Assembly Sequence Analysis

- Goals of this class
  - Understand one algorithmic approach to finding all feasible assembly sequences
  - Make connection between algorithm and assembly feature models
  - See how assembly sequences can be designed
  - Look at some examples
  - See a video of computer-aided assembly analysis

History

- Assembly sequence analysis applied to line balancing (Prenting and Battaglin, 1964)
- Heuristics such as “the fastener method” (1978)
- Bourjault method (1984)
- De Fazio/Whitney method (1987)
- Gustavson exploded view method SPM (1989)
- Baldwin onion skin method (1989)
- Sukhan Lee method (force paths, subassemblies, 1989 +)
- Wilson method (free directions, 1992+)

Role of Sequence Analysis in Concurrent Engineering

- Line balancing applies sequence analysis *after* the product is designed
- Our goal is to push assembly sequence analysis to the *beginning* of the development process
- It can be an important lever in concept design
- It interacts with architecture and affects supply chain, build to order processes, JIT, etc.
- To keep up with designers during fluid concept design, the assembly engineers need a tool that gives fast turnaround

Analysis Alternatives

- Find all feasible sequences
- Find all linear feasible sequences
  - add one part at a time
- Find one feasible sequence
- Find one linear feasible sequence
- The first one is of the most interest to assembly line designers

Process Phases

- Eliminate all truly impossible sequences
  - parts physically block other parts
  - sequences dead end before completion
- What remain are called "feasible" = not impossible
  - the good, the bad, and the ugly
- By various criteria, throw out bad and ugly
  - Criteria include technical and business issues
- This is traditional design:
  - generate requirements
  - generate alternatives
  - use requirements to narrow the alternatives

Classes of Approaches

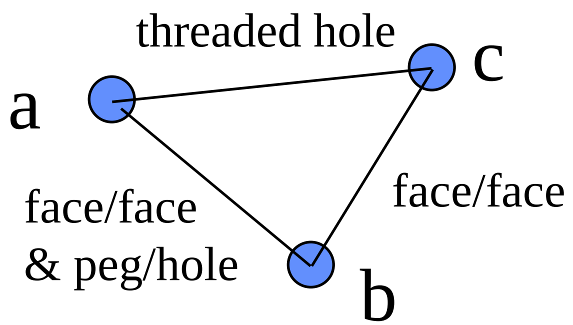
- Most methods assume "one hand"
  - Forbids joining 3 things at one step
- Graph theory analysis of liaison diagram
- Systematic textual analysis of lists of liaisons that contain blockers
- Cut-set methods applied to the liaison diagram
- "Onion-skin" methods that peel off outside parts
- Most of these methods utilize disassembly as the paradigm but it is not necessary
  - "can you remove part X from parts Y,Z,...?" is the same as "can you put part X onto parts Y, Z,...?" under most circumstances

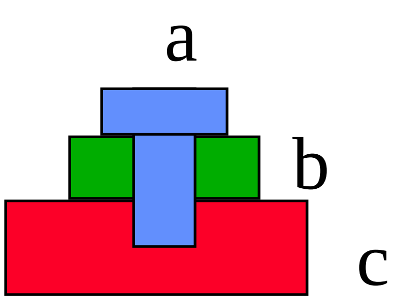
Non-Assembly Steps Can be Included

- Reorientation
- Tests, lubrication
- Temporary disassembly
- These can all be handled one way or another if you are creative

The Liaison Diagram

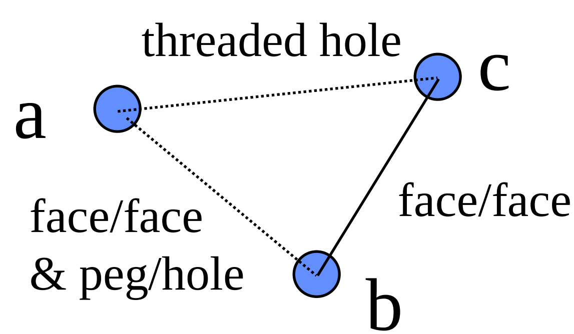
- A simple graph that denotes parts as nodes and connections as arcs
- Can be augmented with information about the connection

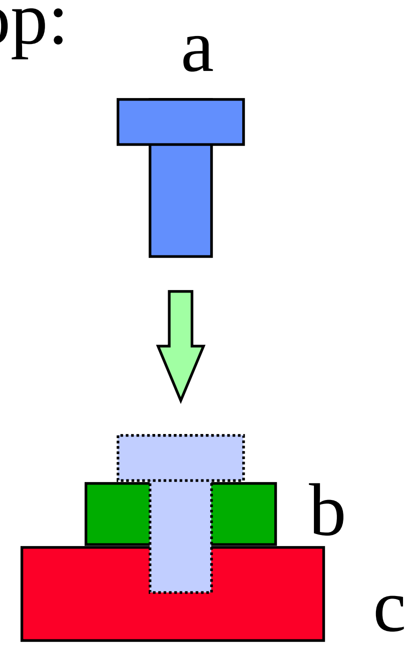




Rules of Liaison Diagrams

- Each part is a node, each arc is a liaison
- Each part has no more than one liaison with any other part
- In a loop of n liaisons, if n-2 arcs are closed, then attempting to close 1 of the 2 remaining will automatically close the whole loop:





Generating Sequences

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Source:
Figure 7-3 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Selecting Sequences

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Source:
Figure 7-4 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

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Figure 7-5 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Two Alternator Sequences

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Source:
Figure 7-11 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Two More Alternator Sequences

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Source:
Figure 7-12 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Rules of Sequence Analysis

- Parts are rigid
- Liaisons (connections between parts) are also "rigid"
- Once a liaison is made, it stays made

Ask and Address Precedence Questions

- Goal of questions is to find out what moves are forbidden
- This is done various ways by different methods:
  - – Computer searches for free paths, using local escape directions and checking for interference
  - – Person detects these
- Typical questions:
    - can this part be added to those parts
    - can this set of parts be added to that set of parts
    - must these parts be present/absent in order to add that/those parts

Subset and Superset Rules Cut the Number of Required Questions

- These are true only if parts and liaisons are “rigid”
- Subset rule:
  - if you can add part X to parts {Y} then you can add part X to any subset of {Y}
  - fewer parts can’t contain blockers that aren’t in the original set
- Superset rule:
  - if you can’t add part X to parts {Y} then you can’t add part X to a superset of {Y}
  - adding parts can’t remove blockers that are in {Y}
  - counter-example in Sony tape deck with motor

Local and Global Freedom

- Local freedom means that the combined escape directions of all liaisons in the query have a common direction (dot product of escape vectors = 1)
- Global freedom means that there is a long range escape path that completely separates the parts in the query
- Local freedom can be detected by the computer just by inspecting the escape directions - easy
- Global freedom requires solving the “piano mover’s problem” - difficult or impossible

Finding Local Freedoms

- Use escape direction vectors:
  - Look at escape direction vectors for each feature
  - Look for common vector for them all
- Conventional screw theory will not work
  - It’s too hard to distinguish one-sided motion limits
- “Dr. Whitney, what do you do about the facets?”

Generate Precedence Relations

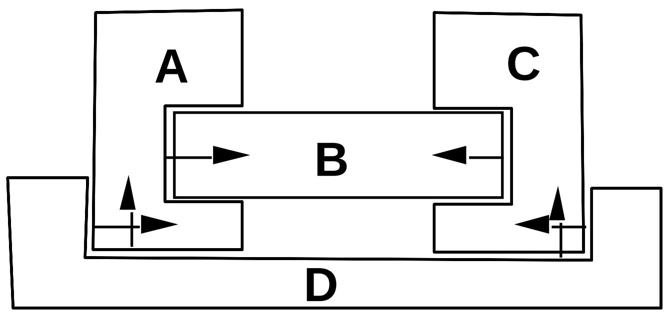
- Example of cookie jar and cookies
  - Can you put the cookies in the jar if the lid is on?
  - “No.”
  - Therefore: cookies to jar > lid to jar

Diagram Feasible Sequences

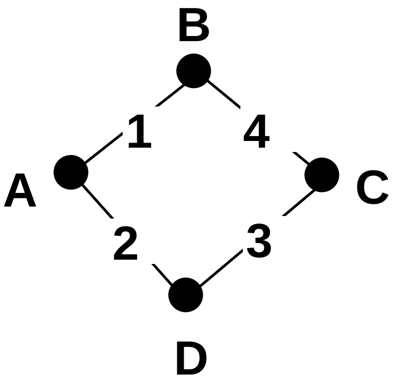
- Network of sequences represents
  - States of assembly = feasible subassemblies showing which liaisons have been completed
  - Transitions between states
- A path through the network is a feasible sequence
  - Cookies to jar, then lid to jar
  - Cookies to lid upside down, then jar to lid, then flip
- We decide later which is better

Simple Assembly Sequence Example

Assembly



Liaison Diagram



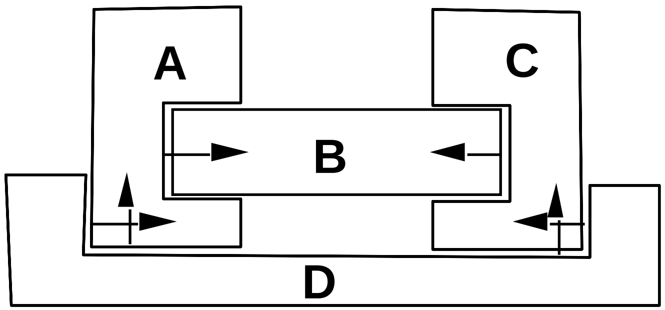
Local escape directions shown by arrows

Bourjault’s Process as Textual Analysis

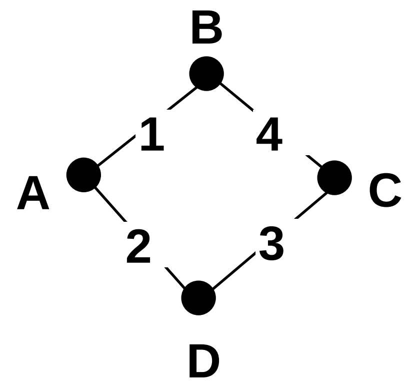
- Analysis question:
- R(a; b, c, d)=Can you make liaison a when b, c and d are already made?
- Ask this question for every liaison a combined with every other liaison b, c, d
- Bourjault’s original process uses graphical analysis based on circuit theory

