Component Diversity and Minimizing Multiple Failures

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Ariane 5 Rocket 501 (in 1996)

- Exploded within the first minute of flight.
- Software bug: guidance computer generated a number too large to process, so it shut down and handed control to the other computer.
- Other computer was a replica of the first, so it made the same decision and shut down.

Downer, J. When Failure is an Option: Redundancy, reliability and regulation in complex technical systems. LSEPS, 2009.
https://en.wikipedia.org/wiki/Ariane_5

- This is an instance of a **common cause failure**, defined as

  Failure, that is a direct result of a shared cause, in which two or more separate channels in a multiple channel system are in fault state simultaneously, leading to system fault. (Rausand 2014)

- (We should not use the term common mode failure; refers to components being in the same functional mode.)
- Related notion is **multiple failure with a shared cause**, defined as

  Failure, that is a direct result of a shared cause, in which two or more items are in fault state simultaneously. (Rausand 2014)

- (In a MFSC, the system still functions.)

Rausand, M. Reliability of Safety-Critical Systems: Theory and Applications. John Wiley & Sons, 2014.

- This motivates the use of **diversity***:* instead of making the second computer a replica for Ariane 5, what if we had forced it to be different?
  - For example, if we had required it to have software written by a different group of people, it's possible that the bug would not have been present in both.
- Diversity guards against **coupling factors** in a system:
  - Same design, hardware, software, installation/maintenance/operation staff, procedures, environment, location.
  - Coupling factors reduce independence of failures.

Rausand, M. Reliability of Safety-Critical Systems: Theory and Applications. John Wiley & Sons, 2014.

Stockpile diversity

- What do people mean when they talk about stockpile diversity? Here are two proposed definitions.
- **Strategic diversity**: Ability to strike from air, land, water (i.e. the triad); different weapon types (B61-3, B61-7); varying yields.
- **Component diversity**: The use of different components to minimize the impact that a faulty component has on the stockpile.
- This talk is about the latter – the concern of multiple failures with a shared cause in the stockpile.

For strategic diversity, see, e.g., Lafleur, J. Triads, Diads, and Interoperability: A Structured Approach to Tracing the Implications of Diversity on Deterrent Force Reliability. PONI, 2013.

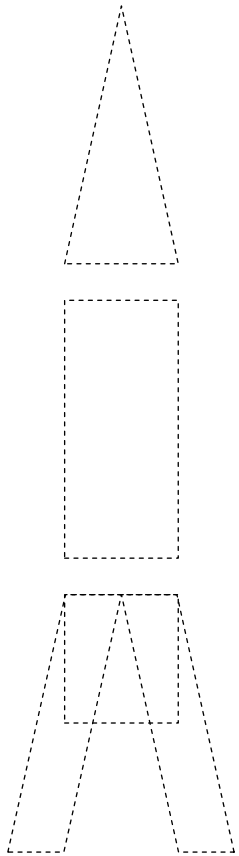
Models for diversity

- What about the beta-factor model?
  - Widely used method for common cause failure analysis.
  - Modify reliability block diagram by inserting a common cause failure "component".
  - Beta is fraction of failures due to common cause.
  - But, determining beta without sufficient data is tricky.
- Littlewood/Miller/Hughes models
  - Interplay of environments and components
  - *Having observed the failure of one of the components makes us more confident that this is a stressful environment, i.e. that the probability of failure is greater for every component, than would otherwise be the case.*
  - Environments/components can also be thought of as inputs/programs.
  - Proofs (!) for the benefits of diversity.
- This presentation: a new model based on a minmax criterion.

Rausand, M. Reliability of Safety-Critical Systems: Theory and Applications. John Wiley & Sons, 2014.
Littlewood, B. The impact of diversity upon common mode failures. Reliability Engineering & System Safety, 1996.

