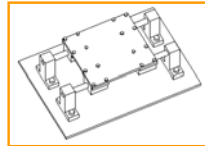
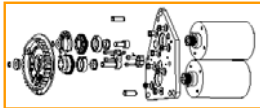
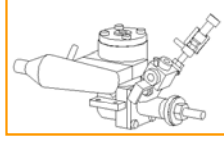
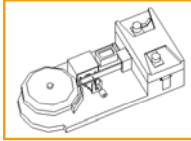
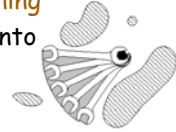


## Assembly Planning

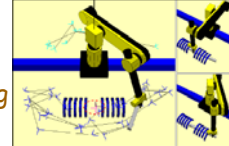


## Levels of Problems

- Parts are assumed free-flying  
→ Assembly sequence planning
- Tools/fixtures are taken into account



- Entire manipulation system is taken into account  
→ Manipulation planning



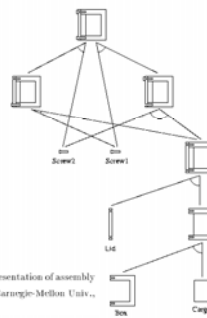
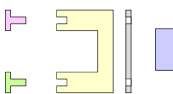
## Applications

- Answers to questions such as:
  - How many parts need to be removed to extract a given part P?
  - Can the product be assembled by adding a single part at a time?
  - How much can the assembly process be parallelized?
- Design for manufacturing and servicing
- Design of manufacturing systems

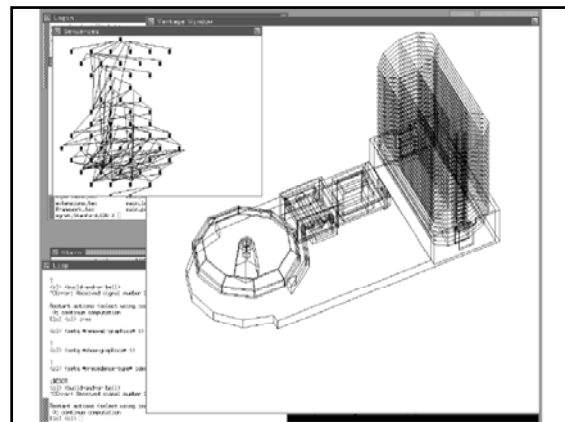
## Assembly Sequence Planning

- Very constrained goal state, but unconstrained initial state  
→ Disassembly planning
- Large number of dofs, but simple paths  
→ Motion space

## Set of Assembly Sequences as an AND/OR Graph

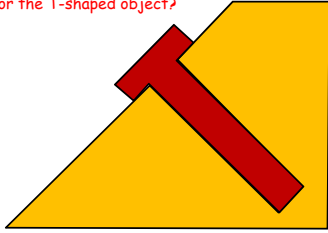


L. S. Homem de Mello and A. C. Sanderson, AND/OR graph representation of assembly plans. Technical Report CMU-RI-TR-89-8, Robotics Institute - Carnegie-Mellon Univ., 1986.

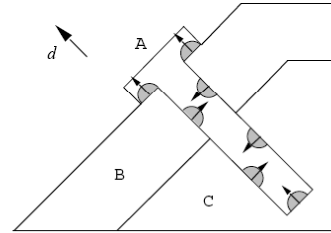


## Contact Analysis

How would you compute a direction of motion for the T-shaped object?



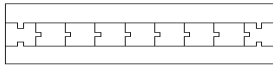
## Contact Analysis



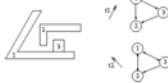
L. S. Homem de Mello. *Task Sequence Planning for Robotic Assembly*. PhD thesis, Carnegie-Mellon Univ., 1989.

