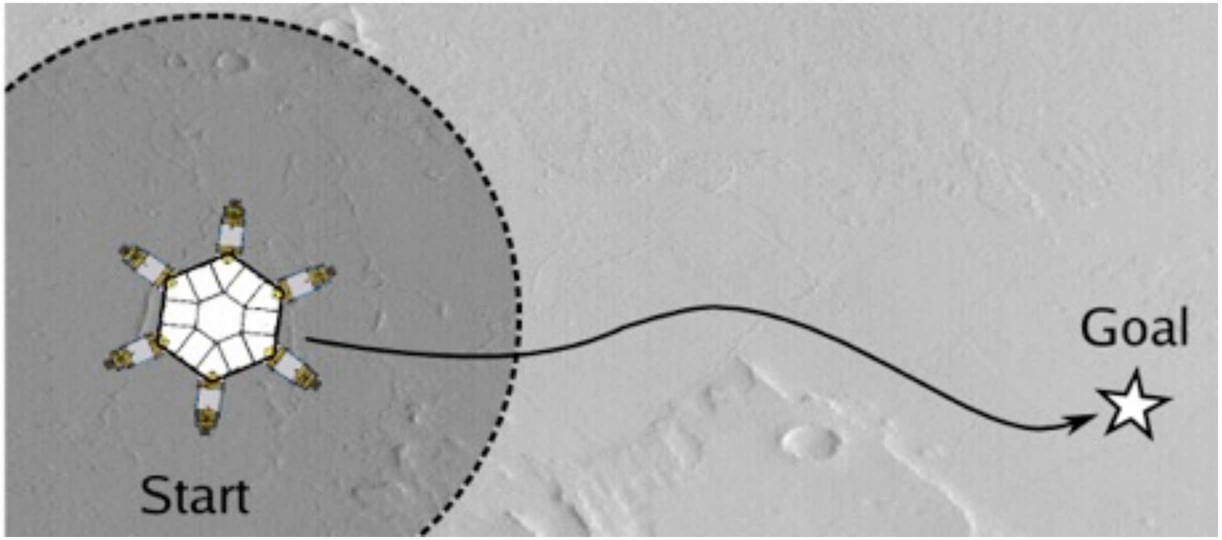






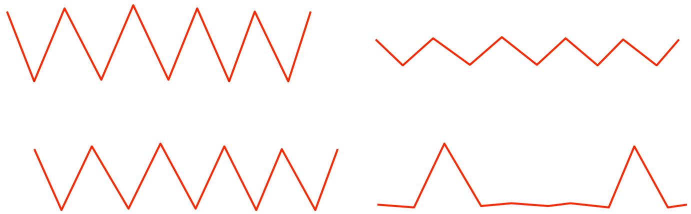
Route Planner

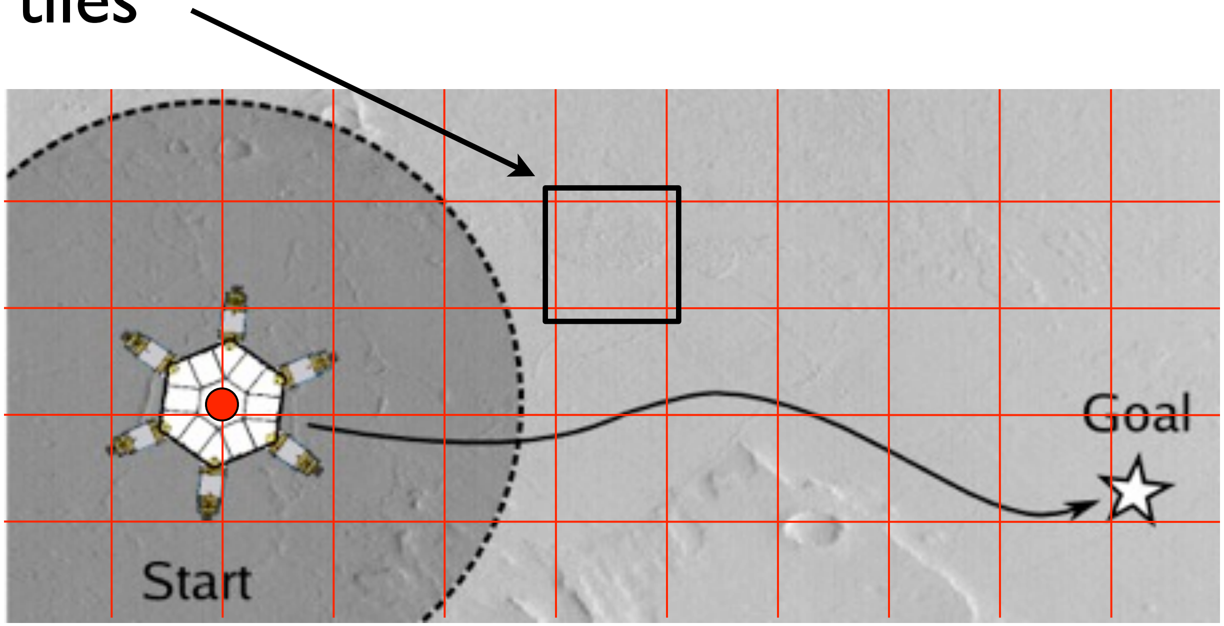
- Given:
  - simple goal point
  - terrain map at varying resolution
- Find: route
- Simplifications:
  - robot is single point
  - terrain roughness as cost



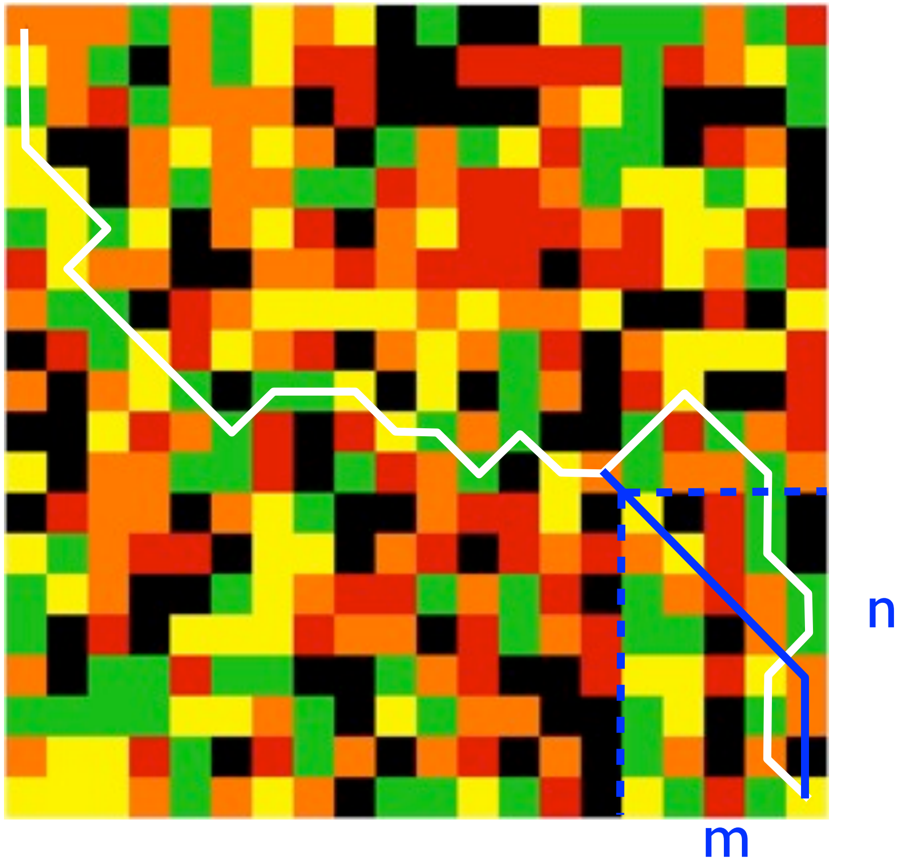
Route Planning Approach

- Regular tessellation
- For each tile
  - steepness = max - min elevation
  - steepness < clearance
  - roughness = std-deviation from mode
  - cost = roughness * steepness
- Overstuffed tiles





Route Planning Search



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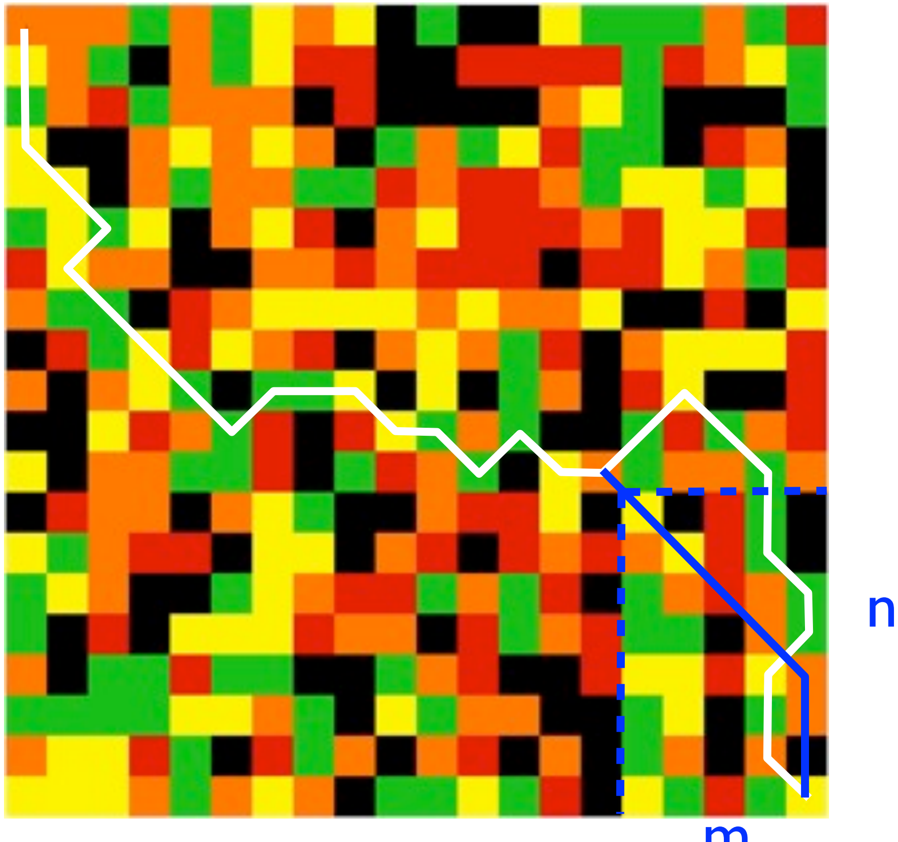
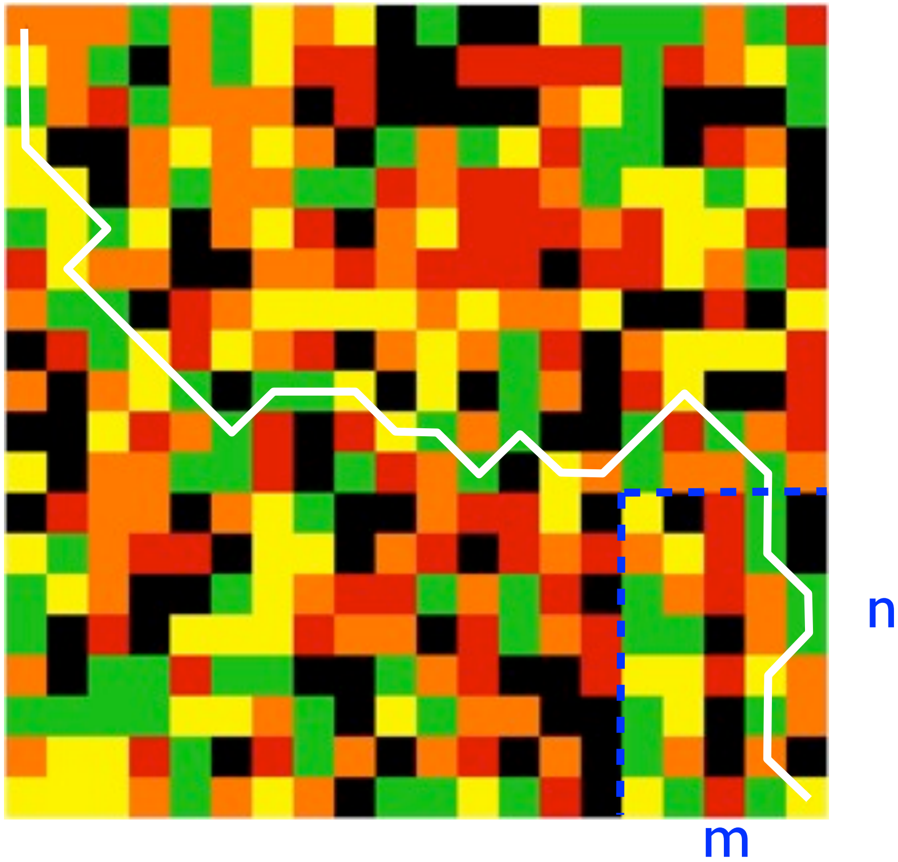
Route Planning Search

- A*
  - D*-Lite
  - distance heuristics
    - n * green



Route Planning Search

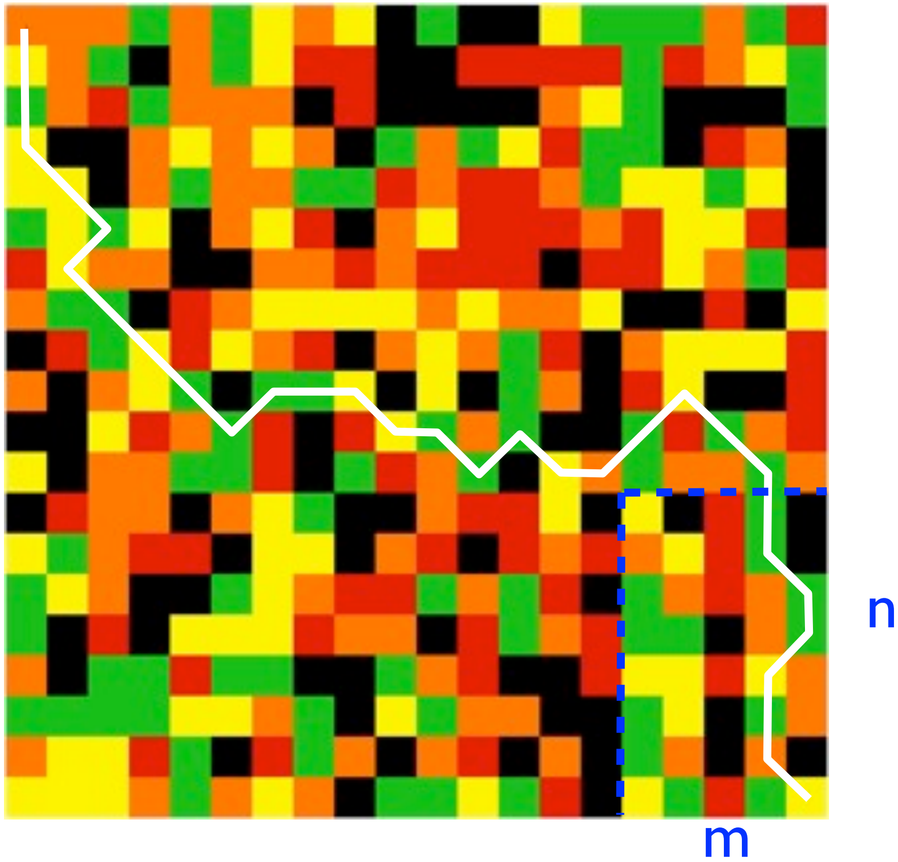
color-cost = [#g, #y, #o, #r, #b]



