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An Introduction to Population-Based SHM: When is a Bridge not an Aeroplane?

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- *Population-based structural health monitoring* (PBSHM) has been proposed recently as a means of addressing certain difficult problems in 'conventional' SHM.
- Main motivation for the framework is to allow data from one structure to strengthen health-state inferences on a different one.
- Main means of allowing such cross-structure diagnostics is via the machine learning discipline of *transfer learning*.

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Homogeneous population:

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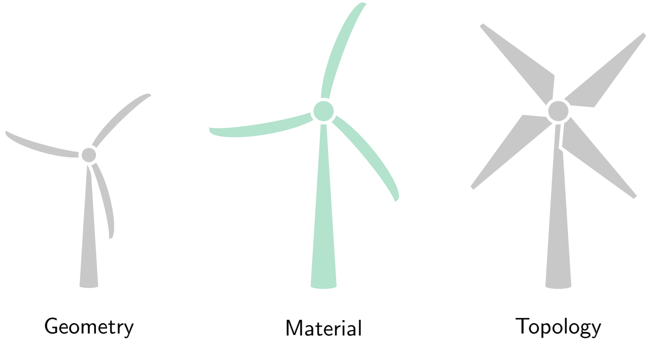
Heterogeneous population:



Population-Based SHM - Population Types

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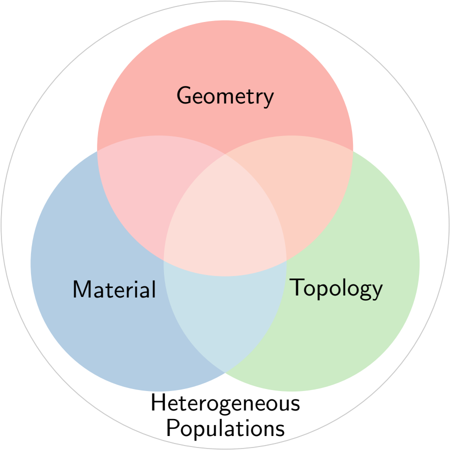

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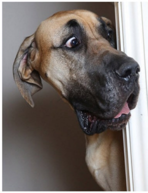
Source

Real | Cartoon



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Transfer Learning

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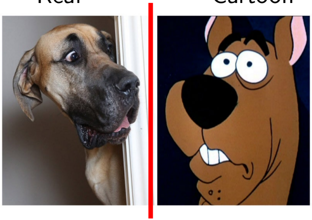

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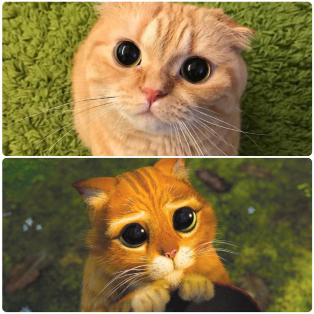

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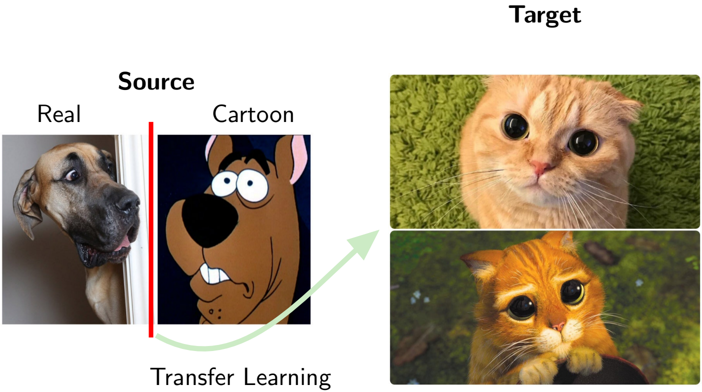
Transfer Learning



