

The Hidden Scale Problem: Mechanisms Change Their Relative Weight With Size

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Abstract

A result obtained at one size is often treated as though scale changes only the amount of material involved. In many physical systems, changing size changes the relative importance of mechanisms. Surface-to-volume ratio, diffusion distance, optical path, thermal mass, stress gradients, defect population and transport time do not scale identically. A thin film can therefore be reaction-limited while a thick section becomes transport- or heat-limited; a small specimen can cool rapidly while a larger one retains exotherm; a feature reproduced at one dimension can disappear when optical and mechanical length scales become comparable with it. This methodological article develops the hidden scale problem. The central proposition is that scale is a state variable whenever changing geometry changes the competition among mechanisms.

Keywords: scale; scaling; geometry; thickness; surface-to-volume ratio; diffusion; optical path; heat transfer; transfer; dimensional analysis

1. Purpose and evidence boundary

HEB-012 addresses transfer across size as a methodological problem. ER-010 retains VPP geometric metrology across scales [2], and ER-185 retains thick-section photocure qualification [3]. The objective here is to identify why simple proportional scaling often fails. The premise extends HEB-001's warning that hidden variables outside the nominal setting can dominate inference [1].

2. Geometry changes ratios, not only dimensions

For geometrically similar objects, volume grows with a characteristic length cubed while surface area grows with length squared. Surface-to-volume ratio therefore decreases as size increases. Processes controlled by interfaces, cooling, evaporation, oxygen exchange or extraction can change relative importance even when shape is preserved.

3. Diffusion time grows faster than distance

A characteristic diffusion time scales approximately with length squared for a given diffusivity. Doubling a diffusion distance therefore does not merely double the equilibration time. Washing, solvent ingress, oxygen transport and leaching can become qualitatively different problems in thicker or more enclosed geometries.

4. Optical path creates depth dependence

In absorbing or scattering media, increasing thickness changes the delivered light field. The surface and core can therefore follow different reaction histories even at one nominal exposure. ER-185 retains the application-specific qualification of thick-section photocuring; HEB-012 uses the case only as a scale-dependence example [3].

5. Thermal scaling changes reaction history

Larger volumes can retain reaction heat because heat generation scales with reacting volume while heat loss is constrained by boundary area and thermal transport. The resulting temperature history can change reaction rate, conversion, stress and degradation. Matching nominal exposure does not match thermochemical history.

6. Defect opportunity changes with stressed volume or area

A larger specimen samples more material and potentially more defects. Strength statistics can therefore change with gauge volume or stressed area even if local material properties are unchanged. A test coupon and a component do not necessarily share the same failure distribution. Classical weakest-link statistics provide one formal basis for such size dependence in strength [4].

7. Feature scale competes with process scale

A printer pixel, cure depth, beam width, layer thickness, support contact or roughness amplitude becomes important when it is no longer small relative to the intended feature. Resolution, dimensional fidelity and anisotropy are therefore scale-dependent observables, not universal single numbers [2].

8. Scale can change the dominant mechanism

At small scale, surface chemistry can dominate; at larger scale, bulk transport or heat can dominate. A small transparent specimen can be optically uniform while a larger filled part becomes scattering-limited. The same chemistry has not necessarily changed, but the ranking of mechanisms has.

9. Dimensional similarity is not physical similarity

Geometric similarity preserves shape ratios but does not automatically preserve dimensionless groups governing heat, mass, momentum or reaction. Transfer requires identifying the governing ratios for the phenomenon of interest. Without that step, 'scaled-up' can describe appearance while hiding a different physical regime.

10. Practical scale challenge

Before transferring a result, identify characteristic lengths: optical path, diffusion distance, wall thickness, thermal length, stressed dimension, feature size and boundary-layer thickness. Test at more than one relevant scale and look for a change in trend, not only a shift in magnitude. Where the intended component lies outside the validated scale range, treat the transfer as an extrapolation.

11. Scaling laws make hidden changes predictable

The simplest scale arguments already warn against linear transfer. For a characteristic length L , area scales as L^2 and volume as L^3 . For diffusion-controlled equilibration, a characteristic time often scales as L^2/D for fixed diffusivity D . These relations do not solve a real experiment, but they identify where proportional intuition fails. Doubling thickness can quadruple a diffusion timescale while doubling a lateral dimension changes heat-loss geometry differently. Dimensional reasoning should therefore precede empirical scale-up: identify which terms grow with length, area, volume or time and which boundaries remain fixed.