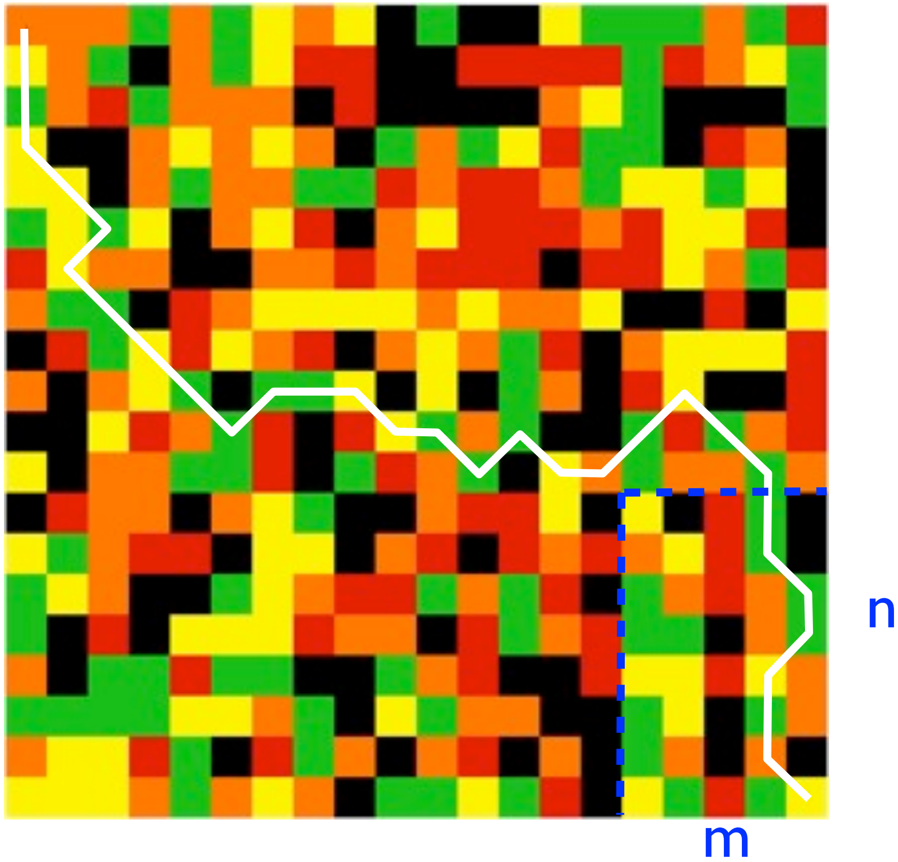
Route Planning Search

- A*
  - D*-Lite
  - distance heuristics
    - n * green
    - m * color-cost + n-m * green

color-cost = [#g, #y, #o, #r, #b]



Route Planning Search



Route Planning Search

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  - D*-Lite
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    - n * green
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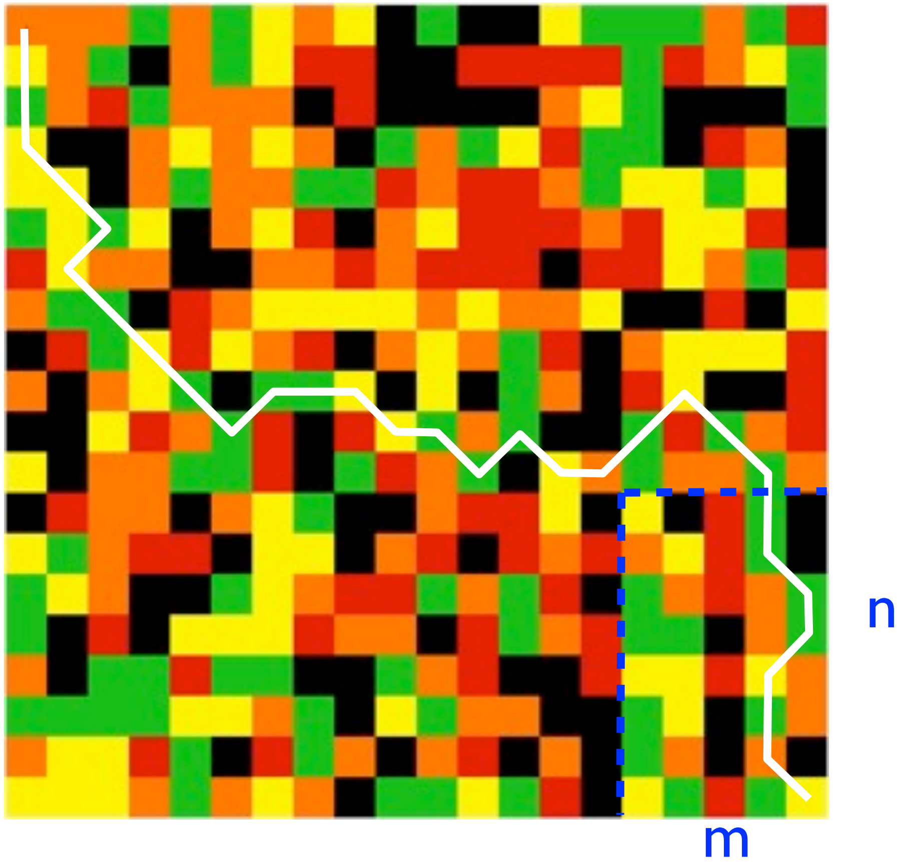
    - n * color-cost



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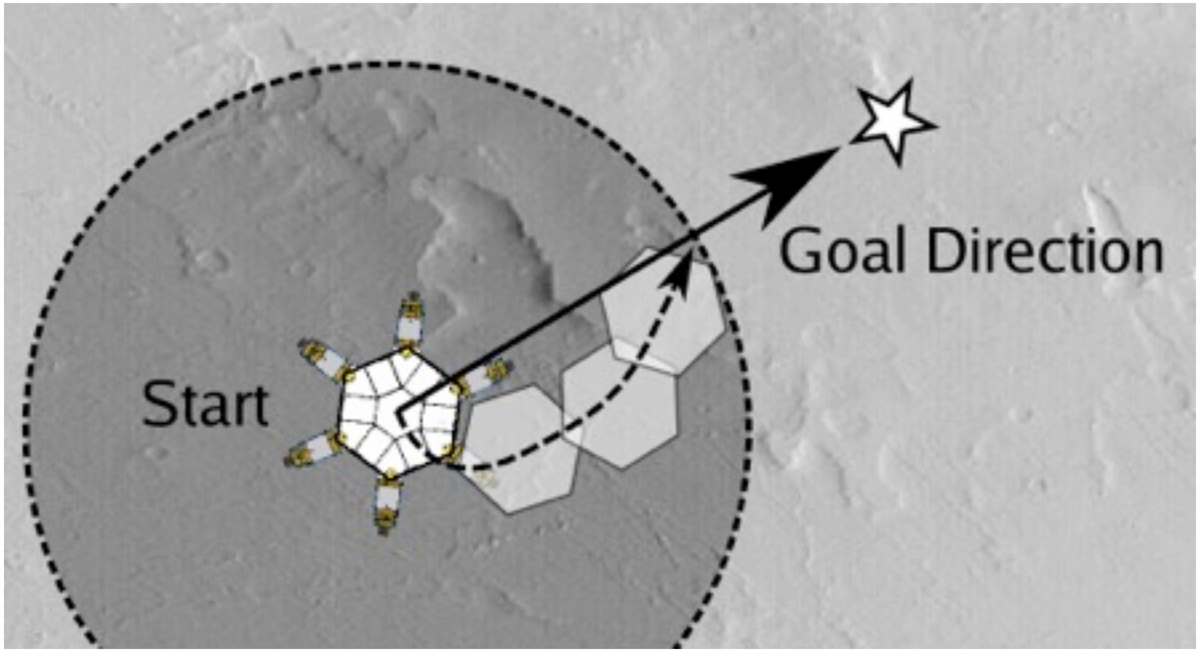
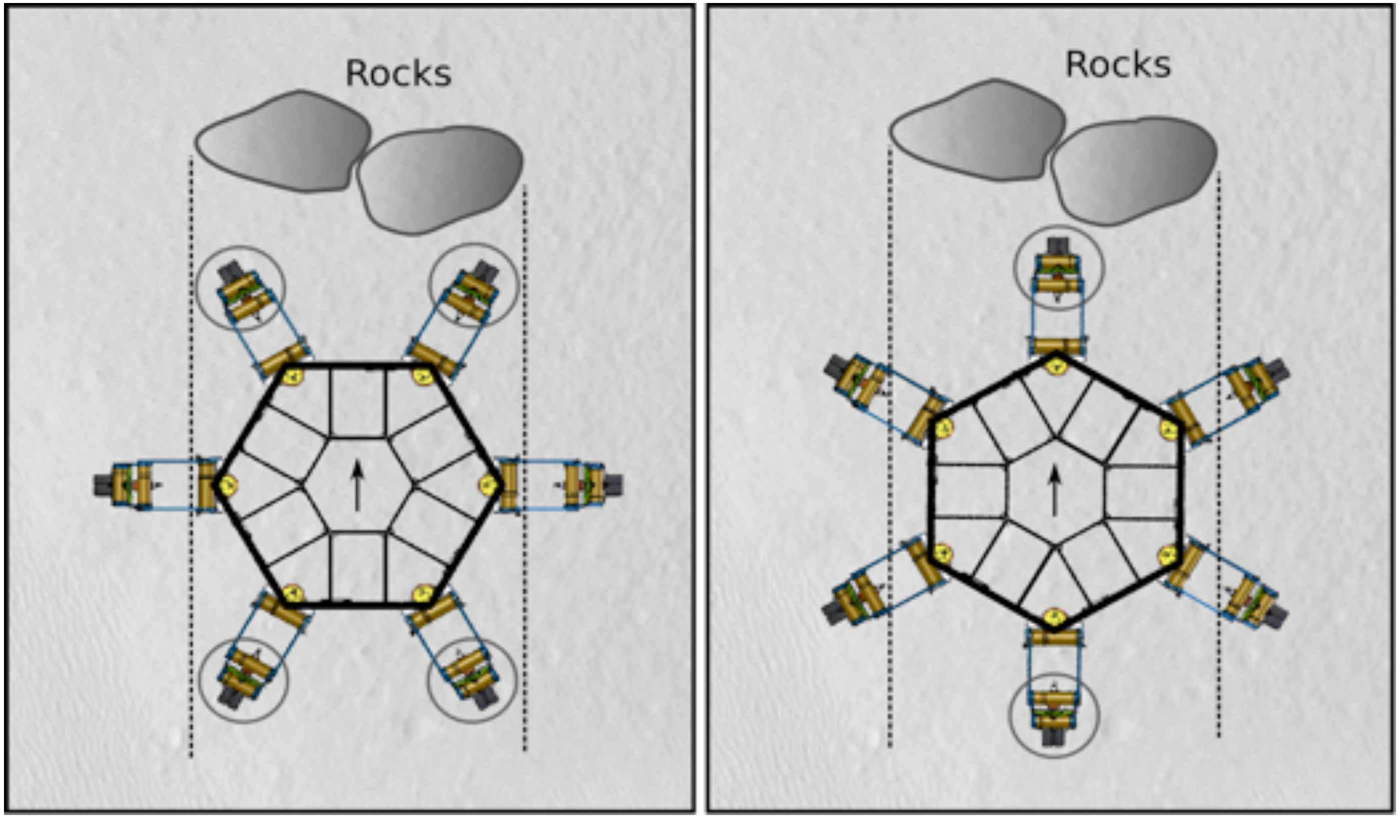
Chassis Planner

- Given:
  - goal direction, horizon, detailed terrain map
- Find:
  - sequence of translations and rotations
  - minimize stepping
- Simplification:
  - fixed leg pose



Chassis Planner



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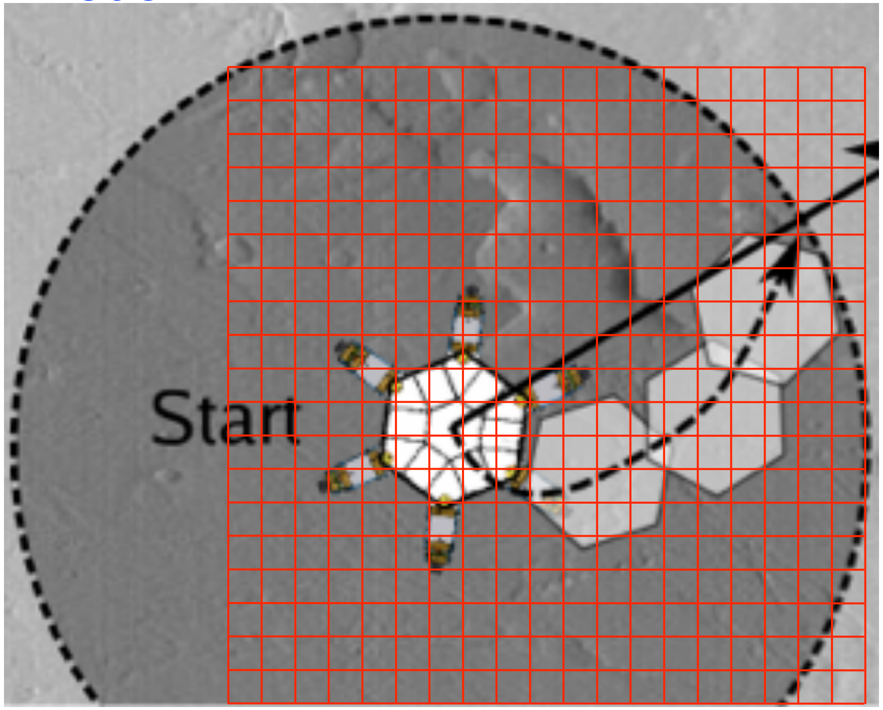
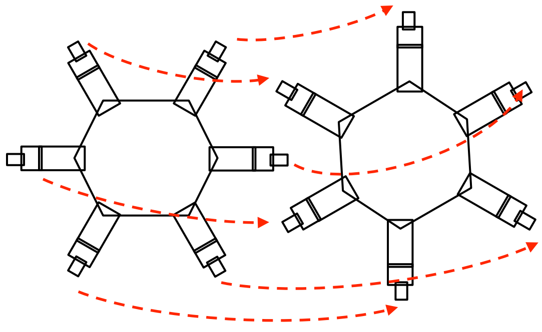
Chassis Planner Approach

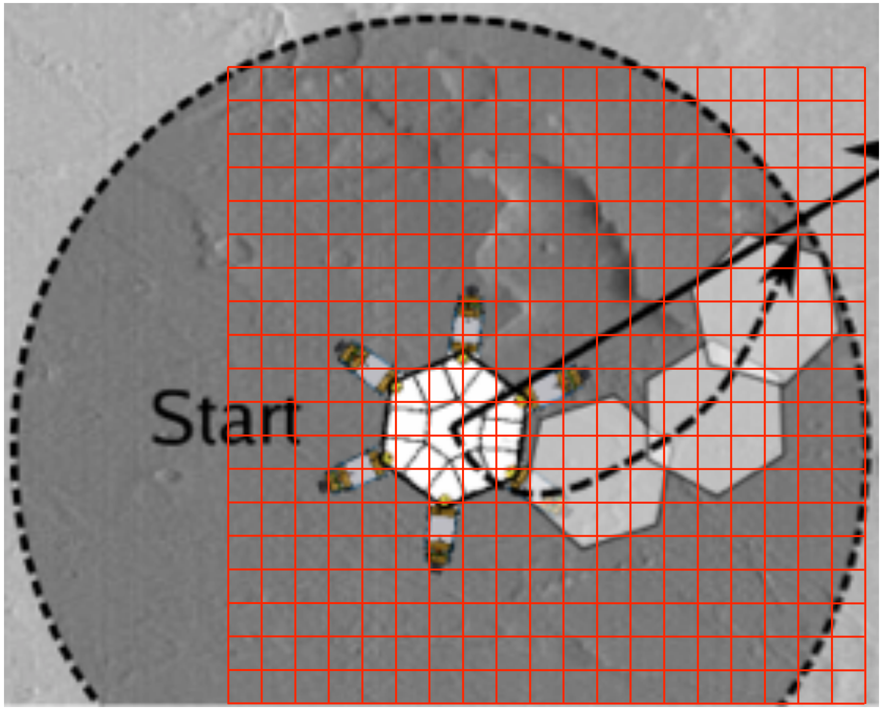
- Fine tessellation of horizon
- For each tile
  - steepness = max - min elevation
  - steepness < clearance (within entire chassis)
  - roughness = std-deviation from mode
  - cost = roughness*steepness
- Overstuffed tiles



Chassis Planner Approach

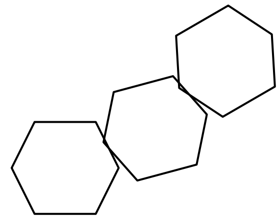
- For successive chassis positions, cost is:
  - sum over leg paths of tile transition costs
- Additional penalties when
  - adjacent legs have significant elevation change at same time





Move Planner

- Given: fixed path for chassis
- Find: sequence of moves
  - Roll
  - Shift chassis
  - Step
- Simplification: delay collision checking



drive 090,1m
rotate -20
roll-wheel 2, 20cm
raise-leg 1
drive 070,1m
lower-leg 1
step-leg 3, loc
…