Bourjault Method

Assembly



Liaison Diagram



R(1;2,3,4) Can't answer because 2,3,4 forces 1
Eliminate 2, 3, or 4
Eliminate 2: R(1;3,4) = No (need to know why)
  Eliminate 3: R(1;4) = Yes (so 4 is not why)
  Eliminate 4: R(1;3) = Yes (so 3 is not why)
  So 1>= 3,4 (i.e., 3,4 together is why)
Eliminate 3: R(1;2,4) = No
  Eliminate 2: R(1;4) already answered Y
  Eliminate 4: R(1;2) = Y
  So 1 >= 2,4
Eliminate 4: R(1;2,3) = No
  Eliminate 2: R(1;3) already answered Y
  Eliminate 3: R(1;2) already answered Y
  So 1>= 2,3

R(2;1,3,4) Can't answer
Eliminate 1: R(2;3,4) = No
  Eliminate 3: R(2;4) = Yes
  Eliminate 4: R(2;3) = Yes
  So 2>=3,4
Eliminate 3: R(2;1,4) = Yes
Eliminate 4: R(2;1,3) = No
  Eliminate 1: R(2;3) = aaY
  Eliminate 3: R(2;1) = Yes
  So 2>=1,3

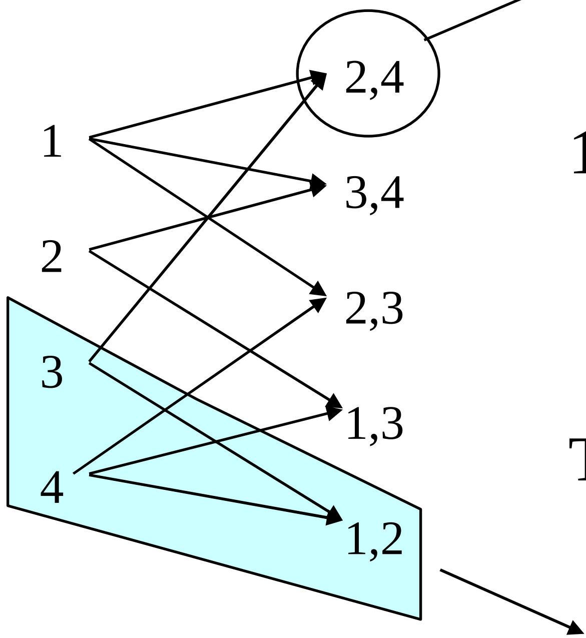
Done by symmetry:

4>=1,2
4>=1,3
4>=2,3

3>=1,2
3>=2,4

Results of Bourjault Method

these two together can’t be first



1,4 do not appear on the RHS,
so they are unprecedented,
so they can be first, in either order