## Planning Approaches

- Generate-and-test

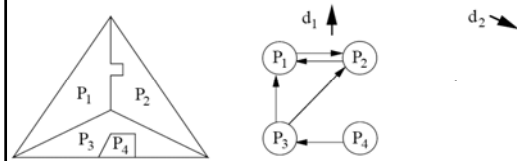


- Generate-and-test plus caching
- Non-directional blocking graph



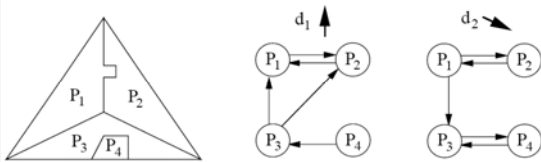
- Interference diagram

## Directional Blocking Graph (for infinitesimal translations)



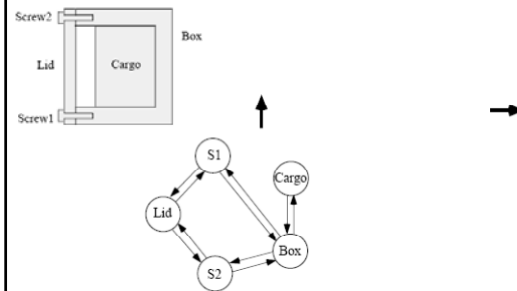
R.H. Wilson and J.C. Latombe. *Geometric Reasoning about Mechanical Assembly*. *Artificial Intelligence*, 71(2):371-396, 1995.

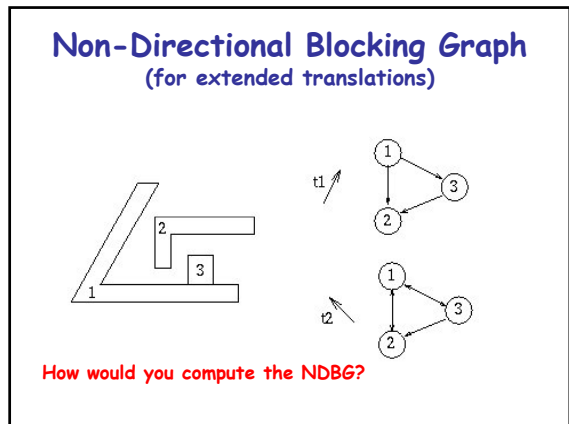
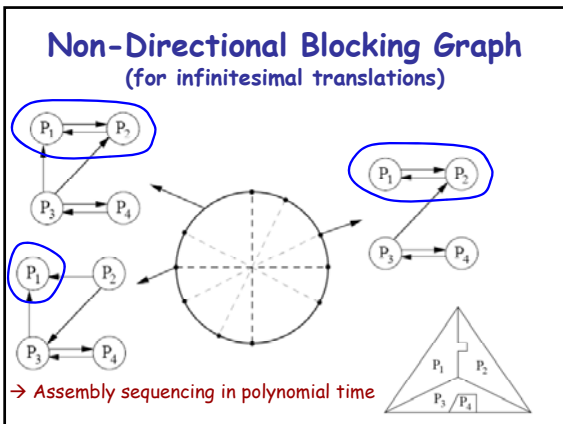
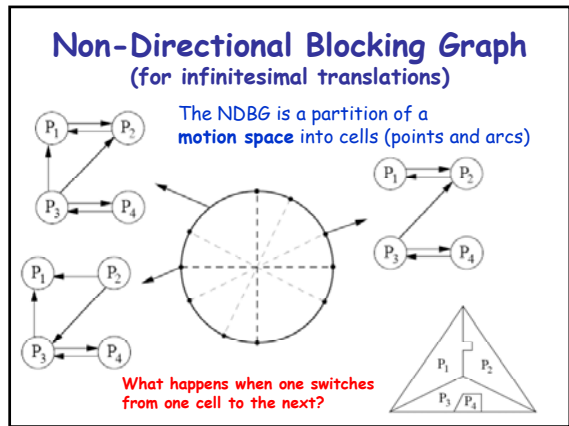
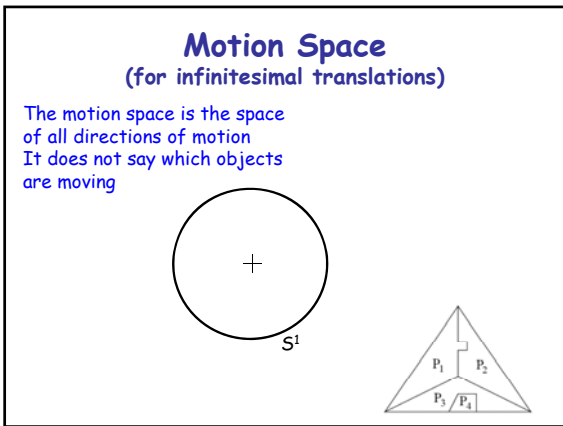
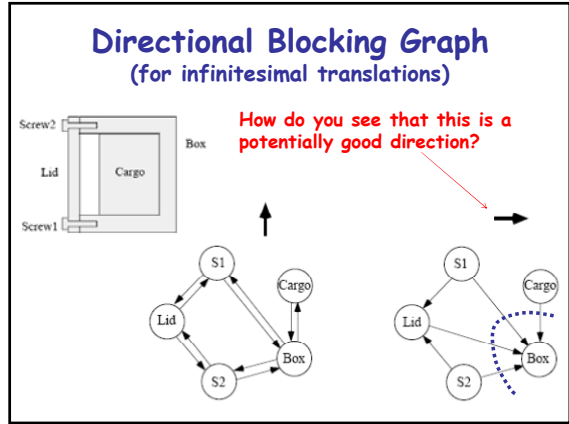
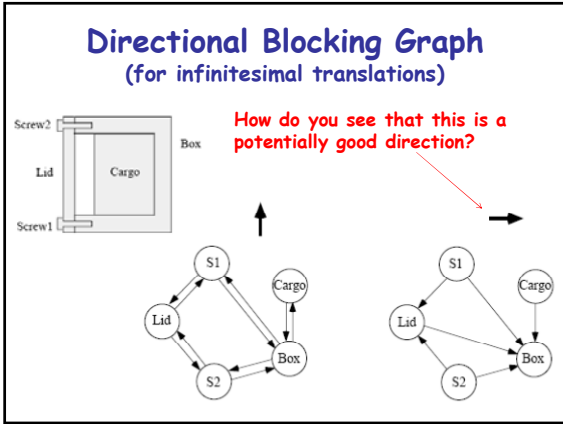
## Directional Blocking Graph (for infinitesimal translations)