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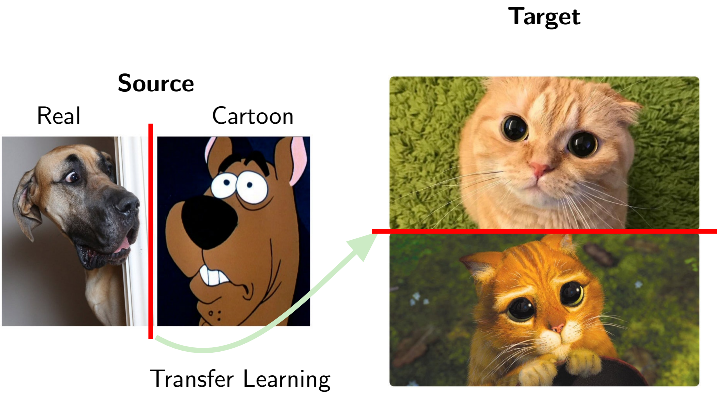
Transfer Learning



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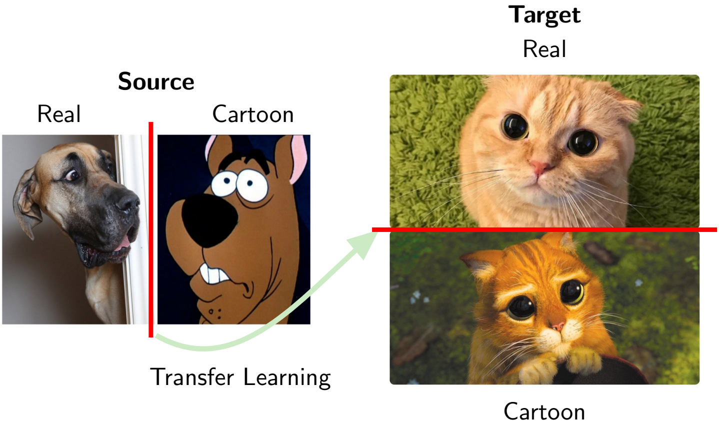
Transfer Learning



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Transfer Learning

- A significant issue in transfer learning is that attempted transfer between wildly-disparate structures will make matters worse.
- In order to deal with this issue, PBSHM is based on an abstract representation of structures, in which structures become points in a metric space.
- The ‘metric’ aspect of the space is crucial, it allows a measure of distance, or similarity, between structures such that transfer should only be attempted between those which are ‘sufficiently close’ to each other.
- The first stage in establishing the representation of a structure is to construct an *Irreducible Element* (IE) model.

IE Models

- An IE model of a structure is intended to capture the essential nature of that structure in terms of a small (if possible) set of fundamental structural elements.
- These elements can be labelled as fundamental engineering objects, e.g. [beam], [plate], [shell] etc., or contextually, e.g. [wing], [deck], [blade].
- The second step in representation is to convert the IE model into an *attributed graph* (AG).
- In the AG representation, individual IEs appear as nodes (vertices) in the graph; information about how elements join together is encoded in graph edges.
- Each node and edge is assigned a vector of attributes which specify details of material and geometry etc.

The Space of Graphs/Structures

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- The important point now, is that the space of AGs is a metric space, as mentioned above.
- The metric here makes use of the *maximum common subgraph* (MCS) between two graphs, as this will correspond to a common substructure in the structures of interest.
- The assumption is that damage state information may be shareable between structures if it occurs in a common substructure.

SHM Problems

- In order to assess how likely it is that one will succeed in transferring SHM problems between structures, one needs a principled means of describing the structure of problems.
- For data-based SHM, the main issue concerns the *label space* of the problem.
- For example, if the problem is to locate damage on a structure to one of N substructures, the label space is simply the discrete set $\{L_1, \dots, L_N\}$, where L_i is unity if damage is present in substructure i, and zero otherwise.

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- The idea of transfer across heterogeneous populations, raises the question of when structures or substructures are sufficiently similar that transfer is possible i.e. does not lead to *negative* transfer, and make diagnostics *worse*.
- In more facetious terms, one might ask the question: when is a bridge not an aeroplane?
- The simple answer to that question is *almost always*, but a more detailed answer is worth consideration.
- Consider a highly-simplified AG for an aeroplane.