12. Optical and thermal scaling can reinforce one another

In a thick photoreactive section, additional path length attenuates light while additional volume can retain more reaction heat. The core may therefore receive less optical initiation but experience a different thermal history from the surface. Increasing exposure to compensate optical attenuation can further change exotherm. ER-185 retains the application-specific qualification of thick-section photocuring [3]. The general methodological point is that scale can couple mechanisms that appeared separable in a thin specimen.

13. Mechanical scale exposes different defect populations

A small coupon samples a limited stressed volume and may avoid rare defects that become probable in a larger component. Conversely, a large geometry can redistribute stress and reduce local concentration compared with a small notched specimen. Scaling mechanical performance therefore requires both material statistics and geometry. A single strength value is not automatically portable between gauge sizes, feature scales and component architectures. The experiment must state what population and stress field the measurement represented.

14. Representative specimens require representative governing dimensions

A test specimen need not copy the whole component to be representative, but it must preserve the dimensions that control the claimed mechanism. For a diffusion-limited process that may be wall thickness or path length; for optical cure it may be attenuation distance; for bending it may be thickness and span; for surface contamination it may be area-to-volume ratio. Choosing a convenient coupon while changing the governing dimension can create a test that is precise but physically irrelevant. The hidden scale problem is controlled by identifying which dimensions carry the mechanism before designing the specimen.

15. The measurement apparatus has a scale too

Scaling the specimen can move it relative to the characteristic scale of the measurement system. A surface probe that samples a small region may be representative on a uniform thin film and unrepresentative on a larger heterogeneous part. A voxel size that resolves a small defect in one geometry may merge it into partial-volume signal in another. A fixture can constrain a small specimen strongly while having negligible influence on a larger one. Measurement scale and specimen scale must therefore be considered together. A transfer study can fail even when the underlying material physics scales acceptably because the metrology no longer resolves the same feature population.

16. Scale-down can create artefacts as well as remove them

Scale-up receives most attention, but miniaturisation is not automatically safer. Very small features can become dominated by surface roughness, pixelation, meniscus forces, oxygen exchange, boundary adhesion or finite particle size. A laboratory microcoupon may therefore enter a regime that the full component never experiences. Scale-down studies should ask whether the simplification preserves the governing mechanism or replaces it with one controlled by boundaries and manufacturing resolution. A representative small test is one that preserves the relevant dimensionless or characteristic ratios, not merely one that uses less material.

17. Conclusions

Scale changes mechanism weighting. Surface-to-volume ratio, diffusion time, optical attenuation, thermal retention, defect opportunity and process-feature ratios do not transform identically. A result can therefore be valid at one scale and misleading at another without any experimental mistake at either scale. Transfer requires a scale model, not a multiplication factor.

References

- [1] Segurolo, J. The Hidden Error Budget: Measurement-System Failure, False Precision and Experimental Design in Laboratory Science. HEB-001. 3Dresyns Independent Technical Articles (2026). DOI: 10.5281/zenodo.22862642.
- [2] Segurolo, J. Metrology of Vat Photopolymerisation: Resolution, Trueness, Precision and Geometric Fidelity Across Scales. ER-010. Zenodo (2026). Concept DOI: 10.5281/zenodo.22017483.
- [3] Segurolo, J. Thick-Section Photocuring of Putties, Gels, Sealants and Potting Compounds: Attenuation, Frontal Cure, Exotherm and Through-Cure Qualification. ER-185. 3Dresyns Engineering Publications (2026).

[4] Weibull, W. A Statistical Distribution Function of Wide Applicability. *Journal of Applied Mechanics* 18(3) (1951) 293-297. DOI: 10.1115/1.4010337.

Knowledge boundary

HEB-012 owns the general reasoning problem of scale transfer. ER-010 retains VPP dimensional metrology; ER-185 retains thick-section photocure qualification; application-specific scale-up remains with its corresponding ER.

Limitations

This methodological article is a bounded synthesis of the controlled HEB and Engineering Review corpus. It does not report a new experimental dataset, does not establish universal numerical thresholds, and does not convert examples from one domain into application-wide specifications. Claims that require application-specific qualification remain with the corresponding technical review or primary study.