R.H. Wilson and J.C. Latombe. *Geometric Reasoning about Mechanical Assembly*. *Artificial Intelligence*, 71(2):371-396, 1995.

## Directional Blocking Graph (for infinitesimal translations)

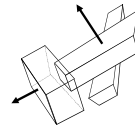




## Sketch of an Assembly Planner

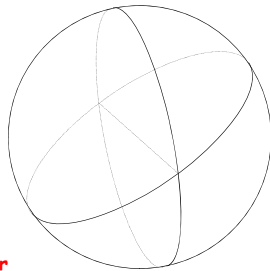
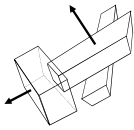
- Plan a sequence that is valid for extended translations
- If one is found, return it
  - ✓ Else plan a sequence that is valid for infinitesimal translations
  - ✓ If none is found then return failure
    - Else use a general motion planner to validate each step of the sequence

## Extension to 3-D (for infinitesimal or extended translations)



What is the motion space?

## Extension to 3-D (for infinitesimal or extended translations)

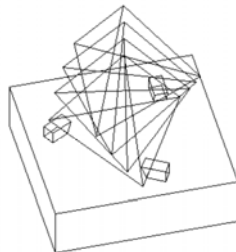
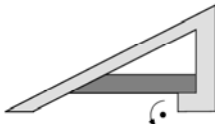


How would you do for extended translations?