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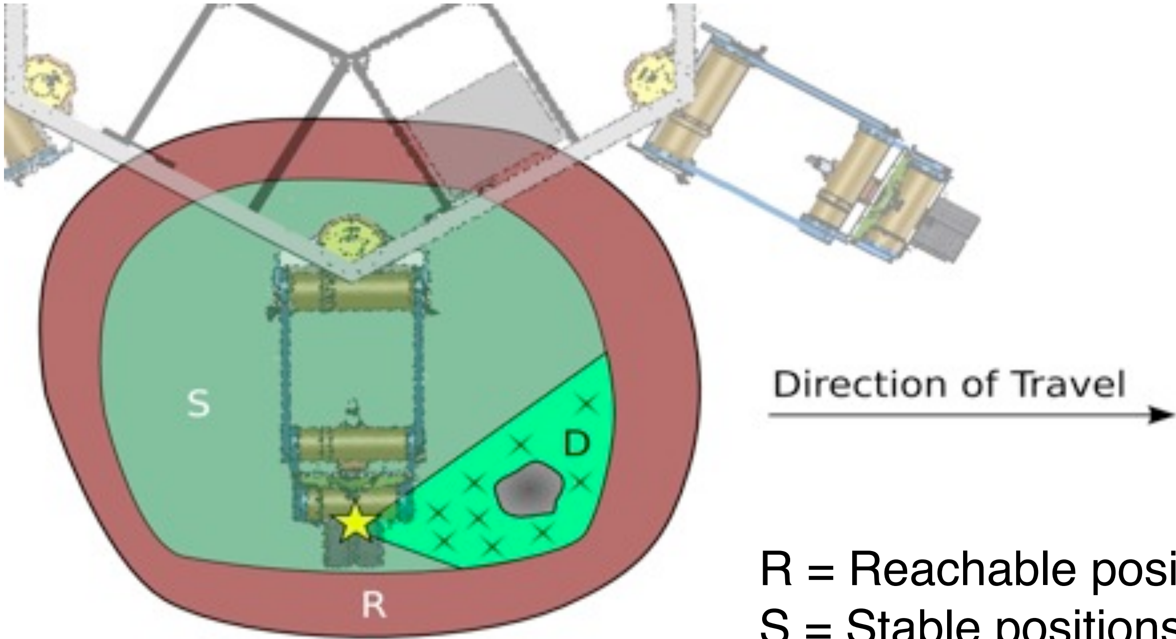
Finding the best move

- Using depth-first search
  1. Roll if possible in the direction dictated by the chassis plan
  2. If lifting a leg will allow further rolling, prefer it
  3. If rotation will allow further rolling, prefer it
  4. For each leg and the chassis:
     - compute the max progress that the leg/chassis can be advanced in the direction of the chassis plan
     - order the leg/chassis moves according to progress along the chassis plan

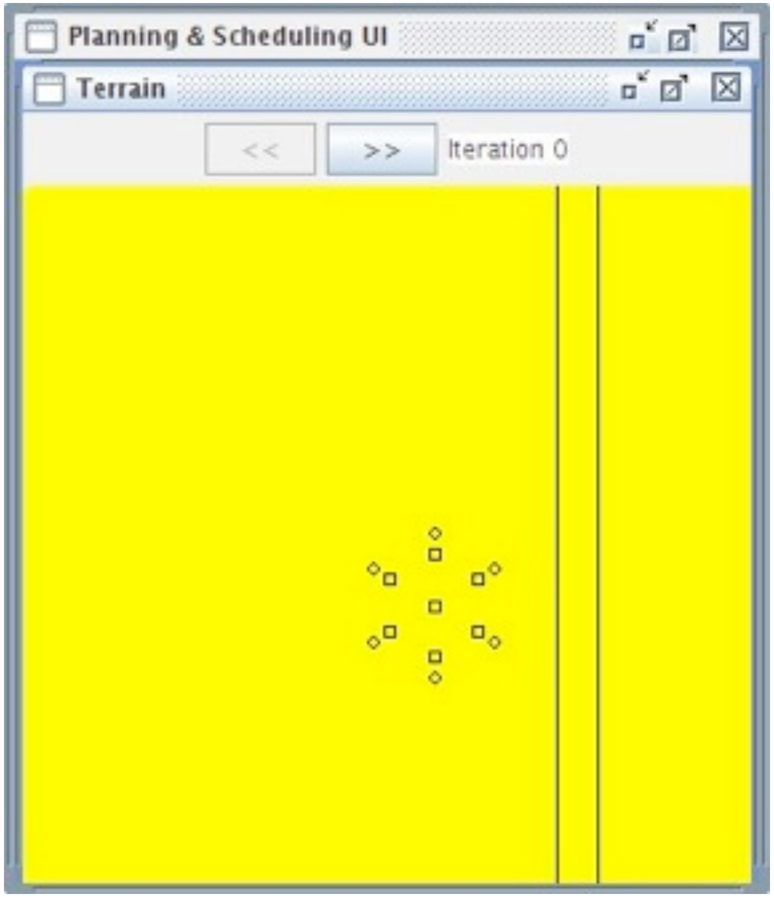
Steps Considered



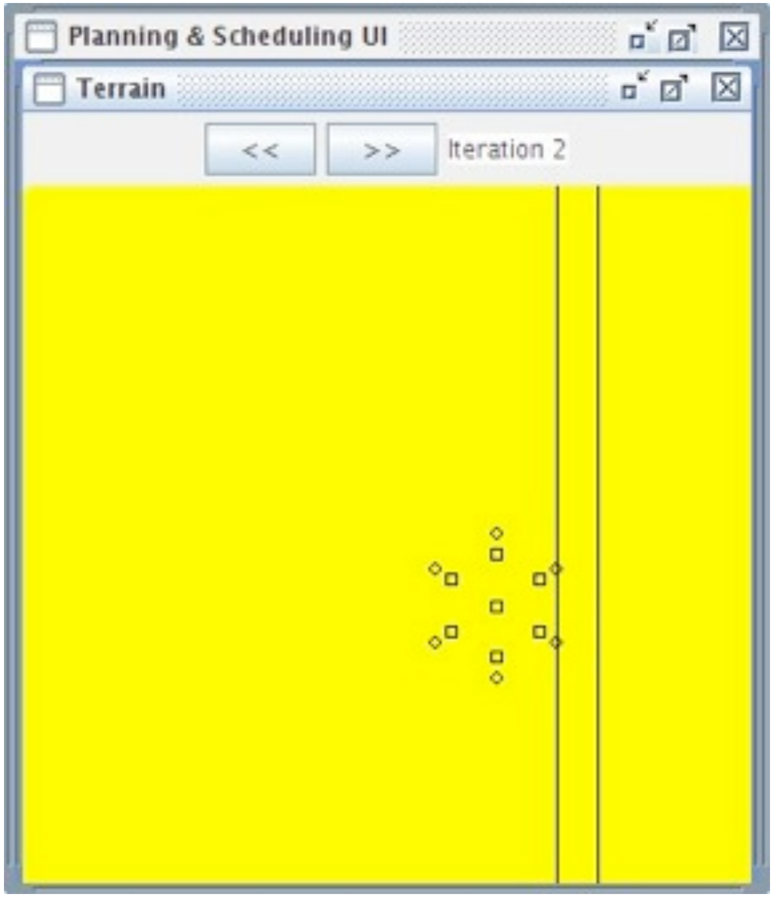
R = Reachable positions
S = Stable positions
D = Desired positions

Reachable and stable regions are computed quickly by the Configuration Space routines

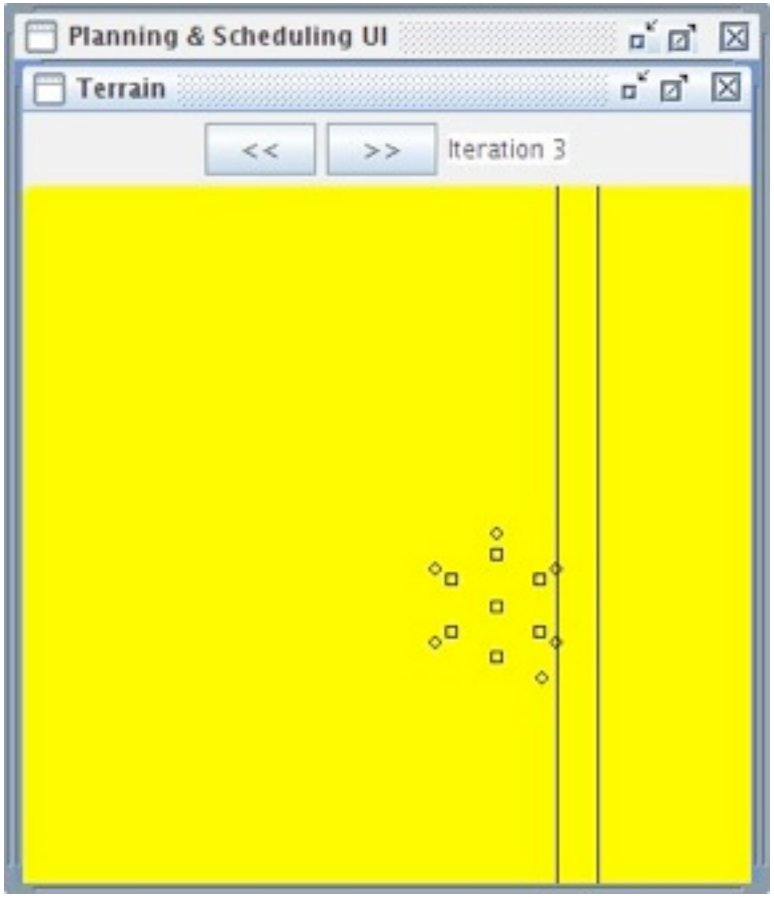
Move Planner



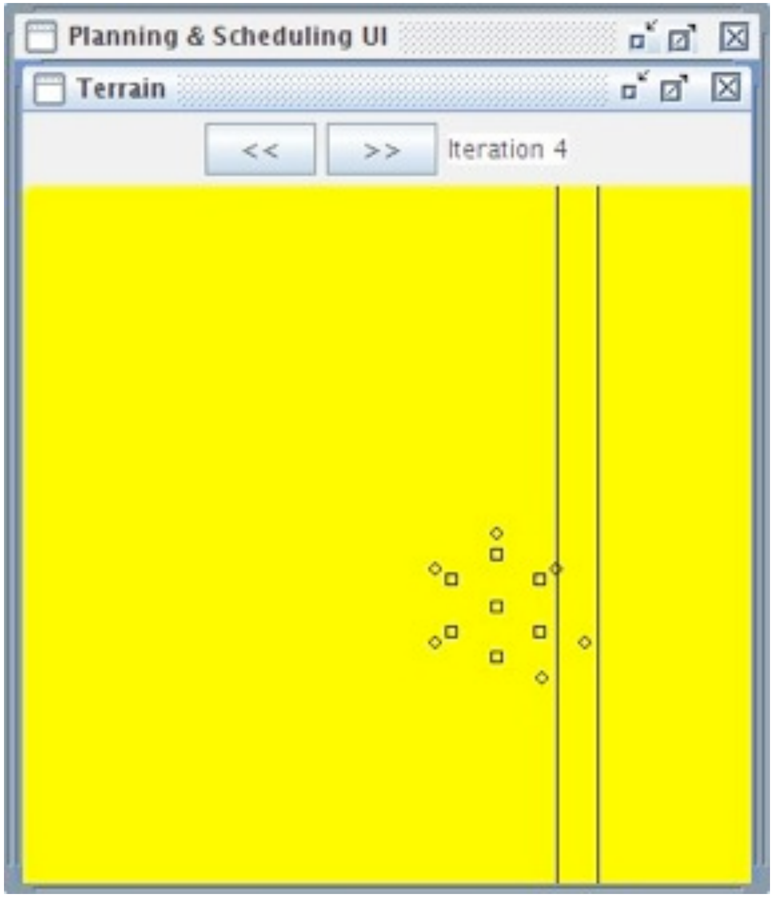
Move Planner



Move Planner



Move Planner



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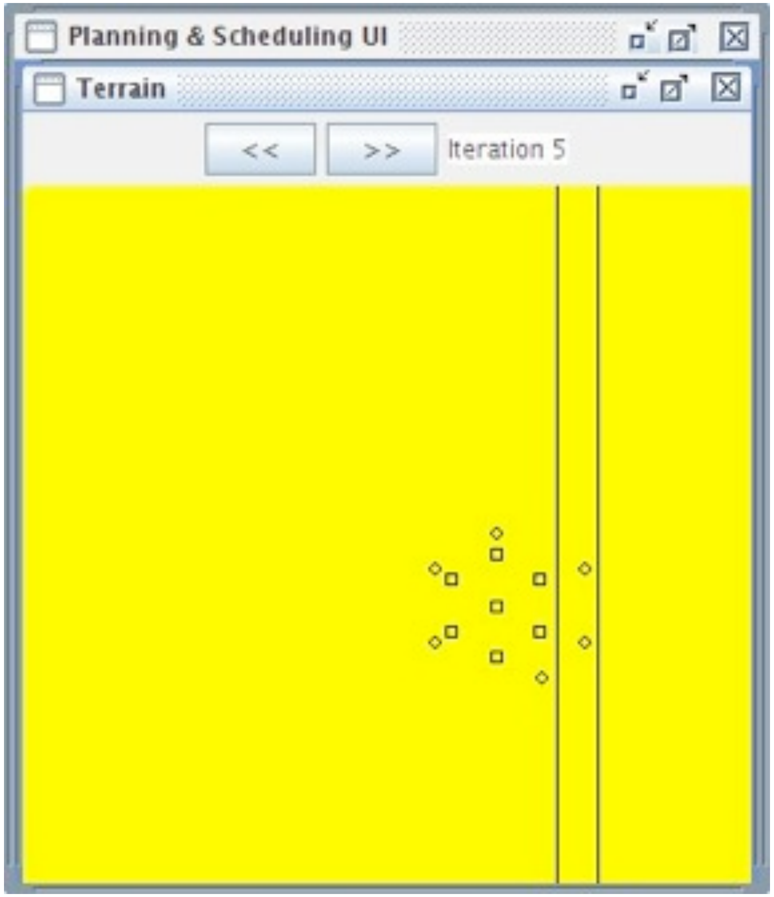
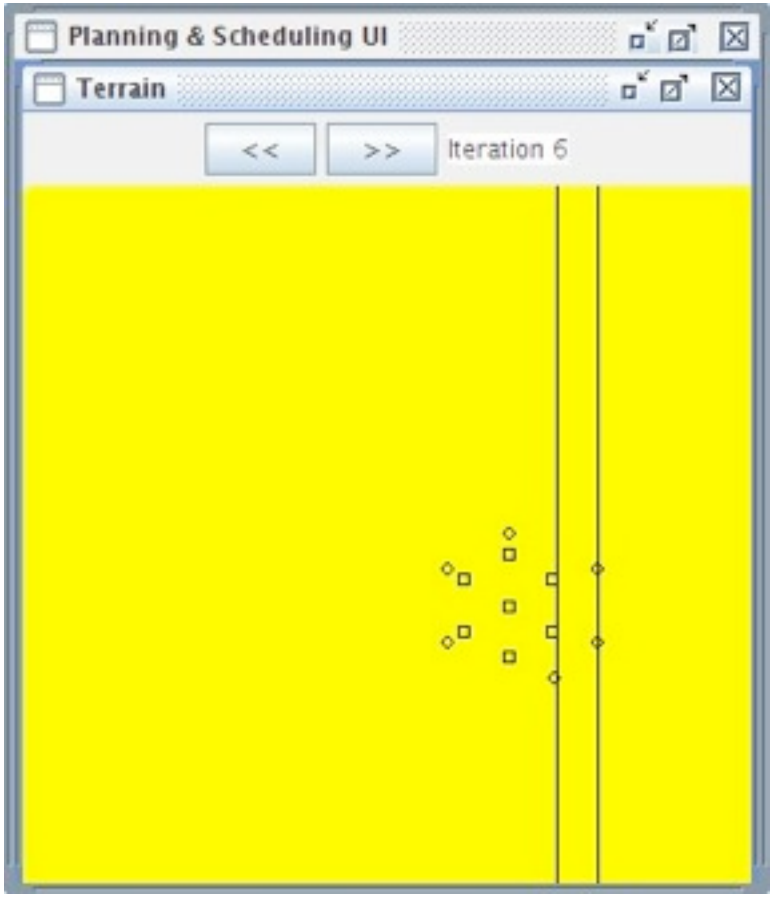
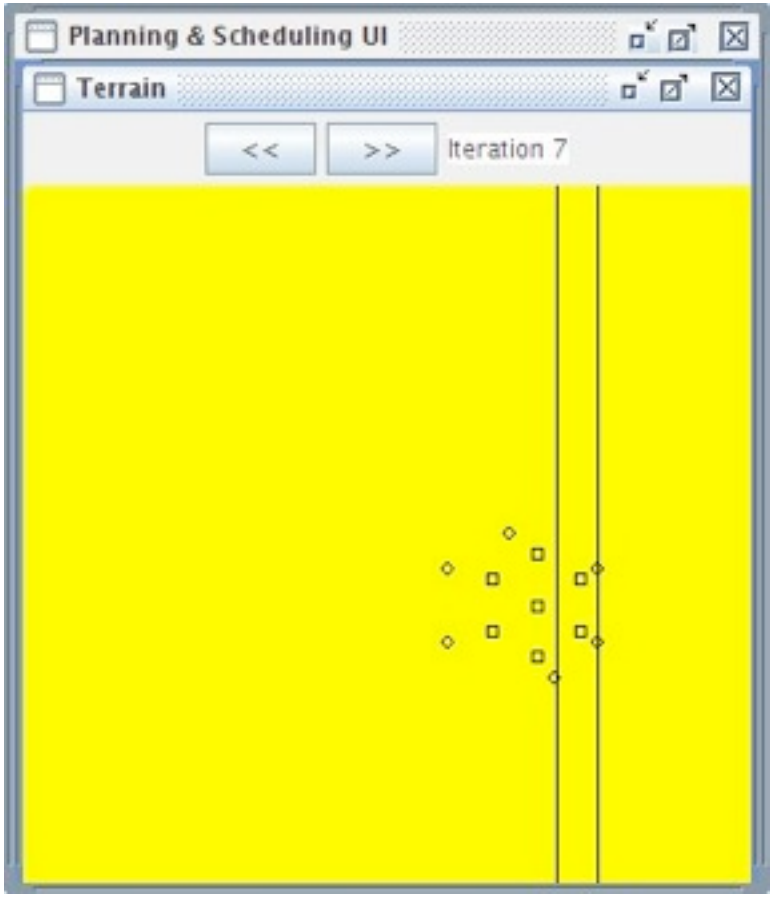
Move Planner