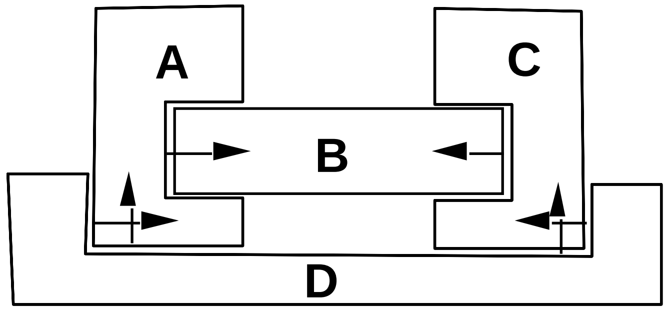
Then 2 and/or 3 can be next

3,4>=1,2

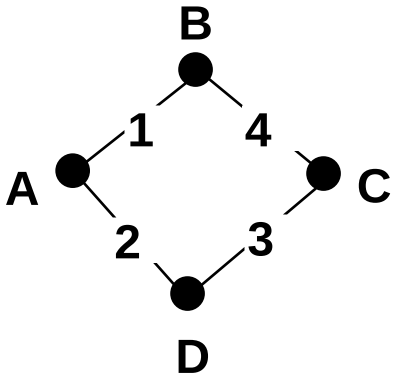
1,2>=3,4
1,3>=2,4
1,4>=2,3
2,4>=1,3

Simple Assembly Sequence Results

Assembly

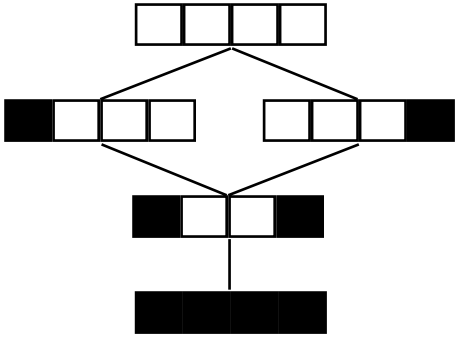


Liaison Diagram

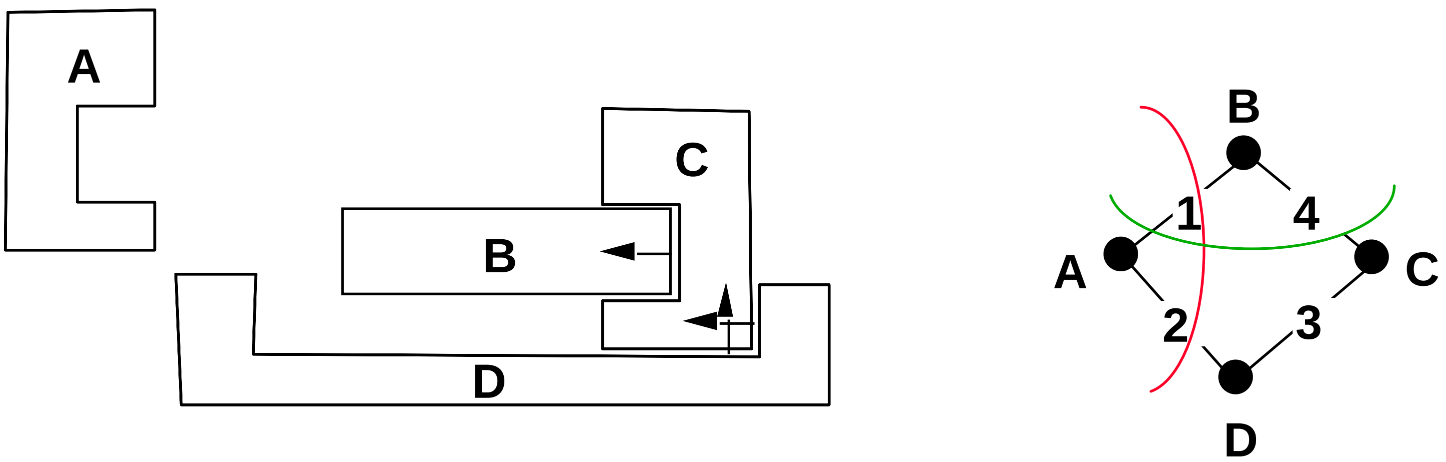


PRECEDENCE RULE: 1 & 4 > 2 & 3

DIAGRAM OF FEASIBLE SEQUENCES



Portion of Cutset Method



All questions except the last are answered by inspecting local freedom

R(1,2;3,4)? No: 1,2 >=3,4
R(1,4;2,3)? No: 1,4 >=2,3
R(3,4;1,2)? No: 3,4 >=1,2
R(2,3;1,4)? Yes: 1,4 unprecedented
so they can be first.

Other Methods

- Randall Wilson checks global freedom using the “weighted blocking graph”
- This is essentially a search for unidirectional escape paths along any of the local escape directions
- The escape directions are generated by inspecting individual surfaces on adjacent parts that touch each other, essentially rediscovering the mating features

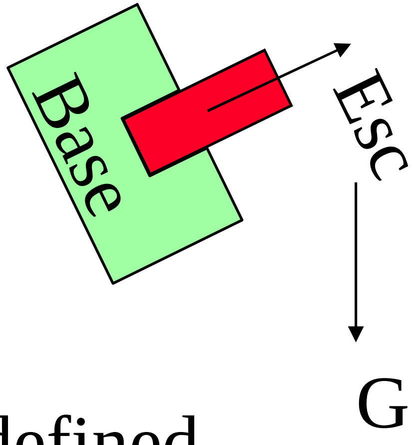
Other Methods, cont'd

- Gustavson and Wolter each generate exploded views by different methods and then generate precedence relations from the order along major explosion directions
- A reasonable assumption is that unless there is some blockage, all moves along one such direction will be done before starting on another
- Gustavson finds a heuristic sequence along major explosion directions using part c.g.s and asks the user to fix any errors

SPAS and Onion Skin Methods

- All local freedoms are checked by the computer
- All global freedoms are queried to the user
- This has two benefits
  - the computer does the easy part without attempting the impossible part or pretending to do it
  - the user must confront the design and become very familiar with it
  - Ref: Daniel Baldwin SM Thesis, MIT, Feb, 1990
  - Ref: Russ Whipple SM Thesis, MIT, June 1990

Stability Checking (Simplified)



- Start with the base part or the part in the fixture
- By definition, it is stable
- Check each of its liaisons
  - compare local escape direction to gravity
  - if part can't slide out then mark it "stable"
- Check the liaisons of each of the newly defined stable parts the same way
- If all parts in the liaison diagram can be marked "stable" then the assembly is stable
- Screw theory can be used to find mobility

Real Assembly Sequence Analysis Example

Images removed for copyright reasons.
Source:
Figure 7-21 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