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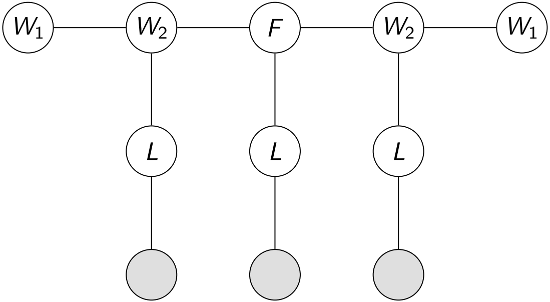
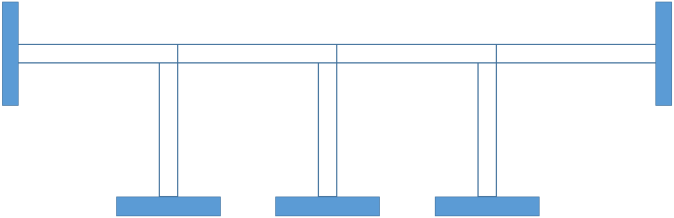
- 

- F corresponds to an IE [fuselage], W_1 to [wing (inner)], W_2 to [wing (outer)] and L to [landing gear].
- Although the figure is very simple, it is generic; many aeroplanes will have this representation at some level of detail.

IE Model of a Bridge

- Now, consider a highly-simplified IE model of a four-span bridge B_4.



- With contextual labelling for the IEs, where S denotes [deck] and P denotes [pillar].

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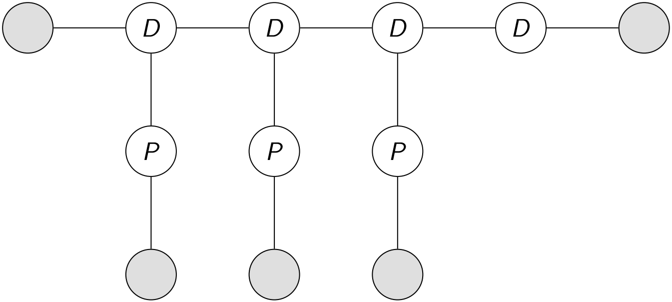
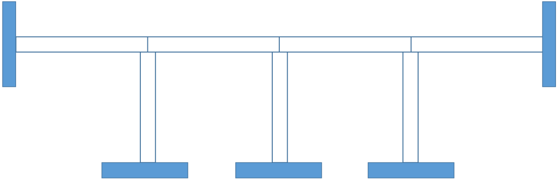
AG Model of a Bridge

- The corresponding AG model of the bridge is,



Uniqueness

- One can actually arrive at different IE-models via the placing of joints.
- The representation of B_4 earlier is, in a sense, minimal.
- Suppose one wished to make the IE model more symmetrical, like,



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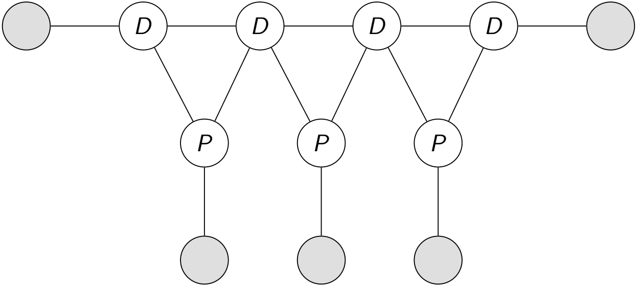
- While symmetry is usually very useful as a guiding principle, in this case it produces a problem.
- The induced AG from this IE model is much more complicated,



Uniqueness III

- Apart from the complexity of the ‘symmetric’ AG, the representation has made it difficult to compare even another representation of the same structure.
- We need rules for the production of IE models, so that ambiguity is avoided.
- In this case the rule might be: *when a pillar IE is placed at the joint between two sections of deck, it should be connected only to the left deck IE*.
- Such rules should be applied whenever any physics does not dictate otherwise.

Comparing the Aeroplane and Bridge

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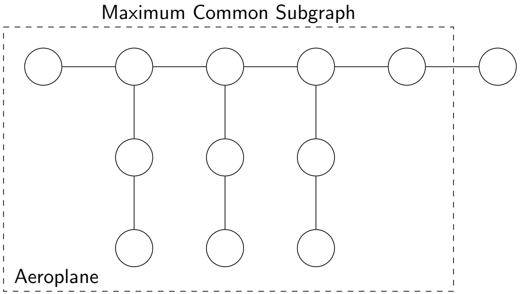
- Now, comparing the graphs at a topological level, one has the situation,



- The maximum common subgraph between the bridge B_4 and the AG for the aeroplane is the entire aeroplane. Up to topology,

$$[\text{bridge}] = [\text{plane}] \oplus [\text{node}]$$

Comparing the Aeroplane and Bridge

- At this level, if the SHM problems for the bridge and aeroplane are location problems, transfer from the bridge to the aeroplane looks straightforward.
- Transfer from the aeroplane to the bridge is an $(L+1)$ problem. (Briefly, this is problem in which the source and target problems for transfer differ in only one label.)
- Furthermore, the additional node in the bridge AG is a ground node.
- Applying some metric on the space of AGs would indicate in this case, that the bridge and the aeroplane are very similar structures, and successful transfer might be indicated.