Example problem

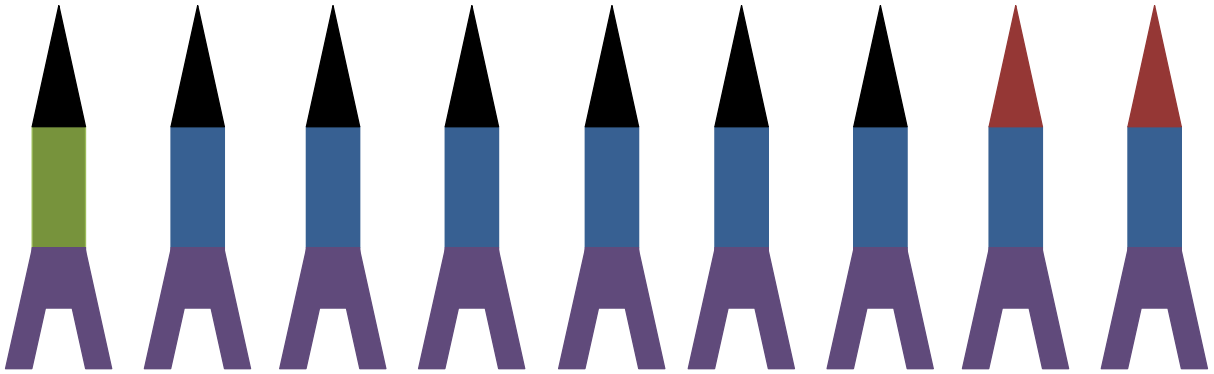
- Building a fleet of nine rockets.
- Analogous to a collection of, e.g., B61s.
- Each rocket requires nose, body, tail.
- We have multiple **brands** of each part.
  - Three nose brands
  - Three body brands
  - Three tail brands



- (Brands can be interpreted as manufacturing date, installation team, software version.)
- As far as we can tell, part brands are equally reliable, but we haven't tested them extensively.

Example problem

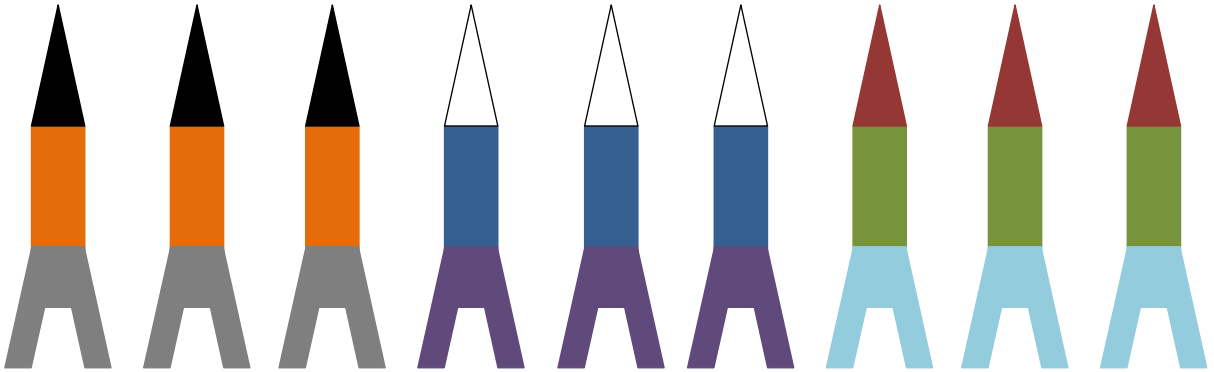
- One option is



- A problem with black noses affects 77% of fleet.
- A problem with blue bodies affects 88% of fleet.
- A problem with purple tails affects 100% of fleet.
- *Interpretation*: not diverse