ASSEMBLY DATA MODEL

PARTS OF REAR AXLE

PARTS	LIAISONS	PRECEDENCE RELATIONS
A = CARRIER ASSY	1 = C TO A	2 > 1
B = BACKING PLATE	2 = B TO A	5 > 4
C = SHAFT	3 = J TO B	1 & 2 & 6 > 5
D = BRAKE DRUM AND T'NUT	4 = D TO C	5 > 7
E = WITHDRAWN PINION SHAFT & BOLT	5 = G TO C	11 > 8
F = INSERTED " " "	6 = E TO A	10 > 9
G = (PUSH IN SHAFT &) C-WASHER & PUSH SHAFT OUT	7 = F TO A	12 > 10
H = OIL	8 = L TO A	12 > 11
I = COVER	9 = I TO A	3 > 1 & 4 & 5
J = BRAKE CABLE, COILED	10 = H TO A	7 > 10
K = FINAL PRESS TEST	11 = K TO A	9 > 11
L = AIR TEST PLUG	12 = M TO A	
M = FIRST PRESS TEST		

Rear Axle

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Source:
Figure 7-18 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Rear Axle Differential Subassembly After Liaison 1 Shaft to Carrier

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Source:
Figure 7-19 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Pinion Shaft Out (Liaison E) and Insert C Washer (Liaison G)

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Source:
Figure 7-20 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Pinion Shaft In (Liaison F)

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Figure 7-19 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Example assembly sequence graph

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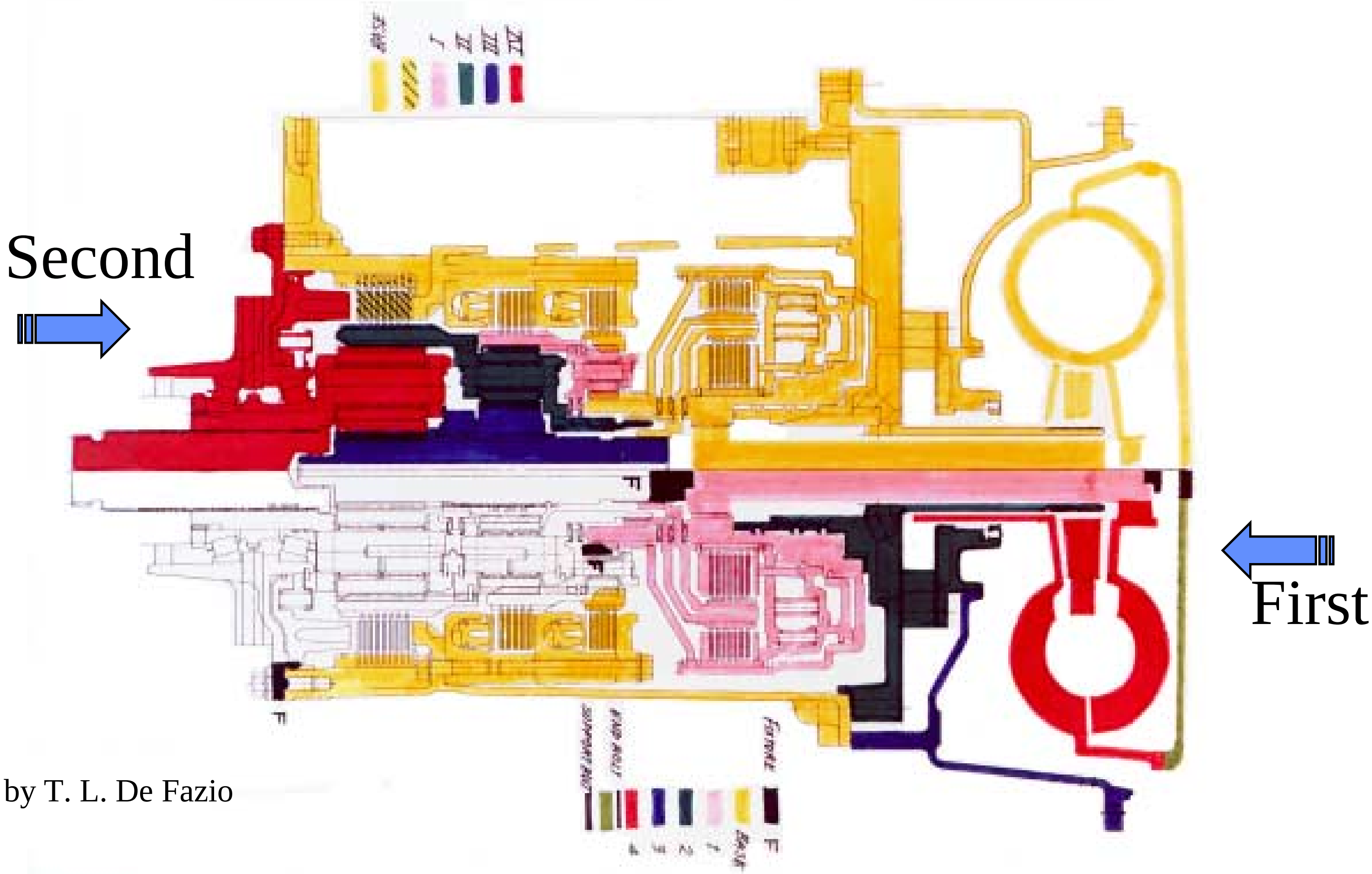
Source:
Figure 7-22 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Each path from top to bottom is a valid sequence. Each box is a valid intermedia assembly state.