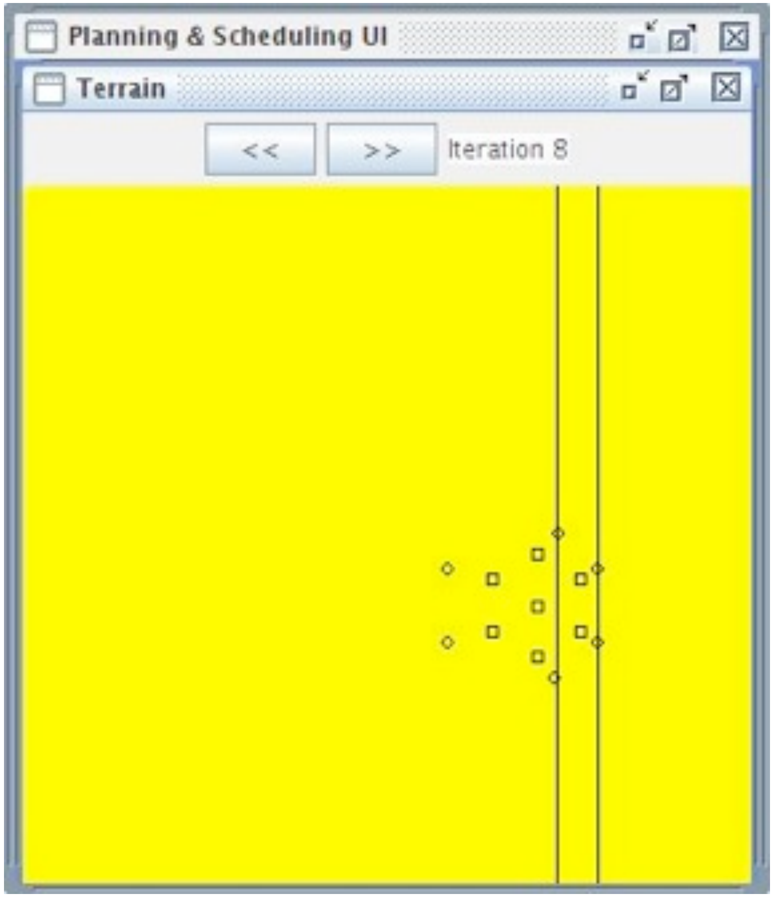
Move Planner



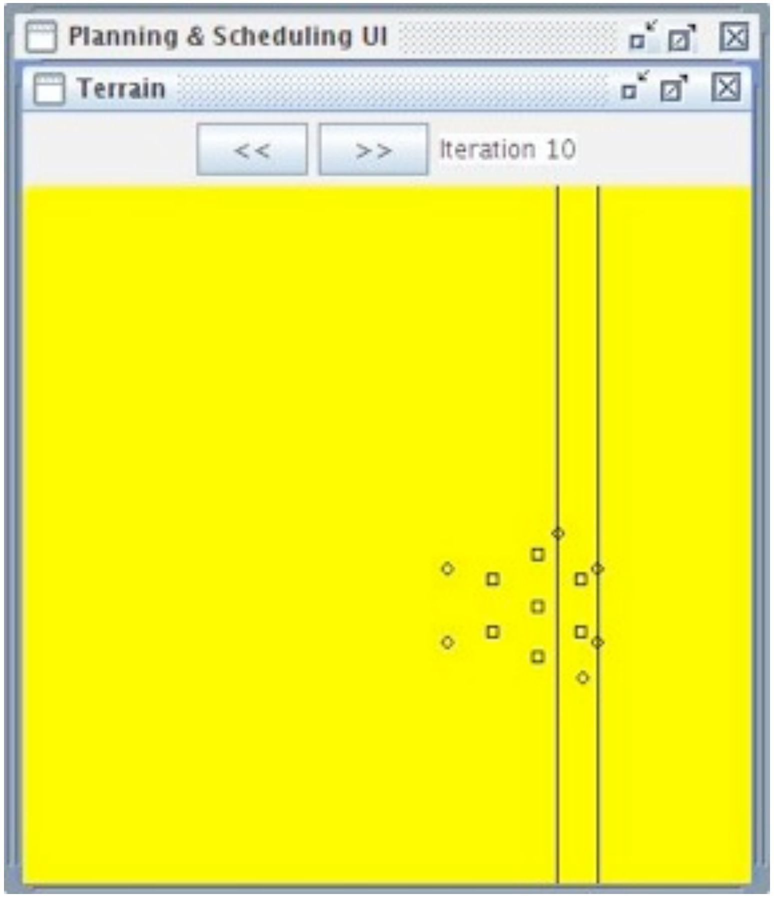
Move Planner



Move Planner

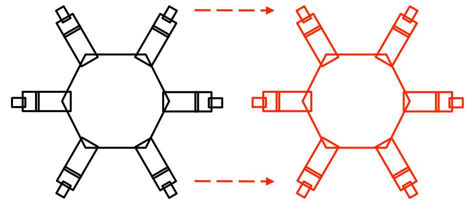


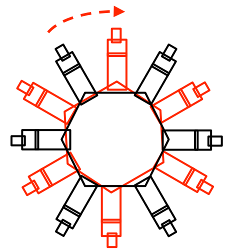
Move Planner

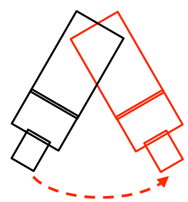


Leg Planner

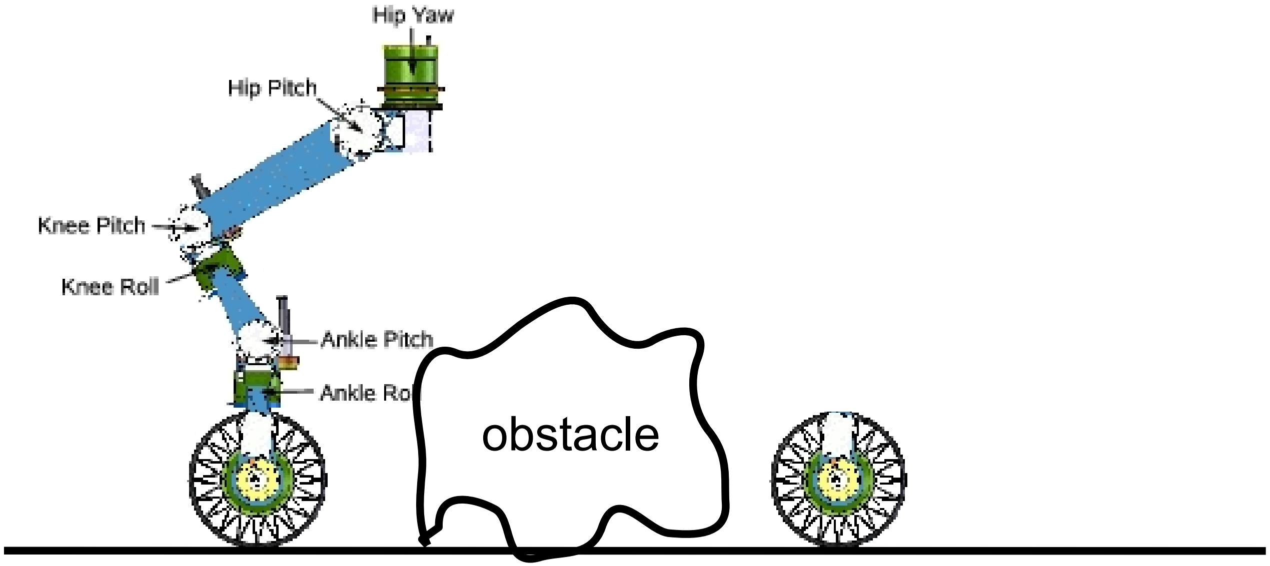
- Given: specific move
- Find: path in joint space
- No collisions
- Respect angle and torque limits
- Simplification: done in isolation



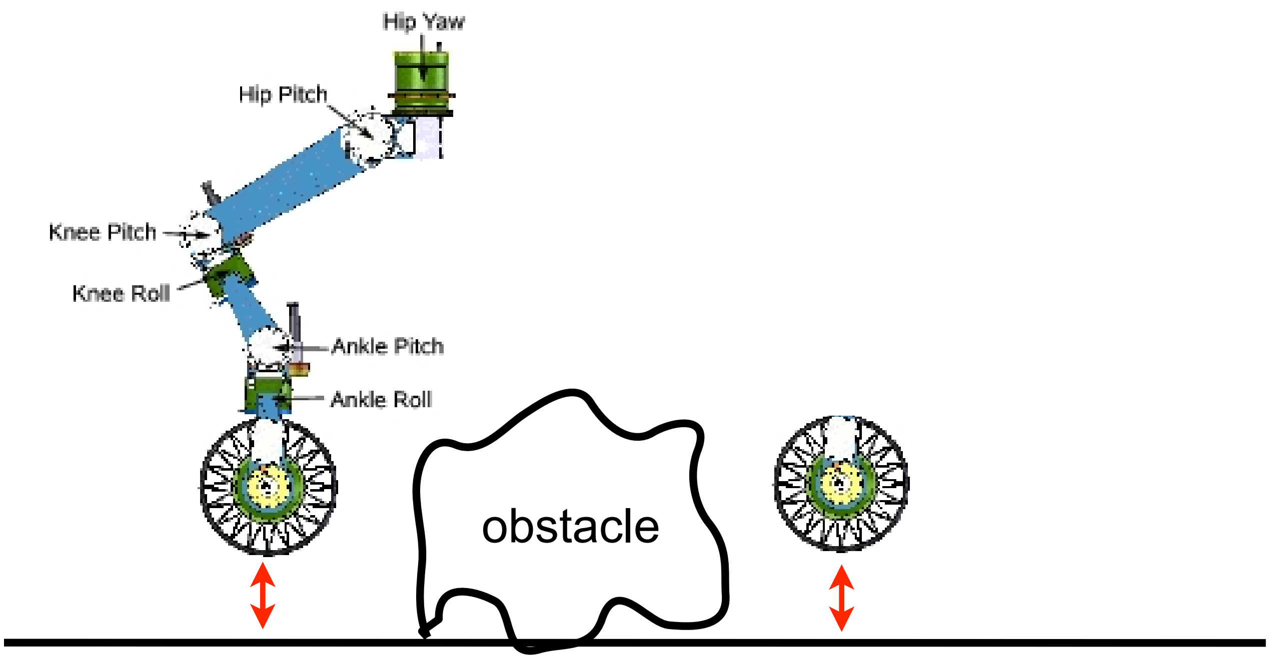




Stepping

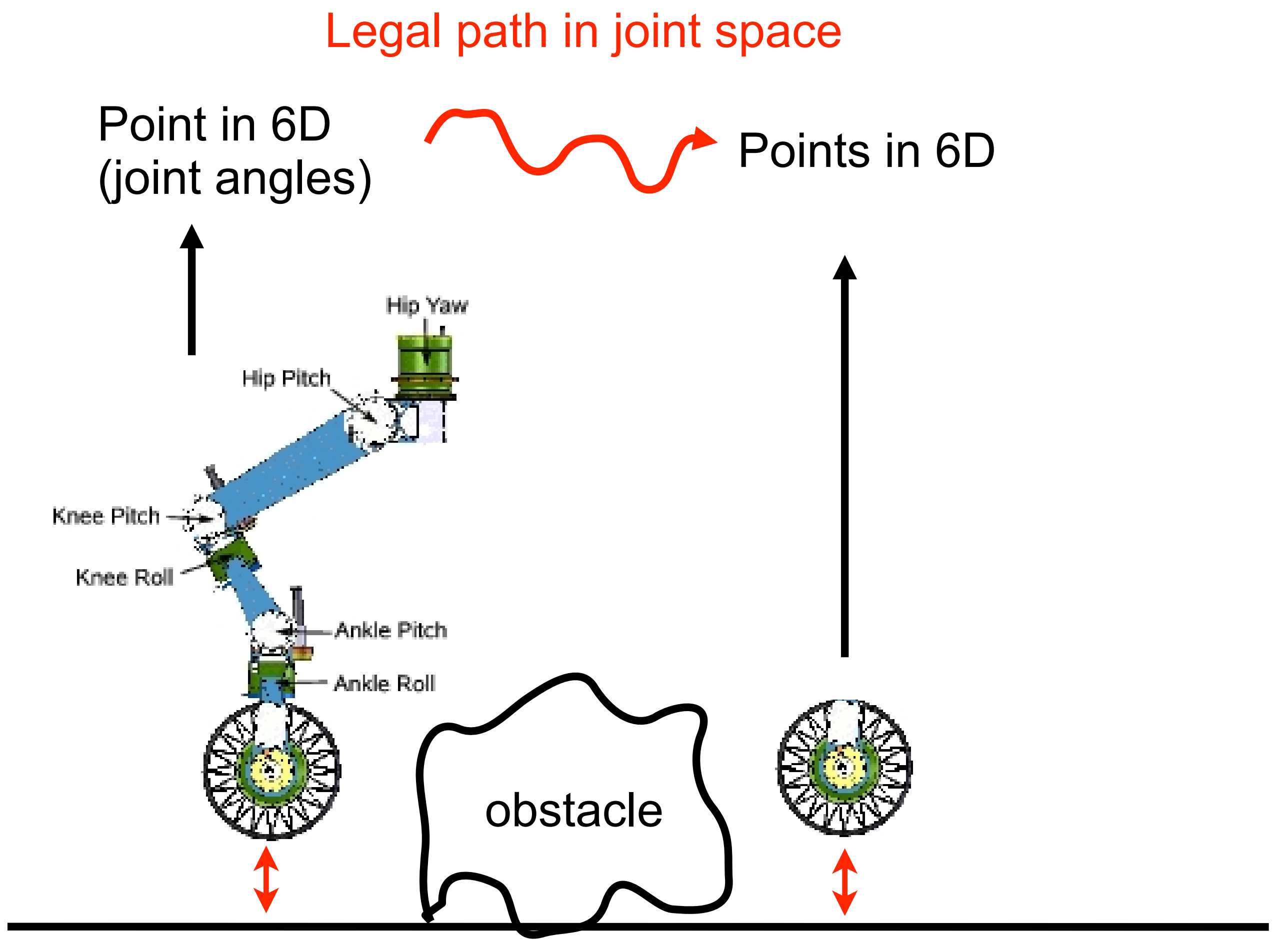

Hip Yaw
Hip Pitch
Knee Pitch
Knee Roll
Ankle Pitch
Ankle Ro
obstacle

Stepping



Raise 10 cm

Stepping



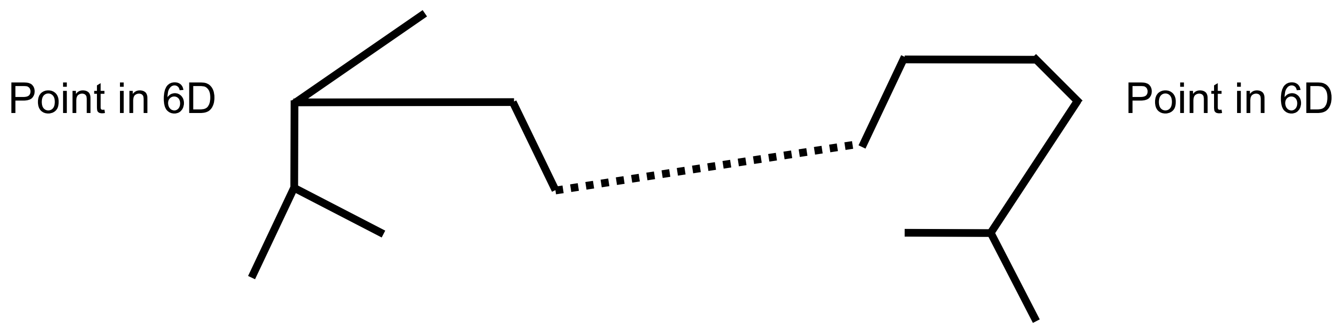
Legal path in joint space
Point in 6D
(joint angles)
Points in 6D
Hip Yaw
Hip Pitch
Knee Pitch
Knee Roll
Ankle Pitch
Ankle Roll
obstacle