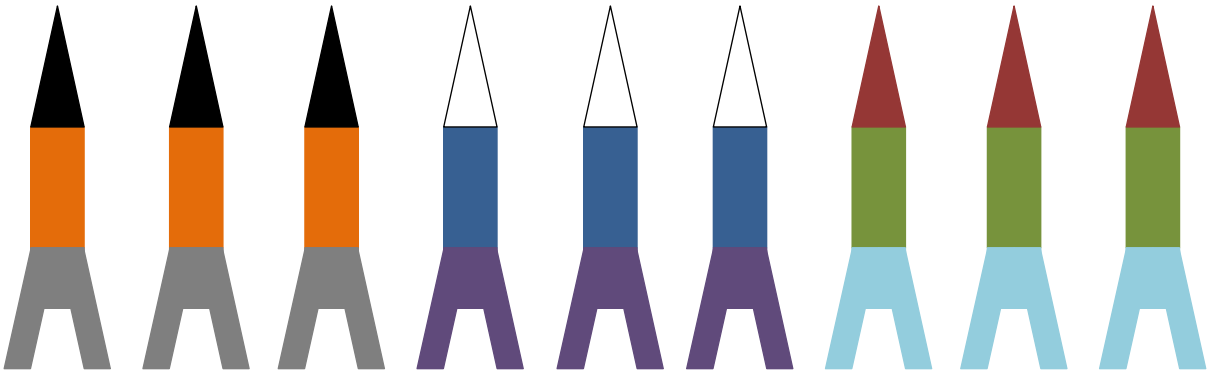
Example problem

- Another option is

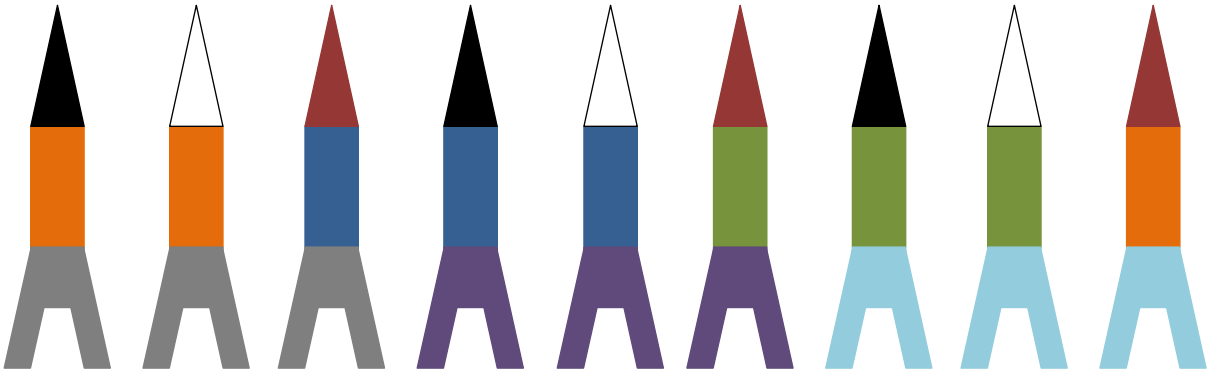


- A problem with any one brand now only affects 33% of fleet.
- *Interpretation*: more diverse
- This configuration **minimizes the maximum occurrence of each brand**.
- Can we do better?

- Consider



versus



- Latter fleet minimizes *pairs* of brand occurrences, and is rightly considered more diverse.
- For example, if orange bodies and gray tails have poor interaction, only 22% of fleet is affected in latter case.

Implementation

- For larger, more realistic problems, can formulate a mixed integer program.
- Match parts (p) to system slots (s) to minimize the occurrence of each brand (b).

$$
\begin{aligned}
\min \quad & z & & \\
\text{s.t.} \quad & \sum_{p:(p,s)\in E} x_{ps} = 1, & & \forall s \in \mathcal{S}, \\
& \sum_{s:(p,s)\in E} x_{ps} = 1, & & \forall p \in \mathcal{P}, \\
& \sum_{s\in\mathcal{S}} \sum_{p\in\mathcal{P}:B(p)=b} x_{ps} \le z, & & \forall b \in \mathcal{B}, \\
& x_{ps} \in \{0,1\}, & & \forall p \in \mathcal{P},\ \forall s \in \mathcal{S}.
\end{aligned}
$$

- Possible extensions: minimizing pairs of brands; multiple brands for each part; multiobjective approach for second, third most frequently occurring brands.