Six Speed Truck Transmission



Drawn by T. L. De Fazio

Juicer

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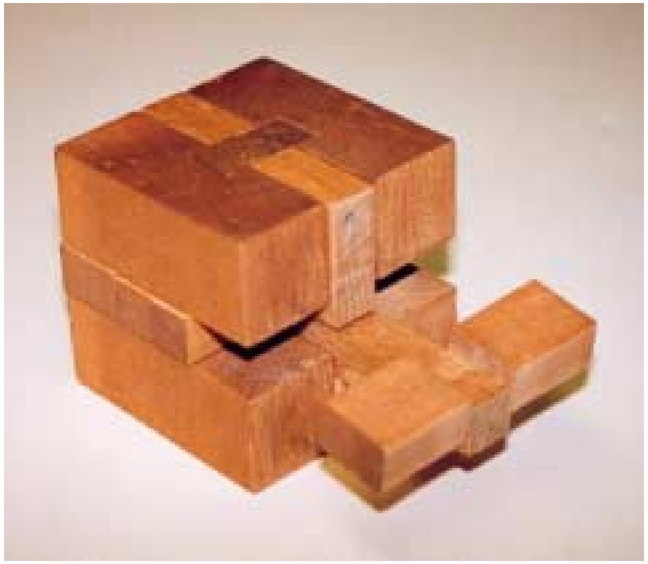
Source:
Figure 7-16 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

Network Complexity Metric

- The liaison diagram is a network
- How complex is an assembly?
- Network complexity metric k: (#arcs) / (#nodes)
  - Node = part, arc = connection between 2 parts
- If n = # parts, then
  - Min $k = (n-1)/n$
  - Max $k = n(n-1)/2n = (n-1)/2$
- Which product will have more assembly sequences?
  - Product with big complexity metric
  - Product with small complexity metric