Algorithm 1: SMPL

- SMPL: Try straight line

Algorithm 2: SBL

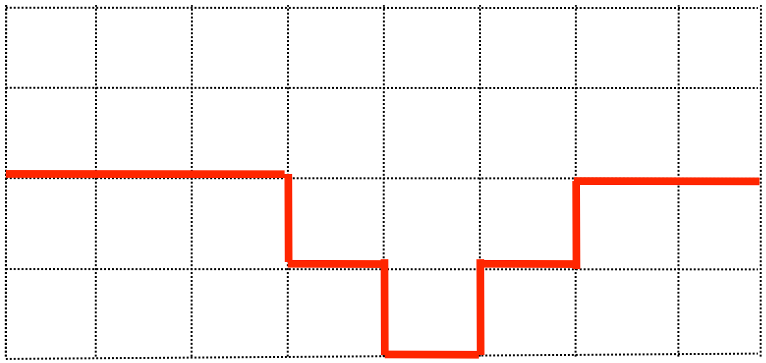
- SBL: Single-query Bi-directional planner with Lazy collision checking
  - Grow two trees, occasionally try connecting



Algorithm 3: CFG

- CFG: A* search in discretized 6D

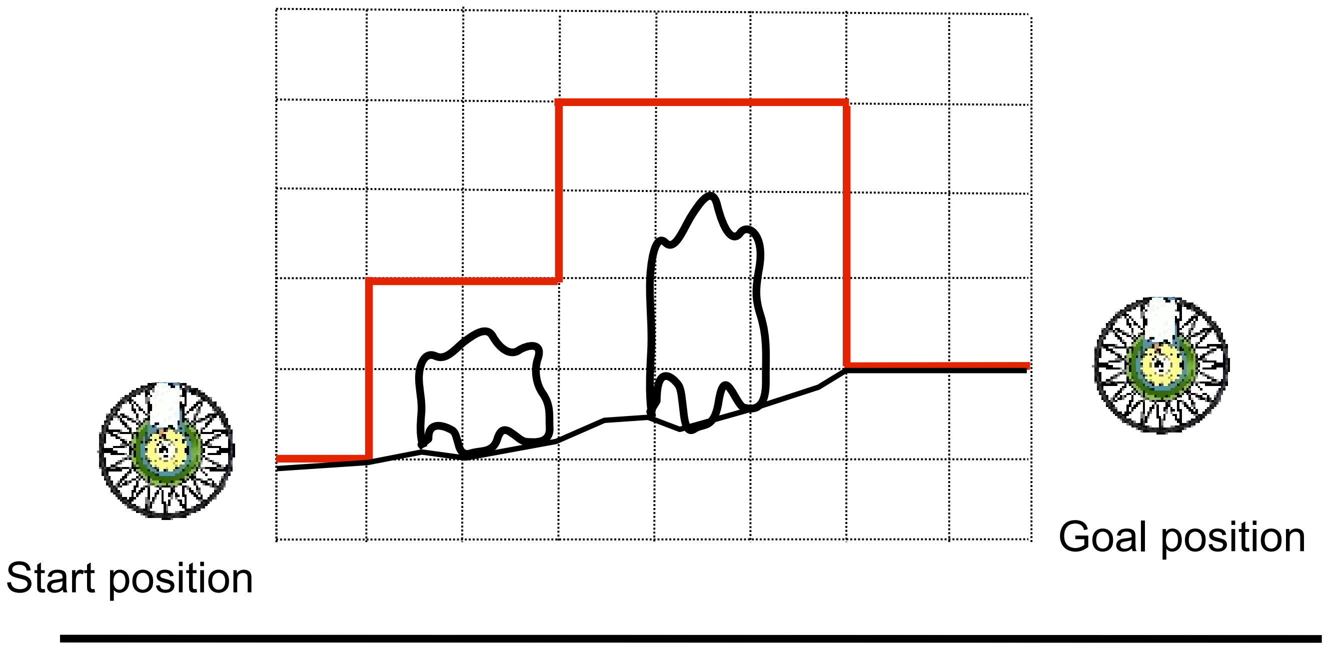
Point in 6D



Point in 6D

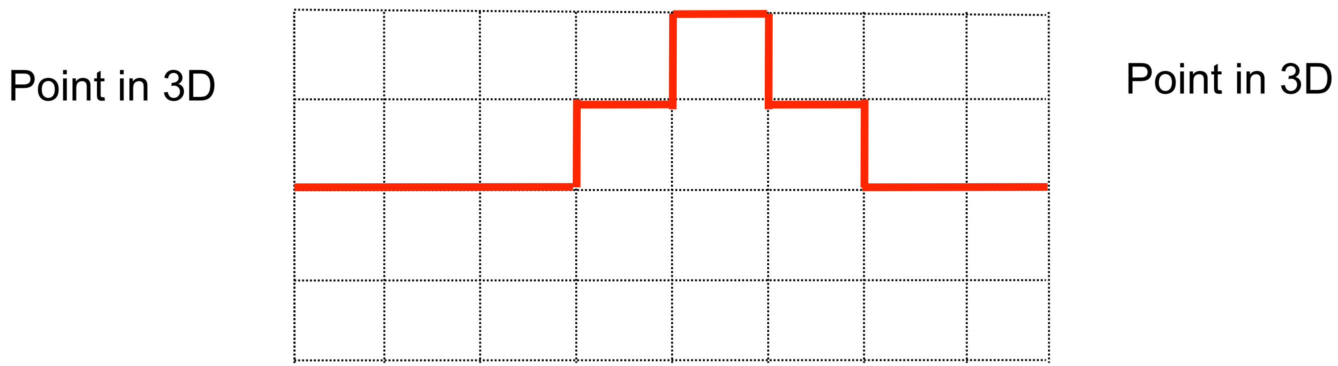
Algorithm 4: TSK

- TSK: A* search in discretized 3D



Algorithm 4: TSK

- TSK: A* search in discretized 3D



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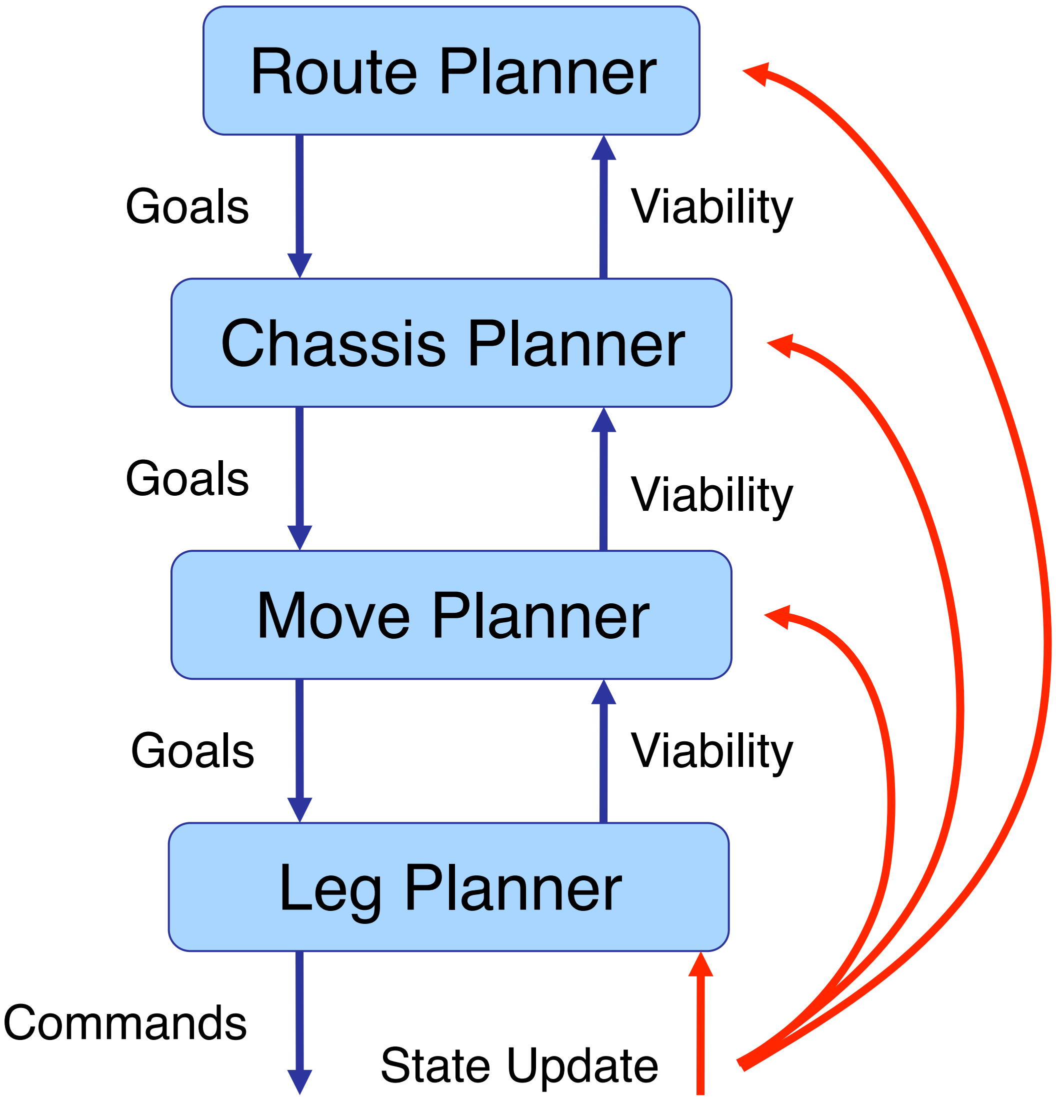
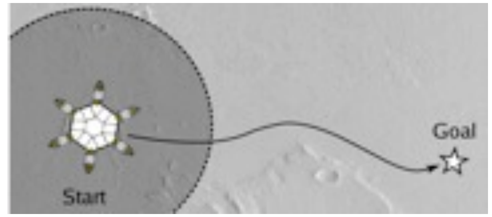
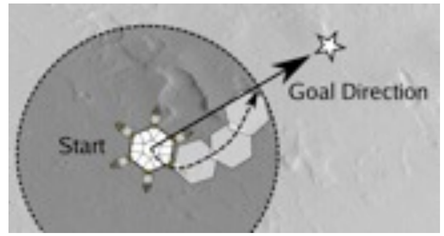
Comparison of path planning

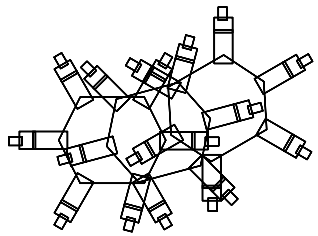
	SMPL	SBL	CFG	TSK
Space	6D	6D	6D	3D
Speed	Fast	Fast	Slow and variable	Fast
Quality	Terrible	Good but variable	Mediocre	Good
Smoothing	NA	Crucial	Helpful	Helpful