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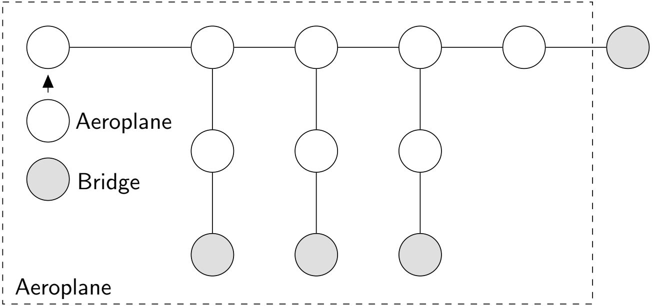
'Metric' for Transfer

Structural Equivalence

- One should consider structural equivalence rather than just topological (i.e. the AGs should be directly equivalent with ground nodes in corresponding places.
- The situation is then,



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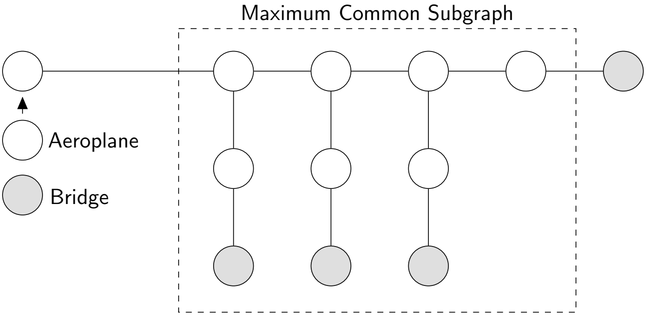
Structural Equivalence

- In the case of structural equivalence, the maximum common subgraph between the bridge and aeroplane structures is reduced a little,



In this case, one would expect the metric distance between the bridge and the aeroplane to increase a little, assuming that an appropriate metric is in use.

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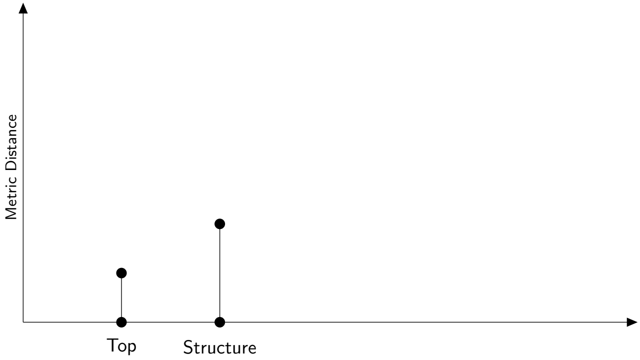
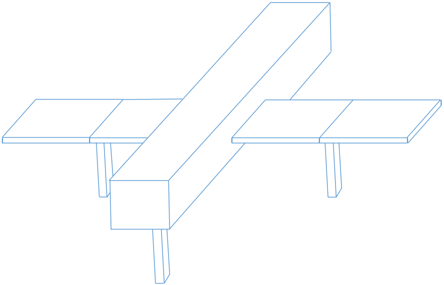


Geometrical Similarity

- At the next level of detail in comparing structures, one must think of the detailed dimensions of the structures of interest.
- These dimensions are encoded in the AG representation via the node attributes. This allows considerable flexibility; e.g., even if all of the IEs in the aeroplane model are [beam] elements, the (crude) representation is still strangely identifiable as an aeroplane (with no tail).