Chinese Puzzle



Some Data on Liaisons per Part

Liaisons per Part

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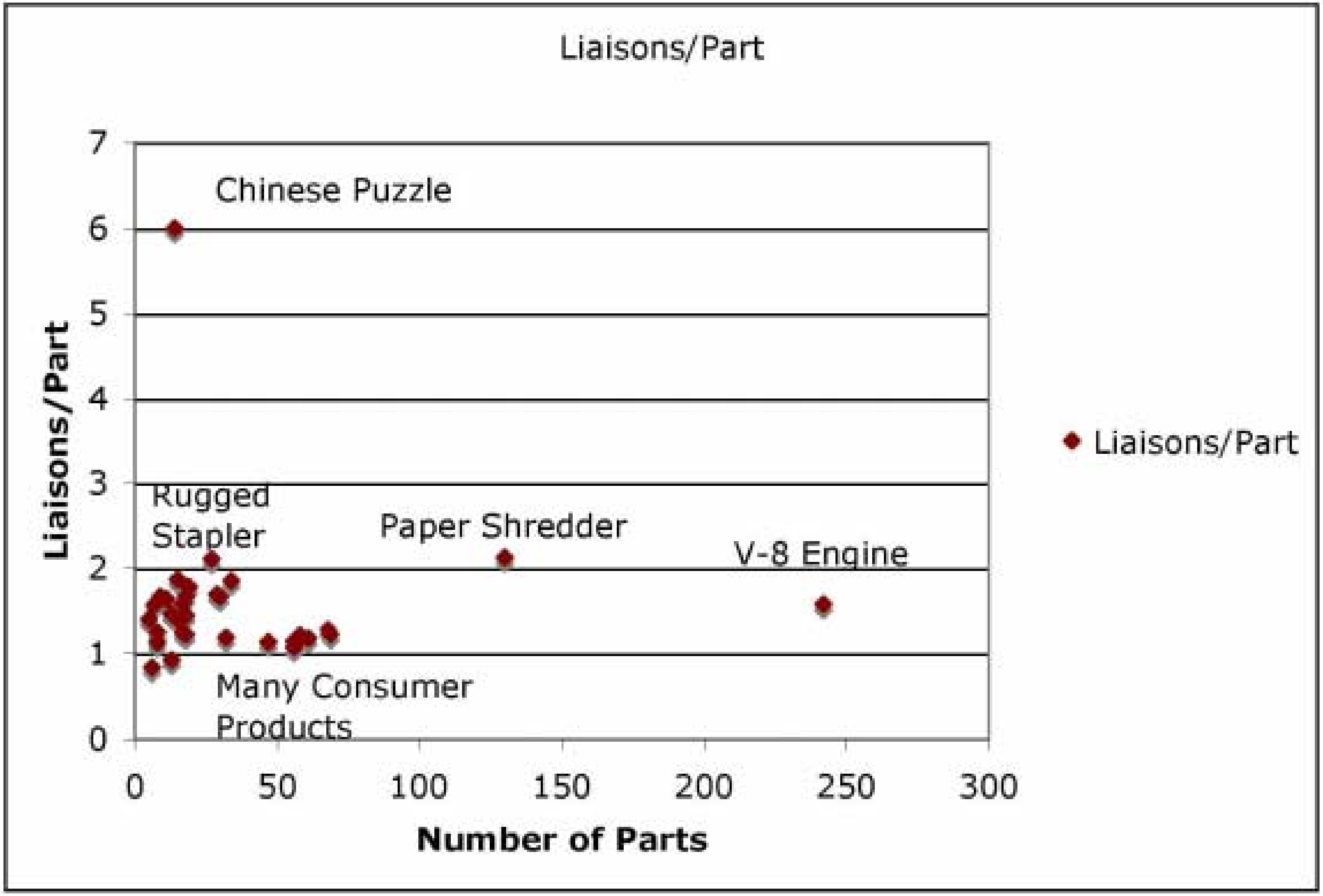
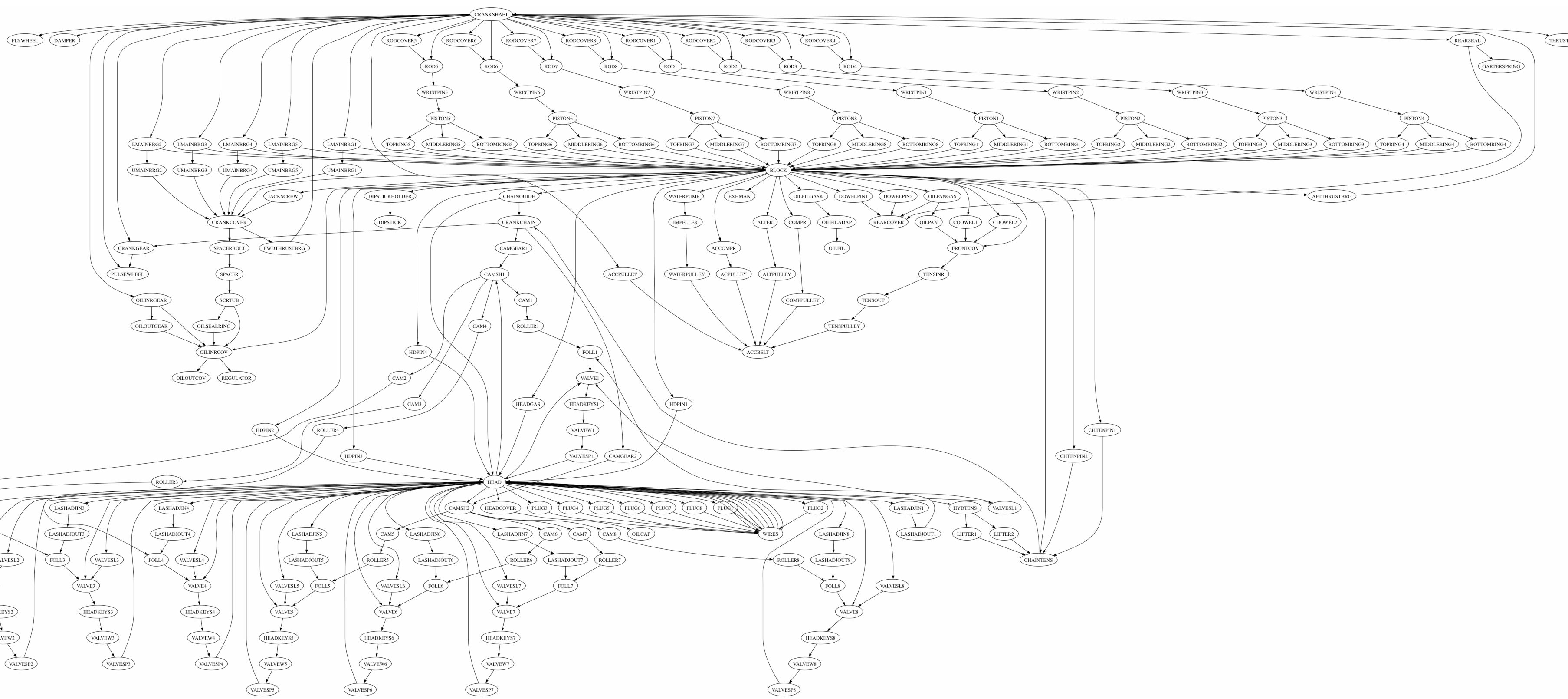
Source:
Figure 7-29 in [Whitney 2004] Whitney, D. E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. New York, NY: Oxford University Press, 2004. ISBN: 0195157826.