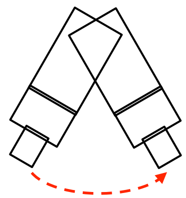
Decomposing the problem



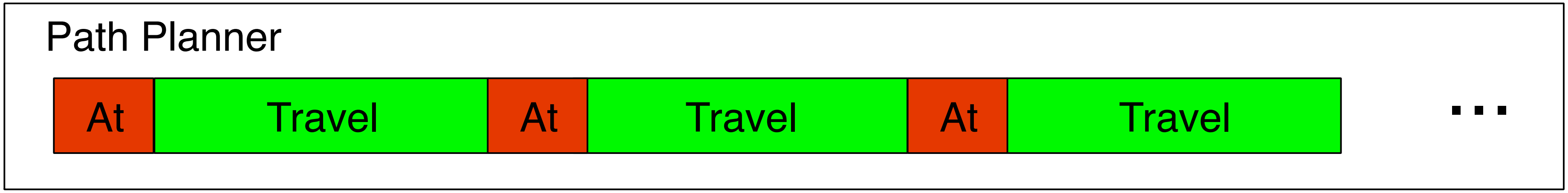




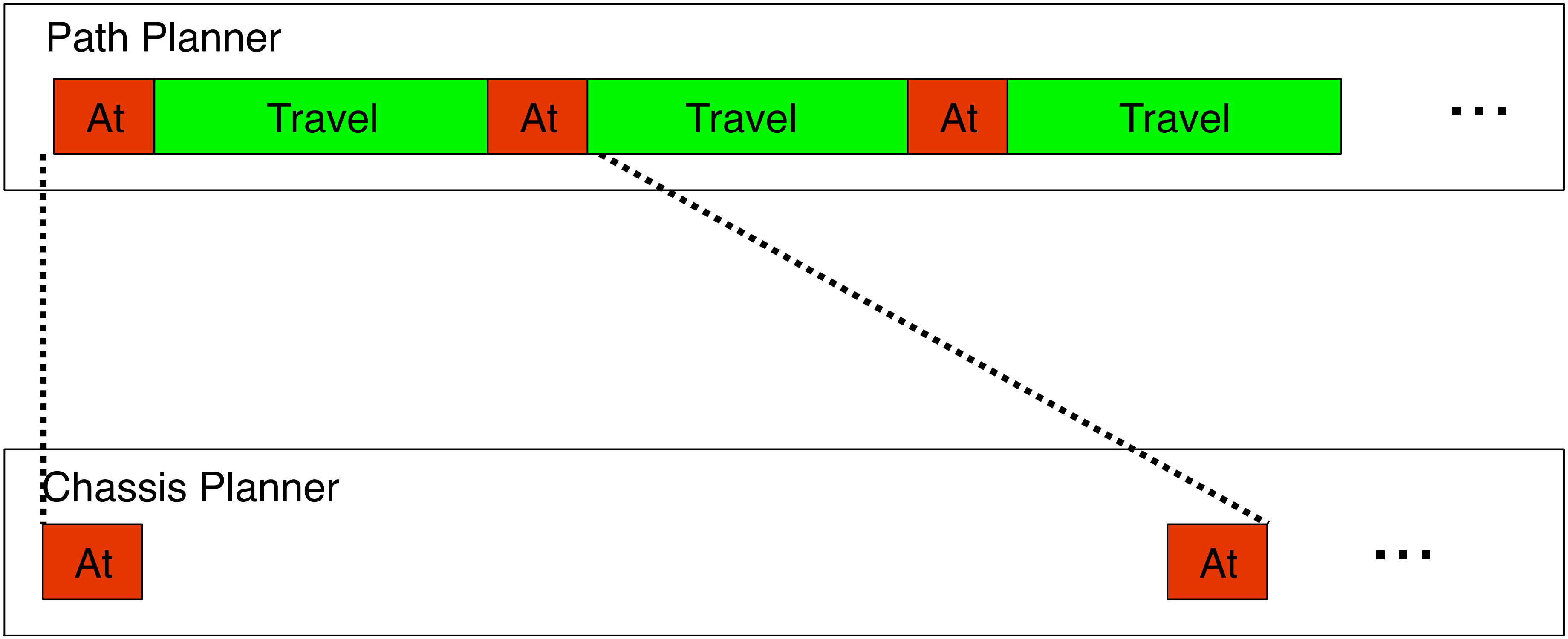




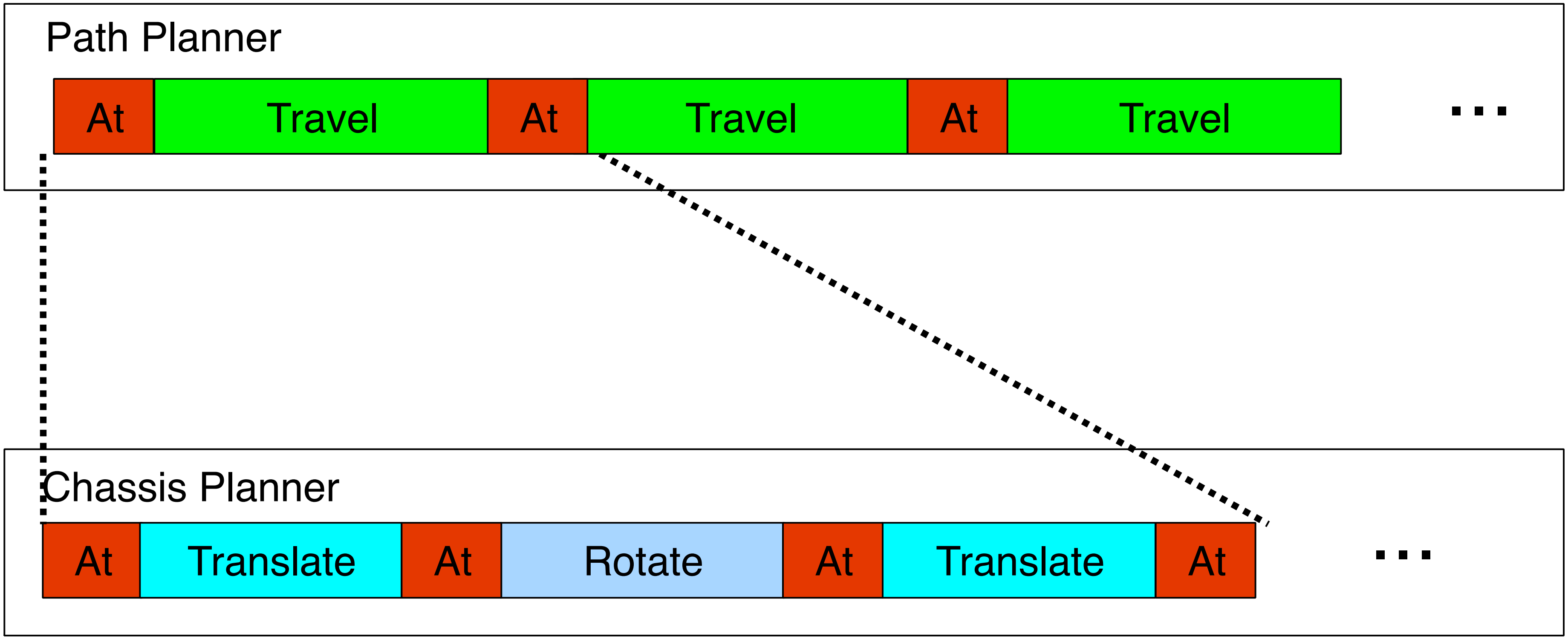
Example



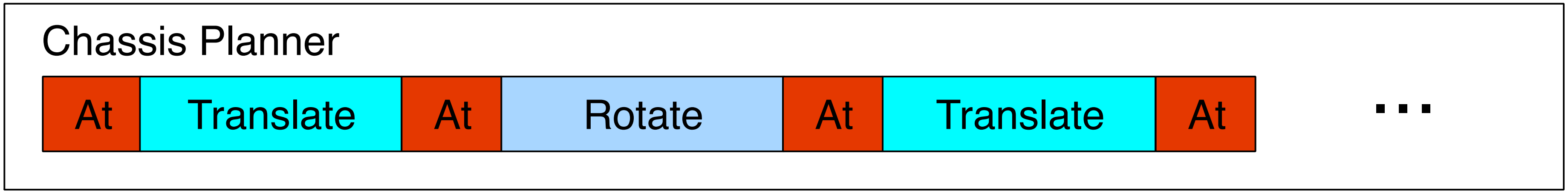
Example


Path Planner
At
Travel
At
Travel
At
Travel
...
Chassis Planner
At
At
...

Example


Path Planner
At
Travel
At
Travel
At
Travel
...
Chassis Planner
At
Translate
At
Rotate
At
Translate
At
...

Example



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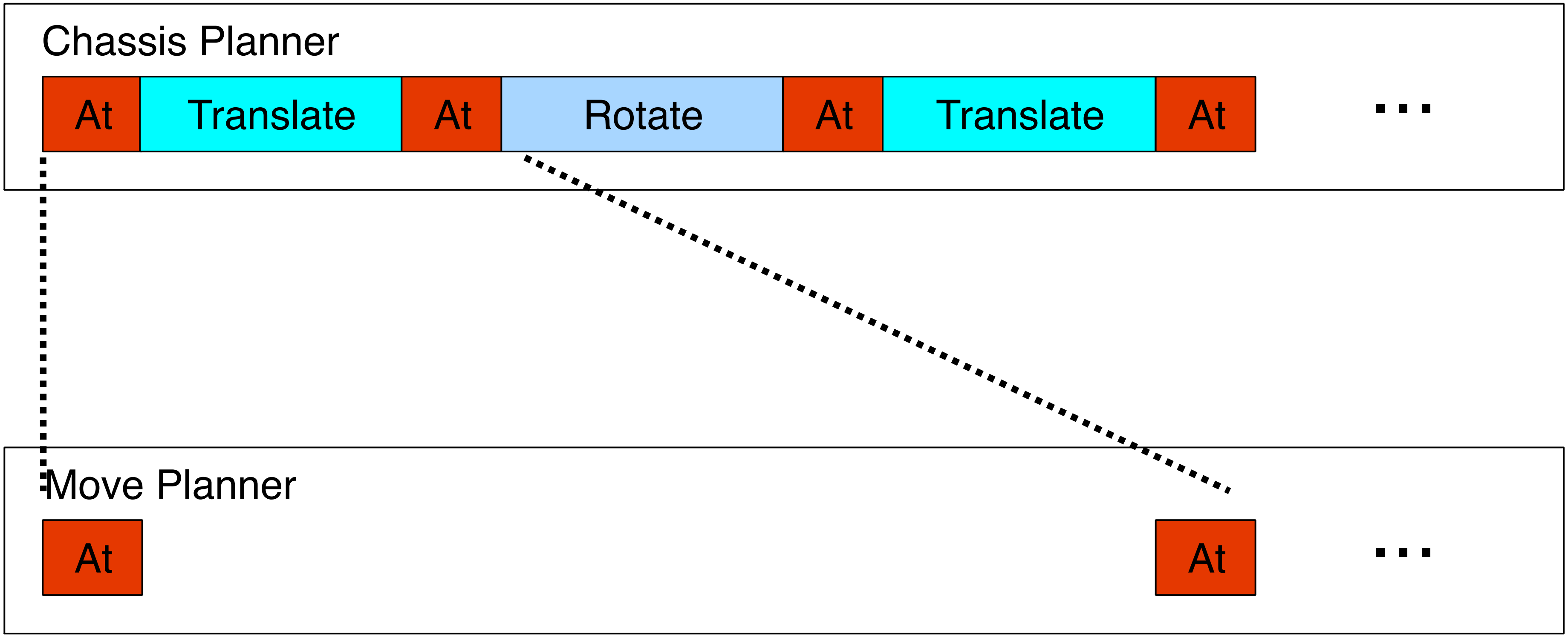
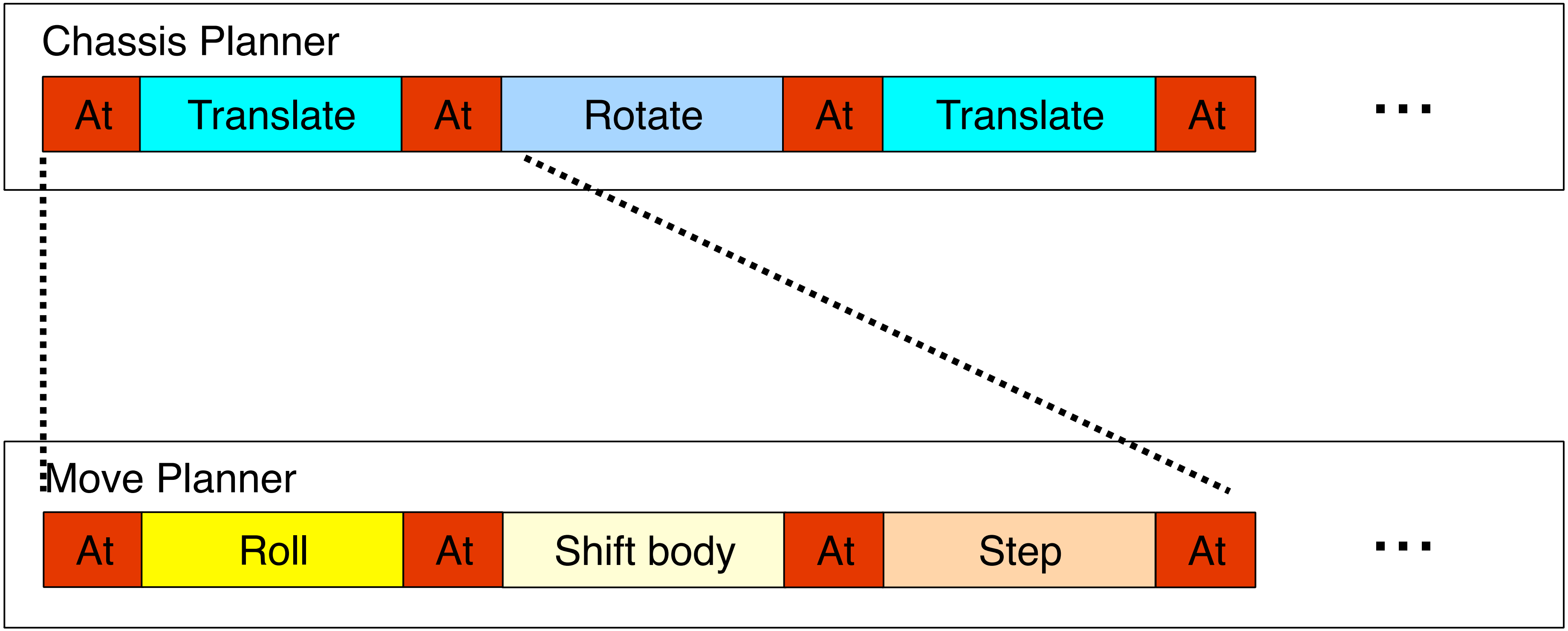
Example



Example



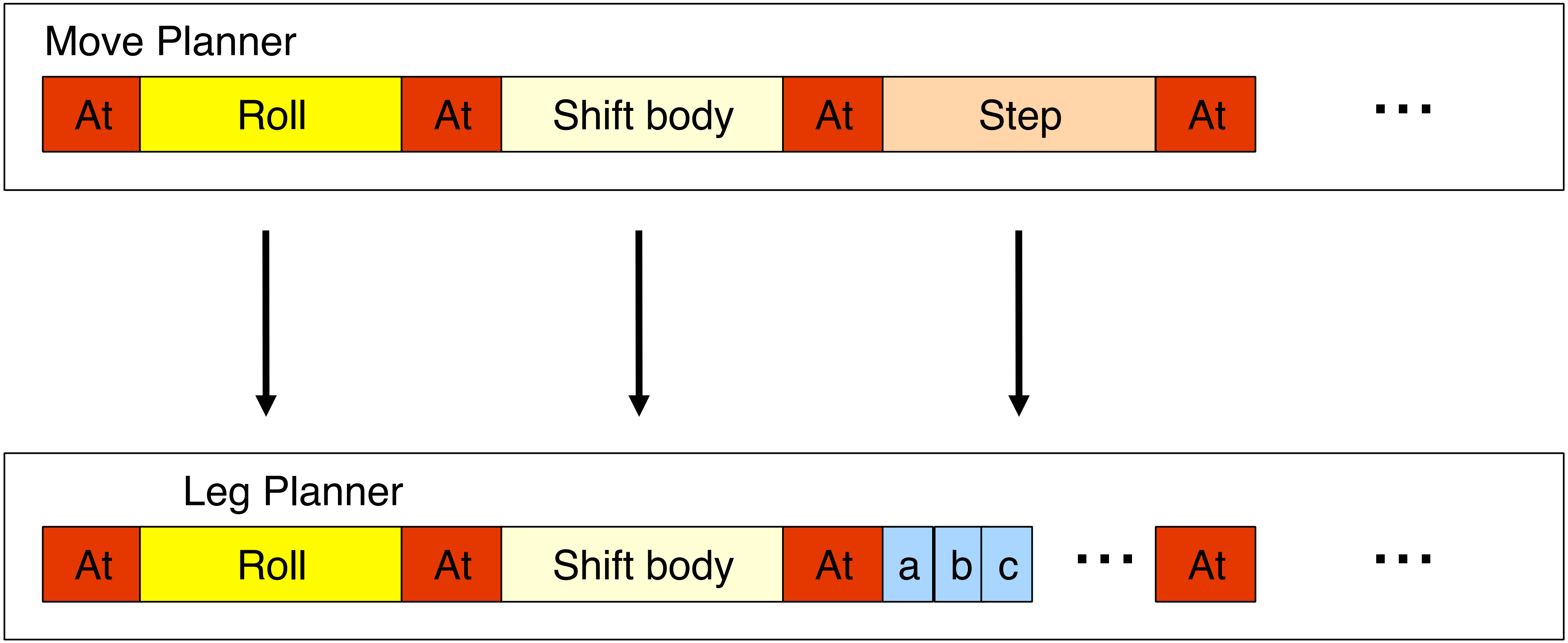
Chassis Planner
At
Translate
At
Rotate
At
Translate
At
...
Move Planner
At
Roll
At
Shift body
At
Step
At
...

Example

Move Planner

At	Roll	At	Shift body	At	Step	At	...

Example



Raise foot 10 cm
Raise foot 40 cm
Rotate hip 50 degrees
Lower foot 40 cm
Lower foot 10 cm