Geometrical Similarity II

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- With this rather crude IE model for the aeroplane, the two structures will move further apart in terms of the metric; because it will take into account the *attributes* which determine *geometry*.
- The edge attributes of the aeroplane AG will also be quite different to the bridge AG because of the different joints.
- For example, the joints between the deck elements in the bridge IE model could be simple butt joints; however, the joint attributes between the fuselage and inner wing elements in the aeroplane will need to encode where on the fuselage the wing is attached.
- Taking geometry into account, the structures move further apart using the AG metric.

'Metric' for Transfer

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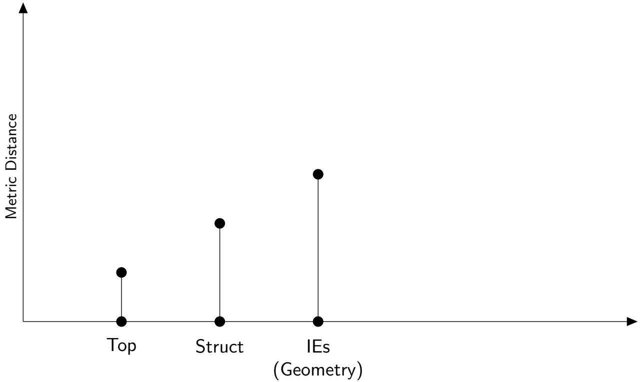

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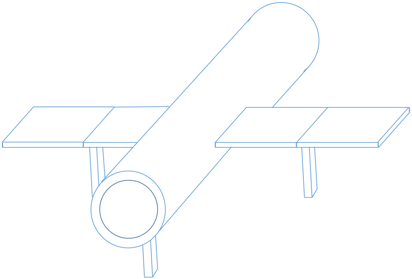
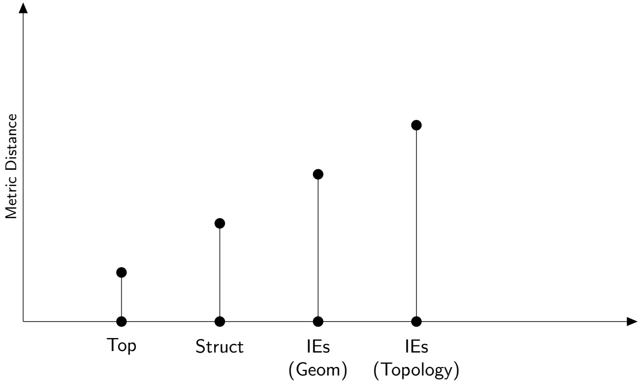
Refinement

- Suppose the aircraft representation is considered far too crude in terms of the approximation [fuselage] = [beam] and the engineers concerned feel that a cylindrical shell is needed,



- In this case, the aeroplane and bridge structures will move further apart again in terms of the metric on the space of AGs.

‘Metric’ for Transfer



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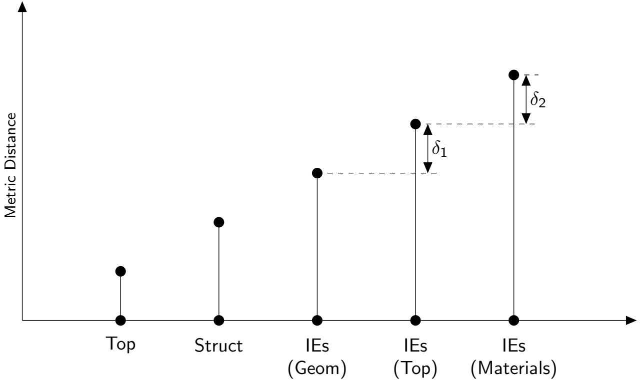
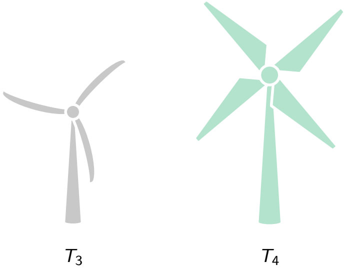
- Finally, the metric needs to take account of differences in material attributes (aircraft are rarely made of concrete); the final result is,



Material Similarity

- We will now consider two wind turbine structures T_3 and T_4, differing in topology and geometry: T_3 is a three-bladed turbine, while T_4 is a four-bladed turbine which is greater in size.
- The two turbines will also be considered to be of slightly different materials.