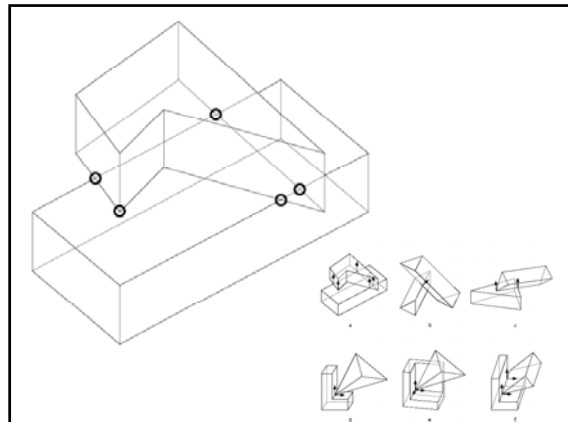
## More Extensions

- What would be the motion space if we allowed parts to both translate and rotate?
- What about multi-step motions, e.g., along  $d_1$  for distance  $l_1$ , then  $d_2$  for distance  $l_2$ , ...?

## Contact Analysis



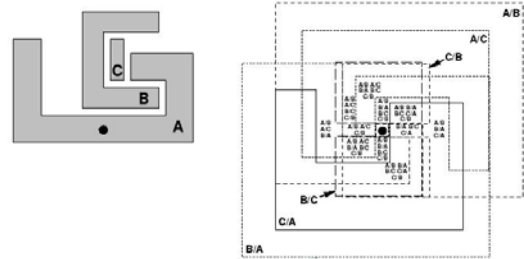
H. Hirukawa, T. Matsui, and K. Takase. Automatic determination of possible velocity and applicable force of frictionless objects in contact from a geometric model. *IEEE Trans. on Robotics and Automation*, 10(3):309-322, 1994.



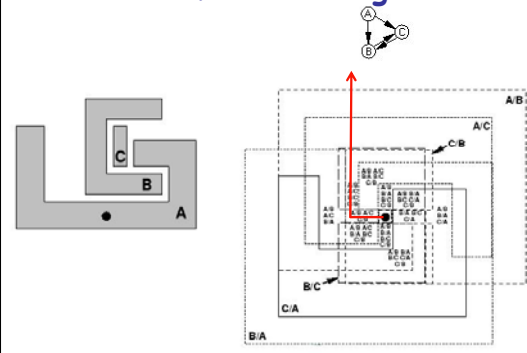
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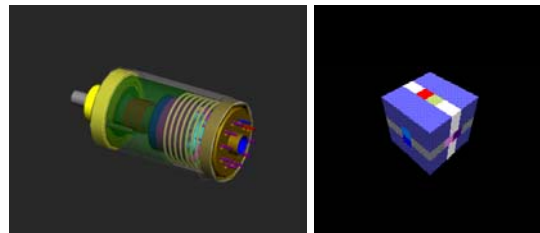
## Interference Diagram



## Interference Diagram



## Assembly Sequences Generated Using NDBGs

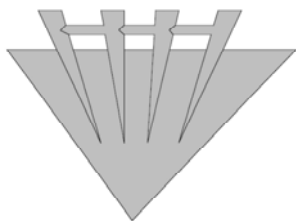


Sandia National Labs (R. Wilson)

Munich University (F. Schwarzer)

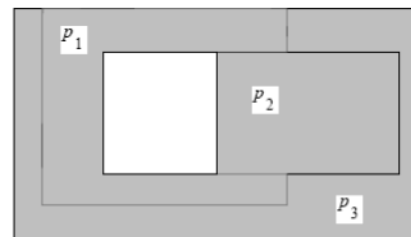
## Number of Hands

B. K. Natarajan. On planning assemblies. In *Proc. 4th ACM Symp. on Computational Geometry*, pages 299-308, 1988.



An assembly that requires  $n$  hands

## Monotonicity of an Assembly



### Monotonicity of an Assembly

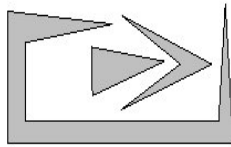


### Example Assemblies



- With translations only
  - monotone
  - two-handed

### Example Assemblies



- With translations only
  - non-monotone, 2-handed
  - monotone, 3-handed
- With general motions
  - monotone, 2-handed

### Nonlinearizable 1-Handed Assembly