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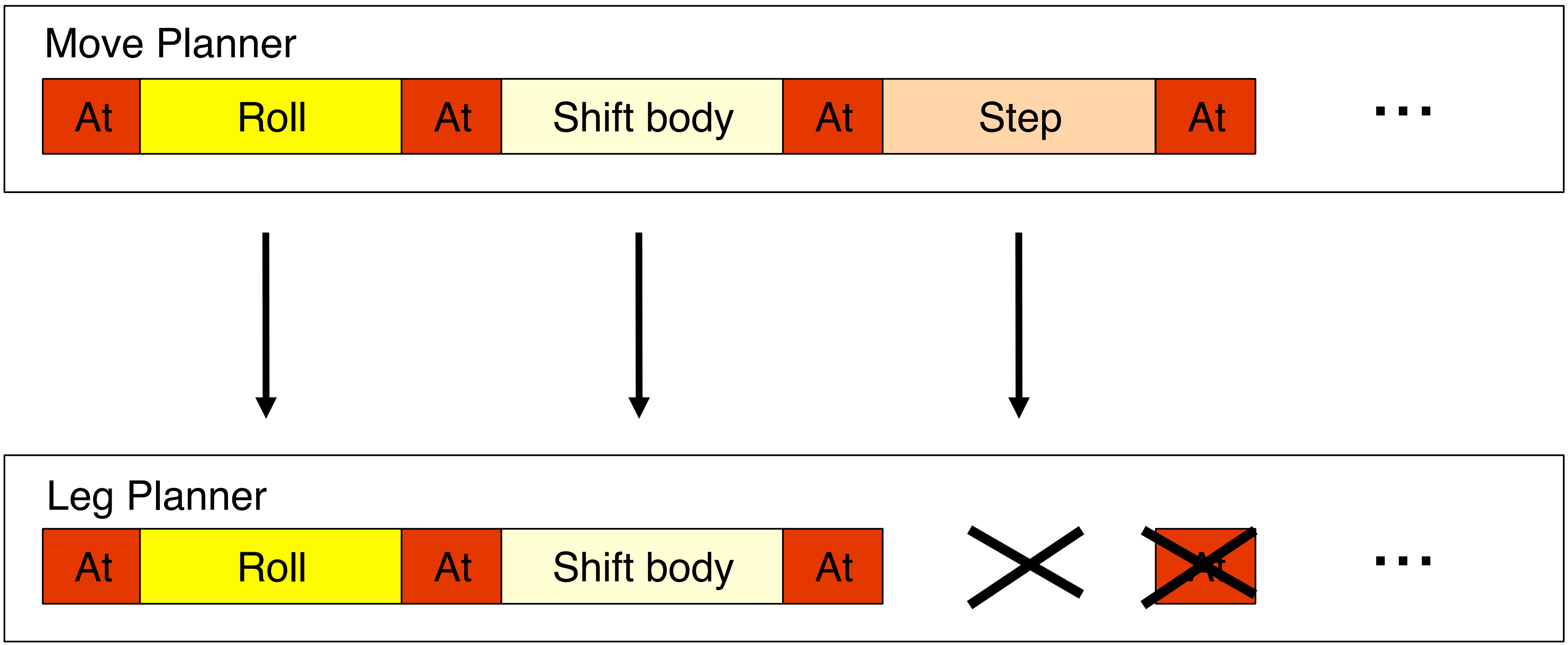
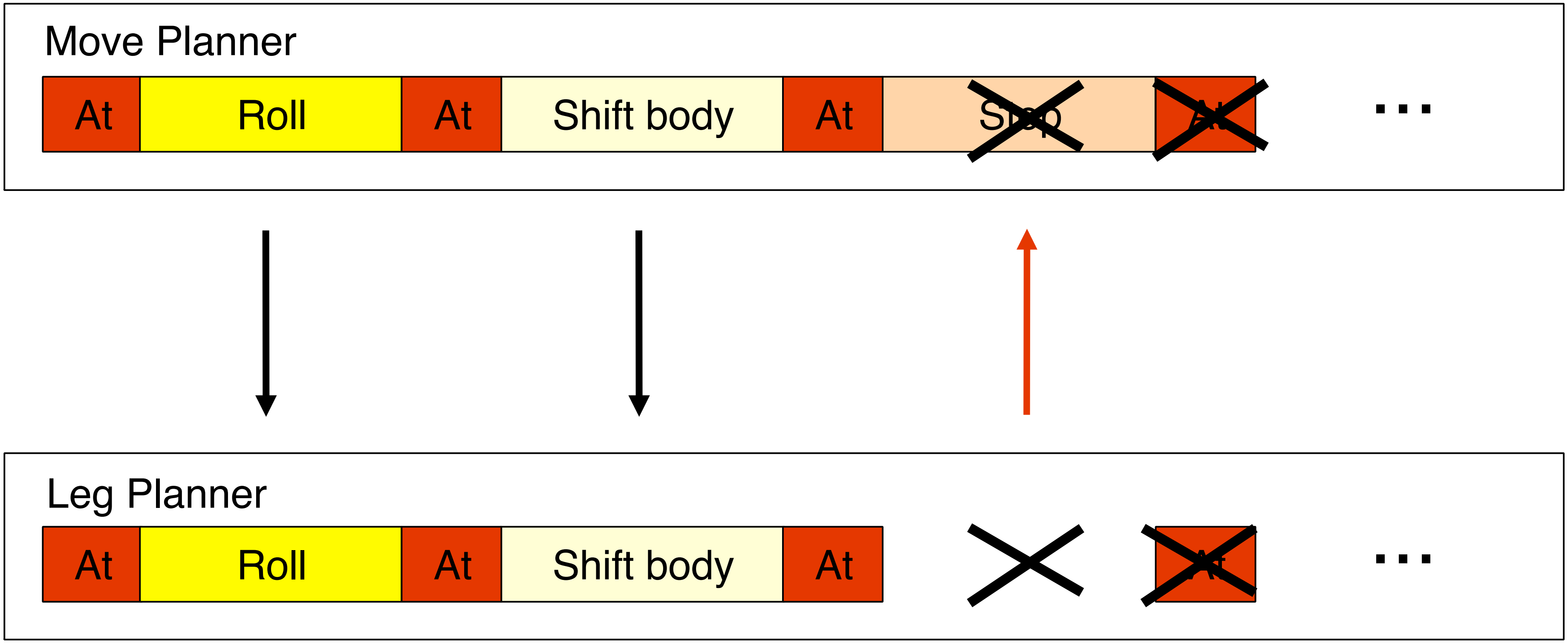
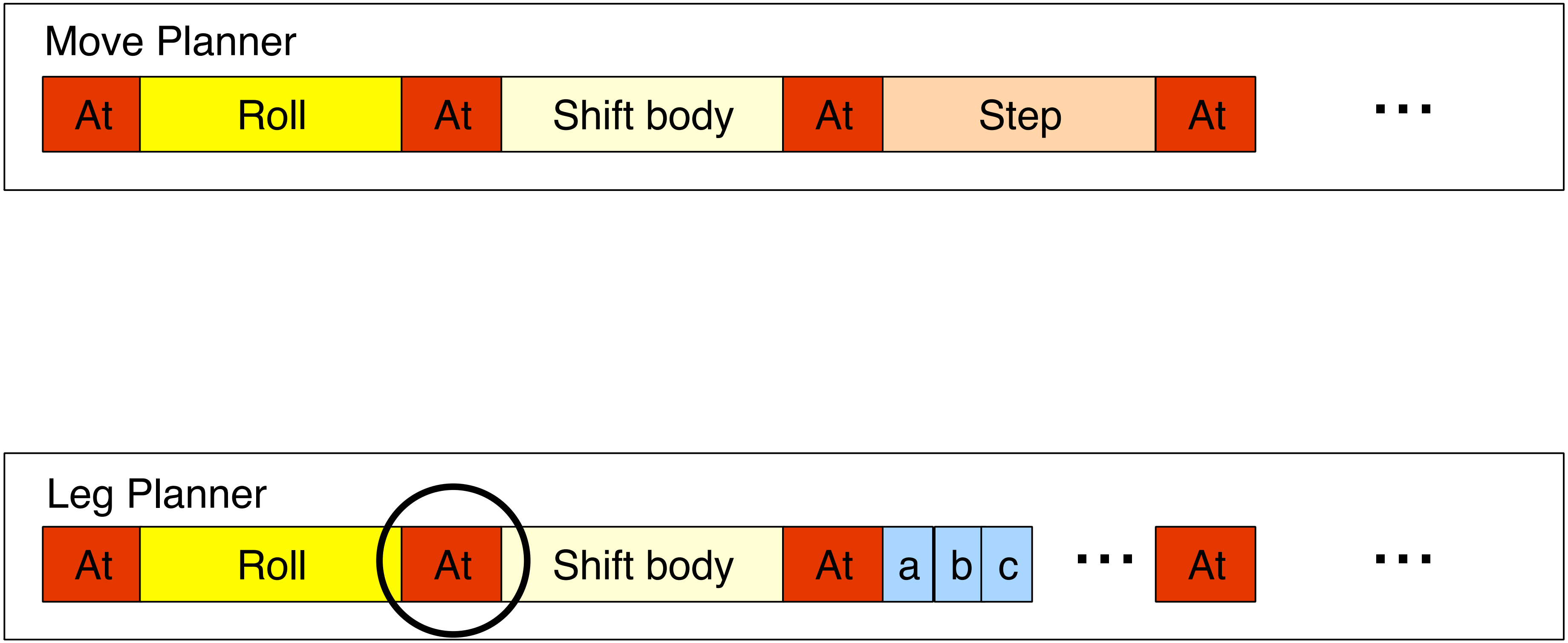
Problem 1: Planning



Problem 1: Planning



Problem 2: Execution



End up in different place or configuration

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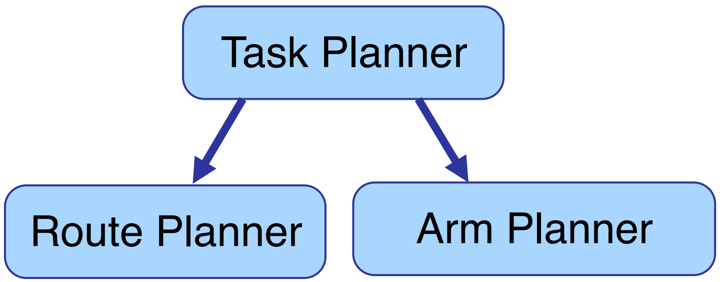
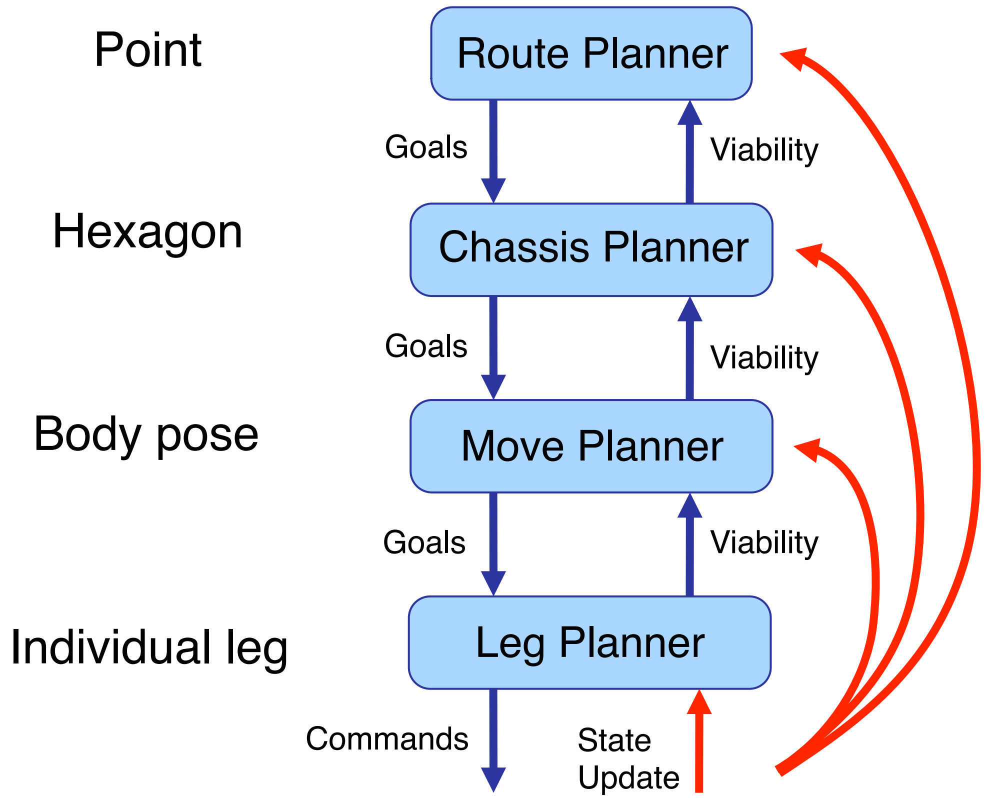
Levels

Typical

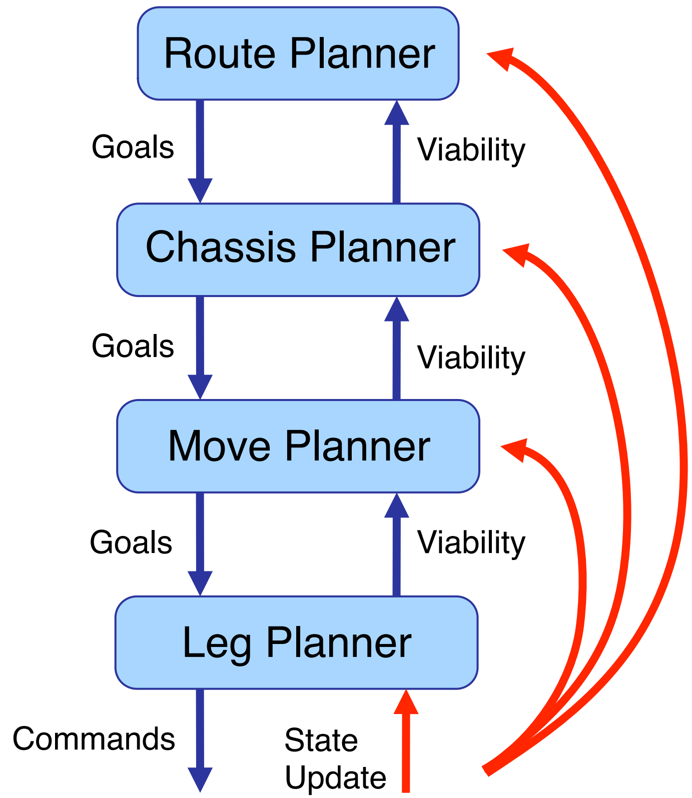


More levels than usual



Architectural Questions

- Level boundaries
  - Chassis x Move
  - Sequential vs Interleaved
    - Move & Leg



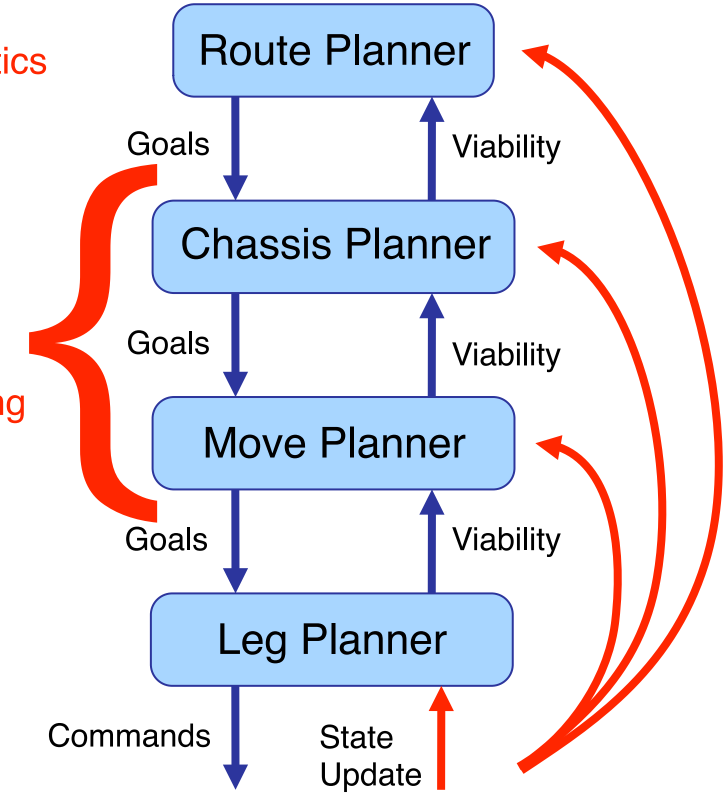
Architectural Questions

- Assymmetry
  - Inoperative Joint
  - Tool usage

Traversability Heuristics

Combine

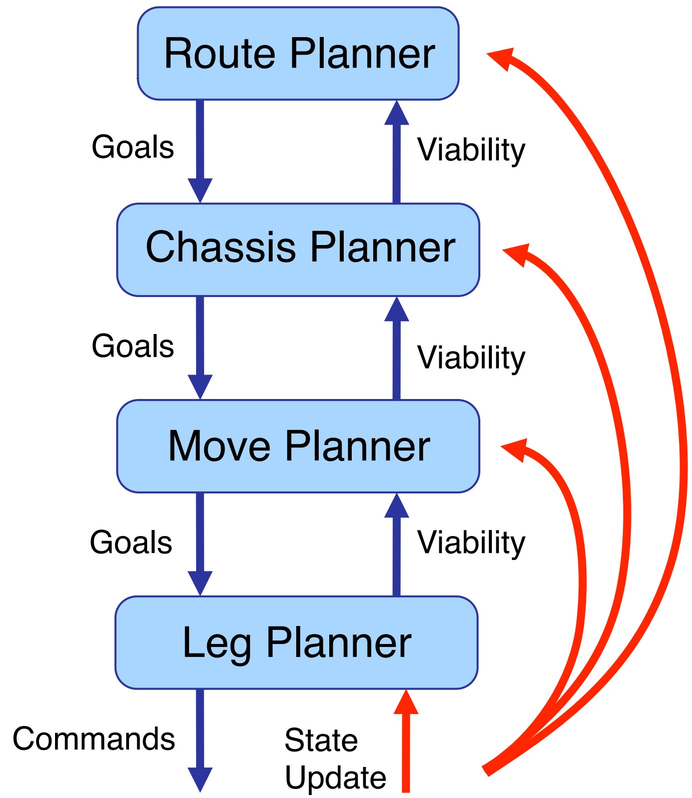
More stability checking



Architectural Questions

- Collision checking
  - Route planner
  - Chassis planner
    - none
    - check frame
  - Move planner
    - none
    - check frame & non-moving legs
  - Leg planner
    - wheels only
    - leg
    - everything

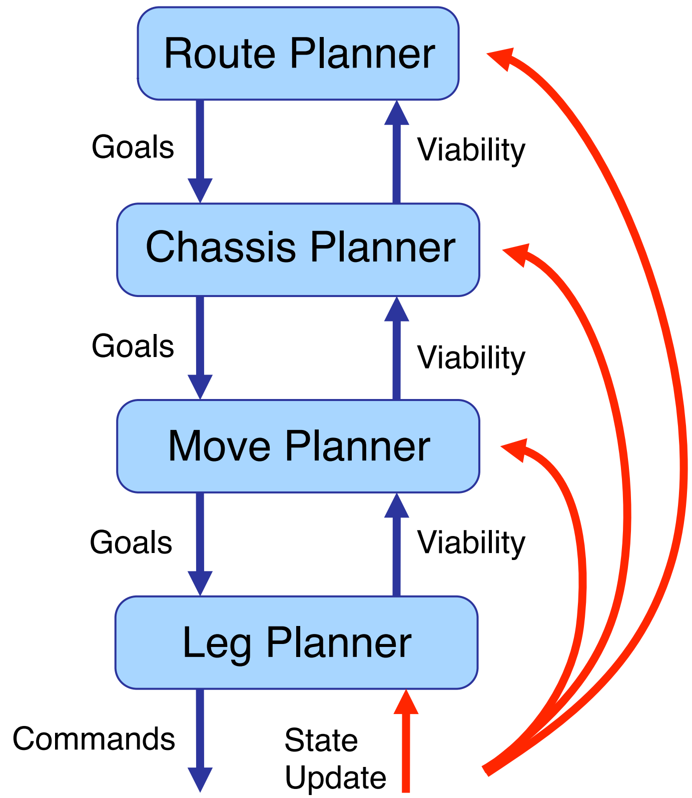
Dependent on terrain difficulty ?