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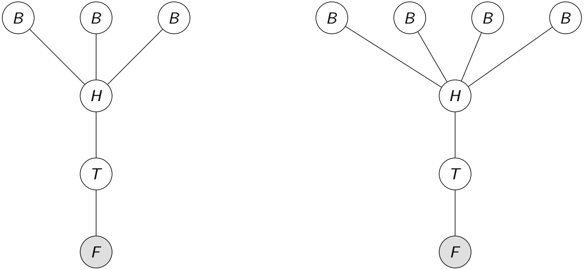
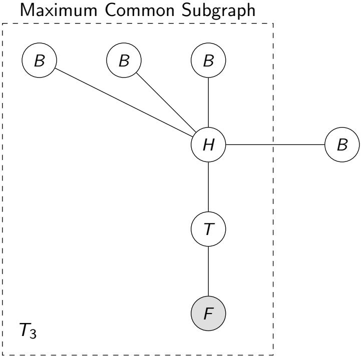
- Main difference between T_3 and T_4 is in terms of topology; they will have different AGs.
- B denotes [blade], H is [hub], T is [tower] and F denotes [foundation] – a specific designation for the ground node.



(a) T_3 (b) T_4

Likelihood of Transfer

- The maximum common subgraph between T_3 and T_4 shows that $T_4 = T_3 \oplus [\text{blade}]$.
- This observation means that the prospect of transfer learning looks positive.



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$(L+1)$ Problems

- Both examples considered in this paper are $(L+1)$ problems in terms of transfer.
- This holds true for *damage location* problems only.
- One has that, where there are two structures S_1 and S_2, at the AG level, $S_2 = S_1 \oplus [\text{IE}]$ i.e. the maximum common subgraph is S_1.
- In terms of the label spaces for damage location problems $\mathcal{L}_2 = \{\mathcal{L}_1, L^*\}$. Transfer from S_2 to S_1 looks likely and transfer from S_1 to S_2 is the simplest sort of extension problem.
- There will still be the possibility of negative transfer. The likelihood should be assessed using the metric on the space of AGs.

Overlapping Problems

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- In the case of the turbines problem, another possibility arises.
- The only real difference (at the level of structural topology), is that T_4 has an extra blade node.
- In practice, it may be that the two towers and hubs, and the blades themselves are similar; if overall geometries and materials are similar, transfer on the MCS would look very feasible, one might not expect negative transfer.
- Even so, extending to the $(L+1)$ problem might be stretch.
- However, in this case, there is the possibility of transferring *twice* on two MCSs, and thus covering the whole of T_4 – all four blades are labelled.

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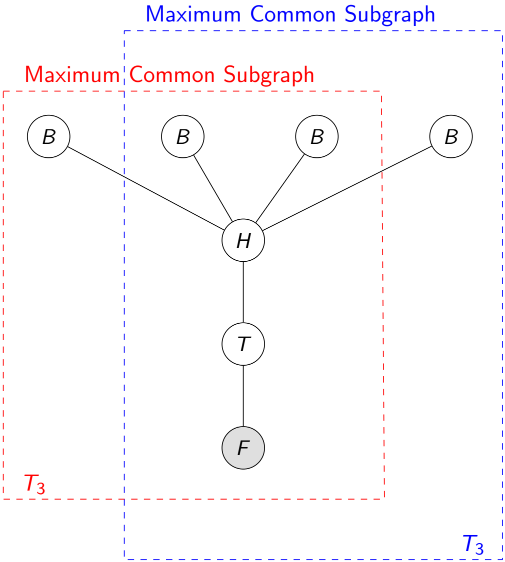

Metrics and Thresholds

- In the bridge-aeroplane case, there will be significant differences in materials and geometry, as well as dimensional mismatches in the IE attribute vectors.
- In this case, the threat of negative transfer will presumably be much greater.
- Dealing with this matter properly will depend on the definition of an appropriate metric on the space of AGs, careful weighting of attributes and the definition of a *threshold*, under which, metric distances will indicate the probable success of transfer.
- The two case studies discussed here can be plotted on the same metric diagram.