More Data: 34 Products



V-8 Engine Liaison Diagram



Constraint Limits Liaisons/Part

$M = 3(n - g - 1) + \sum$ joint freedoms f_i

where

n = number of parts

g = number of joints

f_i = degrees of freedom of joint i

$\alpha = liaisons / part$

$\Downarrow$ = average dof per joint

$g = \alpha n$

$\sum f_i = g \Downarrow = \alpha \Downarrow n$

and

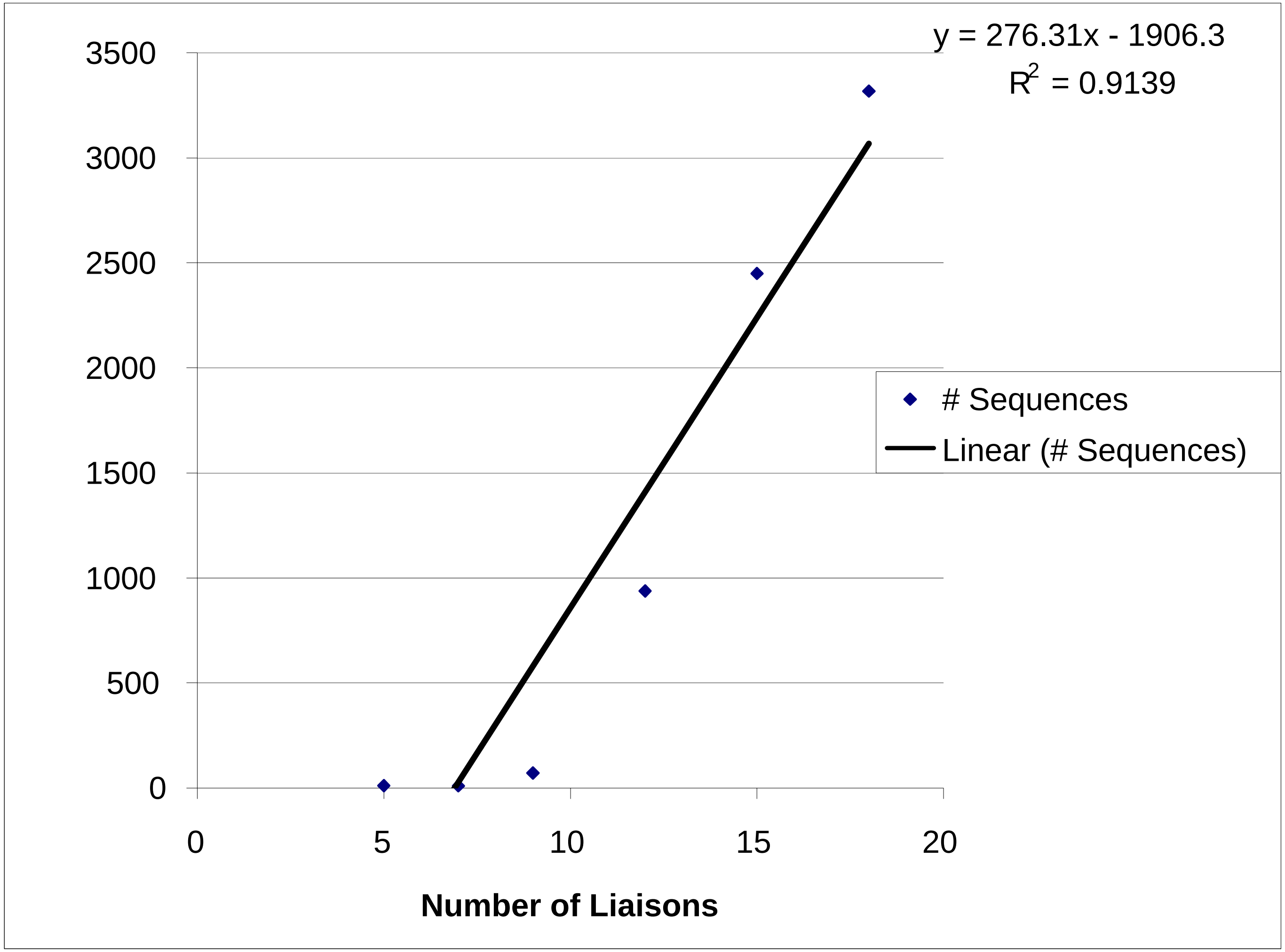
$M = 3(n - \alpha n - 1) + \alpha \Downarrow n$

If $M = 0$

$\alpha = \dfrac{3 - 3n}{n(\Downarrow - 3)} . \quad \dfrac{3}{3 - \Downarrow}$ as n gets large

$\Downarrow$	**α planar**	**α spatial**
0	1	1
1	1.5	1.2
2	3	1.5

Number of Sequences vs Number of Liaisons



	# Parts	# Liaisons	Liaisons/Part	# Sequences
Throttlebody	5	7	1.4	10
Ballpoint Pen	6	5	0.83333333	12
Juicer	8	9	1.125	71
Rear Axle	13	12	0.92307692	938
Transaxle	9	15	1.66666667	2450
6 Speed Transn	11	18	1.63636364	3318
Chinese Puzzle	14	84	6	1

Video

- Made by Randy Wilson and co-workers at Sandia National Labs in 1996
- Obtains one feasible sequence by using feasible escape cones derived from local escape directions
- Permits user to edit this sequence