Architectural Questions

- Horizon
  - Route planner
  - Chassis planner
    - visual horizon ~ 5 meters
  - Move Planner
    - 2-5 meters
  - Leg planner
    - a few moves

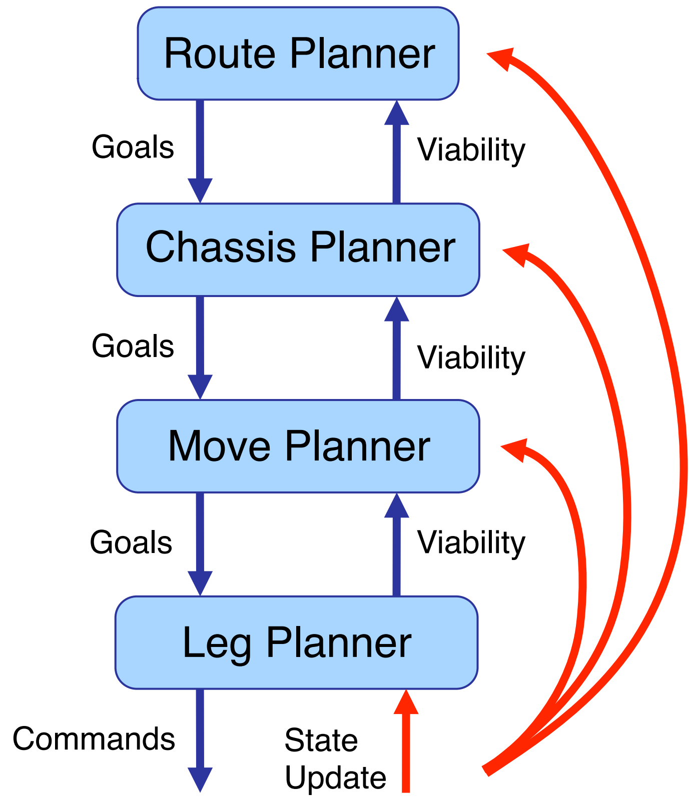
Dependent on terrain difficulty ?



Architectural Questions

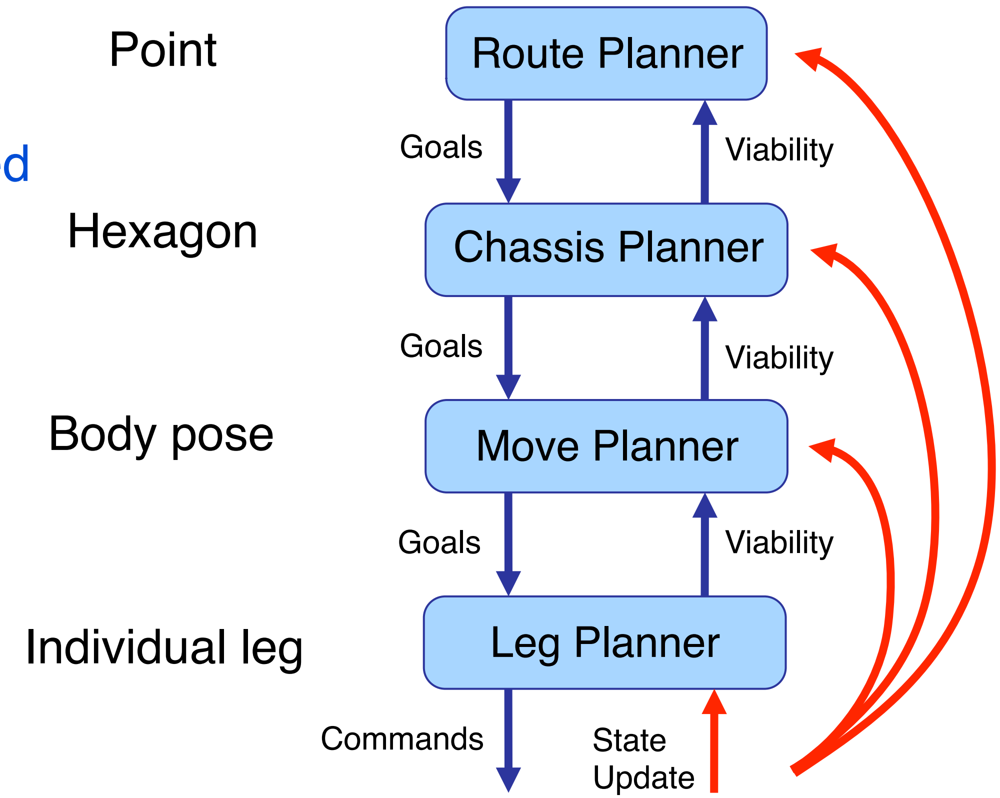
- How often to replan at levels
  - Route planner
    - terrain detail changes roughness
    - cost of Chassis plan is higher than predicted
  - Chassis planner
    - cost of move plan is higher than predicted
    - advancement by more than 2 meters
  - Move Planner
    - after each command

Dependent on terrain difficulty ?



Architectural Questions

- Level breakdown
  - More than usual
  - Boundaries?
    - Chassis x Move
    - Sequential vs Interleaved



Planning Assumptions

- Temporal
  - Action durations
  - Concurrency
- Time constraints
  - Communication windows
  - Illumination of targets
  - Temperature
- Uncertainty
  - Terrain & tracking
  - Duration of actions
  - Energy usage
  - Storage available
- Oversubscription
  - Many conflicting goals
  - Goal dependence

Levels of planning

Making it more Real

- Temporal
  - **Action durations**
  - Concurrency
- **Time constraints**
  - Communication windows
  - Illumination of targets
  - Temperature
- Uncertainty
  - Terrain & tracking
  - **Duration of actions**
  - **Energy usage**
  - **Storage available**
- Oversubscription
  - **Many conflicting goals**
  - Goal dependence

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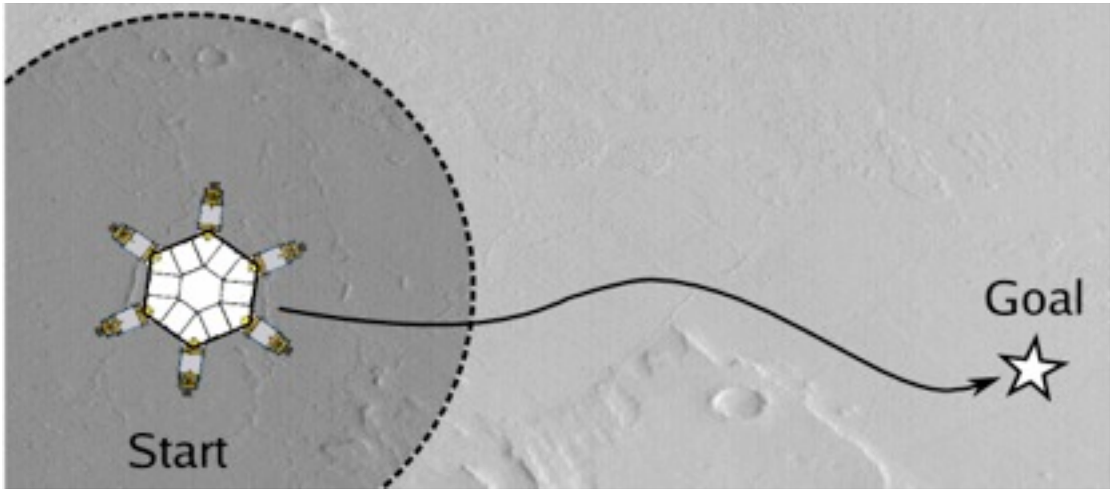
Complicating the Planning Problem

- Given:
  - collection of goals with utilities
  - time & resource constraints
  - uncertain durations & resource usage
- Find:
  - command sequence
  - prefer rolling to stepping



Impact

- Route Planner
  - need oversubscription planner

goals have utility

constraints on time & resources

maximize utility subject to constraints on time & resources

choose which goals to satisfy

Impact

- Route Planner
  - need oversubscription planner

goals have utility

constraints on time & resources

maximize utility subject to constraints on time & resources

choose which goals to satisfy

Net-Benefit Planner

goals have utility

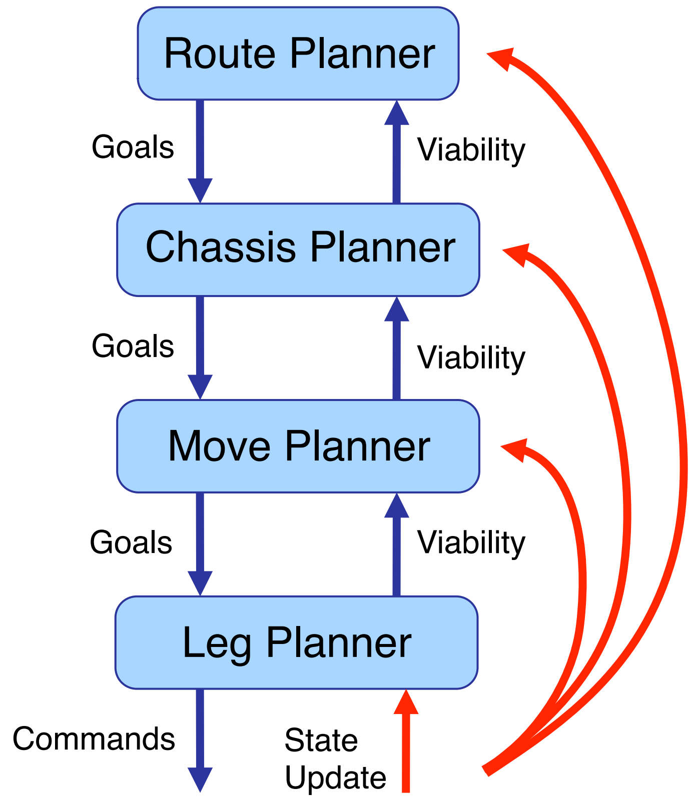
actions have costs

maximize utility of goals

not the same!

Impact

- Other Levels ?
  - Uncertainty in time and resource usage
    - impacts time constraints
    - constantly simulate expectations
    - more replanning required



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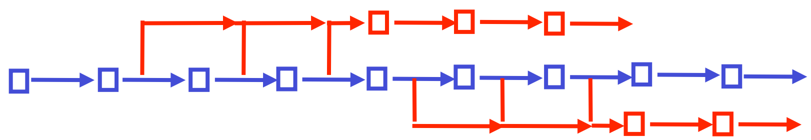
Contingency Planning

- Uncertainty in continuous quantity
- Discretization usually not viable
- Uncertainty is cumulative
  - the condition needs to be predictive
  - if probability of completing this goal drops below x, do plan2 instead



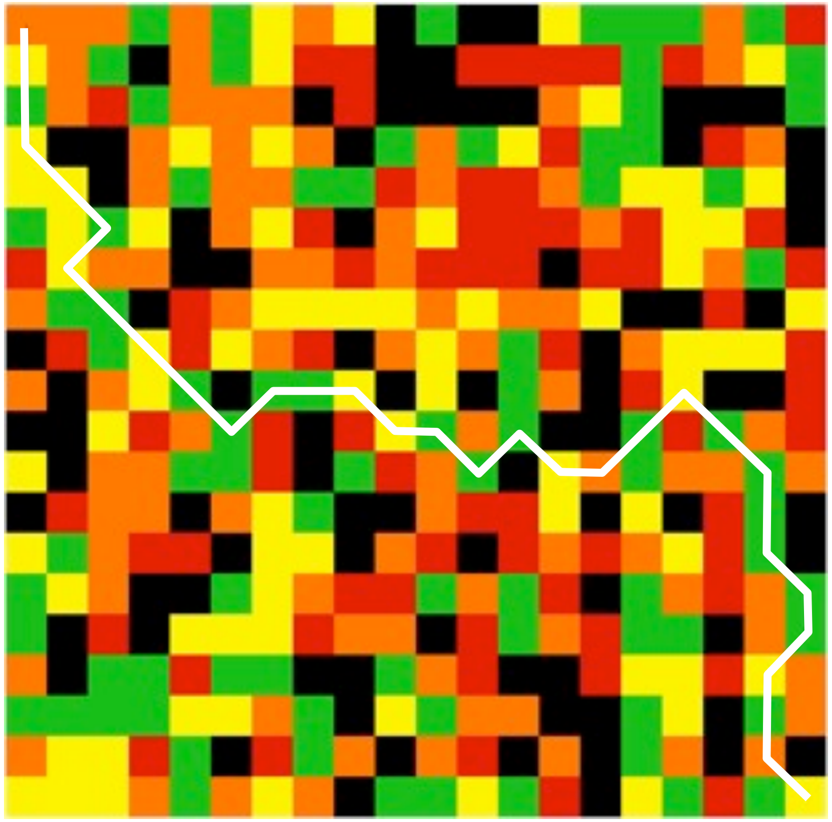
Making it more Real

- Temporal
  - Action durations
  - Concurrency
- Time constraints
  - Communication windows
  - Illumination of targets
  - Temperature
- Uncertainty
  - **Terrain & tracking**
  - Duration of actions
  - Energy usage
  - Storage available
- Oversubscription
  - Many conflicting goals
  - Goal dependence

The Tracking Problem

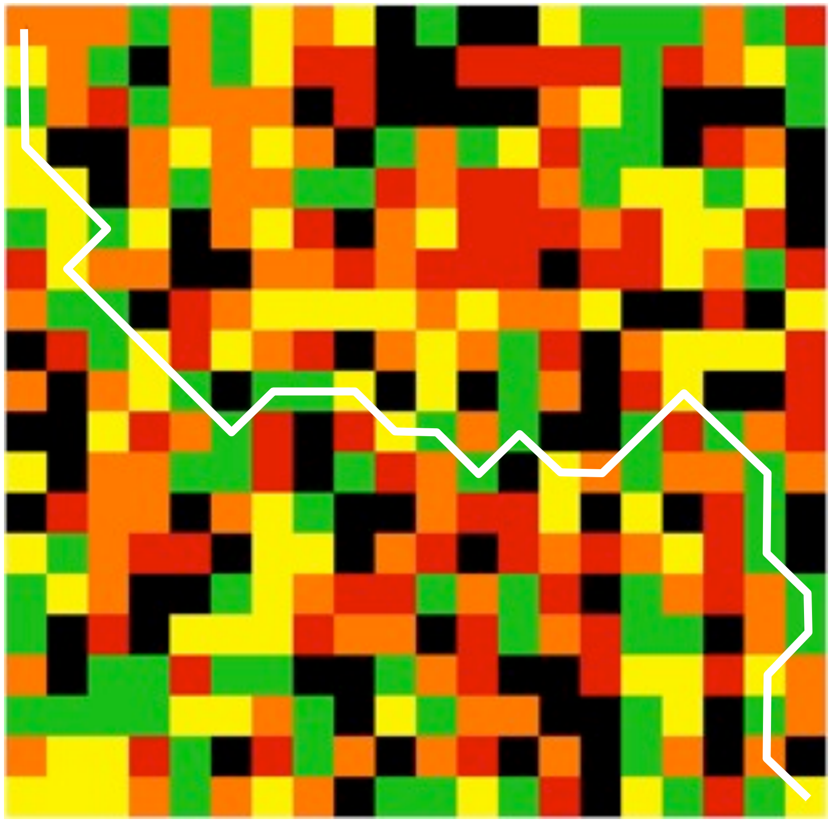
- Navigation and localization difficult
  - beyond horizon - only gross features from satellite images
  - choose paths near trackable features

Route Planning Search



Route Planning Search

cost = steepness * roughness * navigation-cost



Take Home Messages

- Multiple levels of planning
  - 4 levels of path planning
  - 3T+++
- Good abstraction is key
  - allows feedback from lower level failures
  - minimizes backtracking between layers
- Task planning interacts primarily with highest layer
  - more serious with time constraints and duration uncertainty
- Levels break down with tool usage or damage