Metrics and Thresholds II

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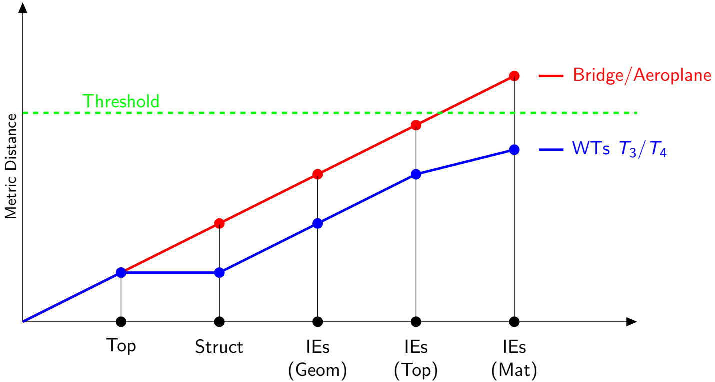
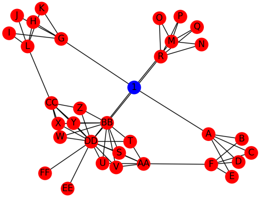
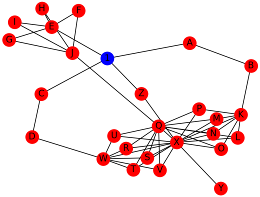


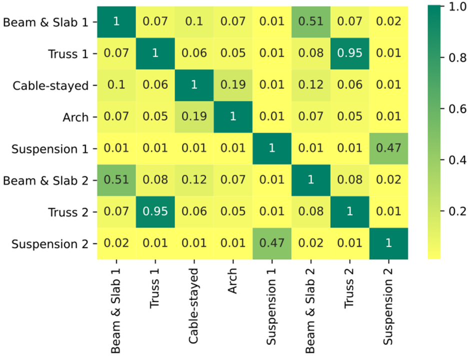
Real Bridges

- On a somewhat amusing note; it can happen that the layout of the AG suggests a form for the structure of interest which is positively deceptive.
- Here are the AGs for two IE-models of real bridges; the layout suggests aircraft more than bridges; in fact, they appear birdlike.





Eight Real Bridges



Gnat/Piper Transfer

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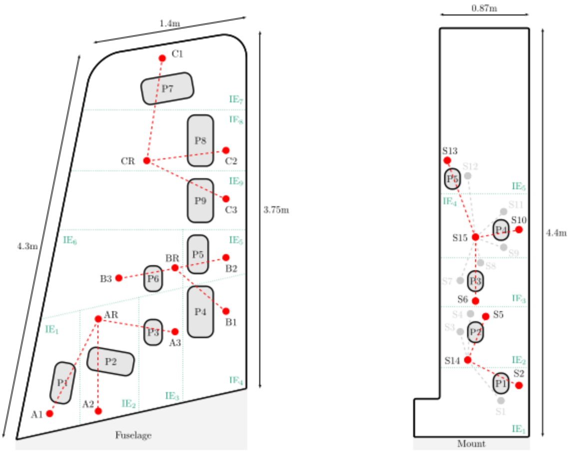

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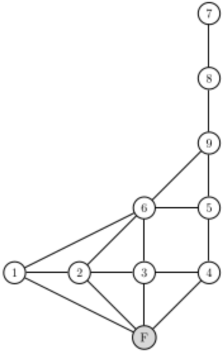
AG Models



Analysis

- Idea was to train a classifier on five panels of the Gnat (source), that would work on Piper (target).
- Problem was how to choose which five – which would give positive transfer?
- including variations in the feature ordering, there are 15120 possibilities, choosing panels at random.
- Restricting to isomorphic AG models – number is reduced to 4!
- TL algorithm was *domain adaptation* (kernel-based).
- Of the 15120 'random' transfers, 0.6% gave perfect classification after transfer.
- Of the 4 isomorphic models, 1 gave perfect classification – 25%.

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Conclusions

- Paper presents a pictorial overview of some of the ideas at the heart of population-based SHM.
- The abstract ideas at the heart of the theory are explored via simplified case studies.
- A number of highly-idealised irreducible element (IE) models and attributed graphs (AGs) are shown for some engineering structures: a bridge, an aeroplane and two wind turbines.
- The question of making comparisons between structures is discussed in terms of their maximum common subgraphs.
- The paper touches briefly on some open problems like the 'rules' for generating IE models and how one might set thresholds for transfer.

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Questions?