

Physics and Metaphysics of Scale

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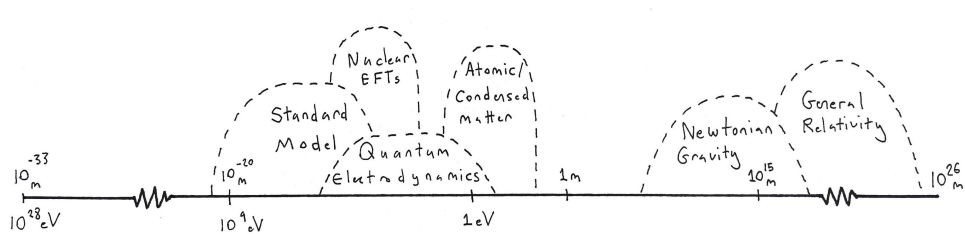
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Central APA, 21-24 February, 2024

- 1 Motivation
- 2 Physics of Scale
- 3 Metaphysics of Scale

Different Scales, Different Theories

Physicists use different theories to describe the world on different scales.



Epistemic vs Metaphysical Views of Scale

Two views:

- 1 Physicists use different theories at different scales for epistemic/pragmatic reasons; e.g. non-fundamental theories are preferred because they allow us to derive predictions which would be difficult to obtain from a more fundamental theory.
- 2 Physicists use different theories to describe different scales because the world exhibits different nomic structure on different scales; **non-fundamental theories are preferred because they carve nature at its joints better** in the domains in which they apply.

Batterman vs Woodward on Variable Choice

Batterman (2021) criticises Woodward (2016) for relativising our choice of representation entirely to the modeller's interests:

I argue that mesoscale parameters are natural variables in the sense that they are the best variables with which to characterize certain dominant, lawful behaviors of many-body systems...In arguing this I am addressing metaphysical concerns about the proper way to carve nature at its joints. (Batterman, 2021, 136)

Fundamentality and Naturalness in Metaphysics

- ① **Dependence:** non-fundamental things metaphysically depend on more fundamental things.
- ② **Naturalness:** natural representations carve nature at the joints (often connected to laws, inductive projectability, reference, etc).

Orthodoxy in analytic metaphysics runs these two together, seemingly ruling out the possibility of natural non-fundamental theories.

Non-Fundamental Naturalness Possible?

Can we make any sense of the idea that different physical theories provide more natural representations at different scales without endorsing some form of strong metaphysical emergence?

Some metaphysicians have recently developed ideas which seem to open up this possibility: Alastair Wilson (2024), Gómez Sánchez (2023), Jessica Wilson (2021).

Why Care about Scale?

Scale relative laws in physics could be an instructive special case for the broader debate about special science laws.

The case of physical laws at different scales is more tractable because we have a well-developed formalism for relating physical theories describing different scales: the [renormalisation group](#).

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Fields

A field is an assignment of quantities to space-time regions.

$$\phi(x), \quad x = (\vec{x}, t)$$

Our current most fundamental physical theories are quantum field theories.

Lagrangians

The dynamics of a field theory are specified by a Lagrangian.

$$\mathcal{L}(x) = \underbrace{\frac{1}{2}[\partial\phi(x)]^2}_{\text{kinetic term}} - \underbrace{\frac{1}{2}m^2\phi(x)^2}_{\text{mass term}} - \underbrace{\lambda\phi(x)^4}_{\text{interaction potential}}$$

The Lagrangian fixes a set of allowed field configurations.

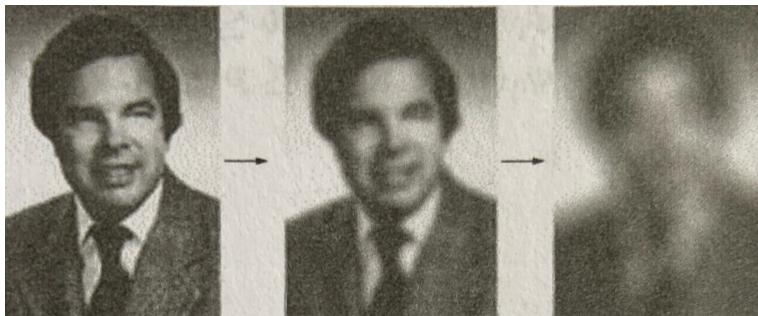
Beyond the T-Shirt Conception of Laws



The standard model Lagrangian is our current best stab at the world's most fundamental laws.

However, physicists usually do not use the standard model Lagrangian at lower energy scales.

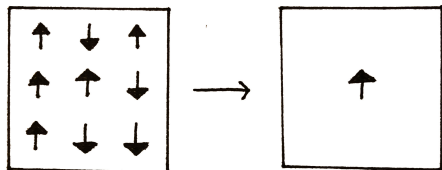
Course-Graining



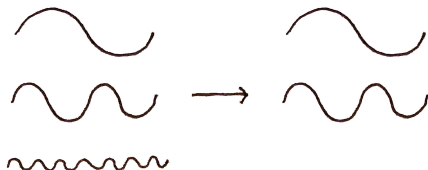
- 1 Remove the small length scale/high energy degrees of freedom of your theory.
- 2 Modify your Lagrangian so as to reproduce the same (or very similar) long-length scale behaviour.

Coarse-Graining

- 1 Remove small length scale/high energy degrees of freedom.



Real space coarse-graining



Momentum space coarse-graining

- 2 Modify the Lagrangian: $\mathcal{L} \rightarrow \mathcal{L}'$

Renormalisation Group Flow

Is it always possible to eliminate high-energy degrees of freedom in this way (Koberinski and Smeenk 2023)?

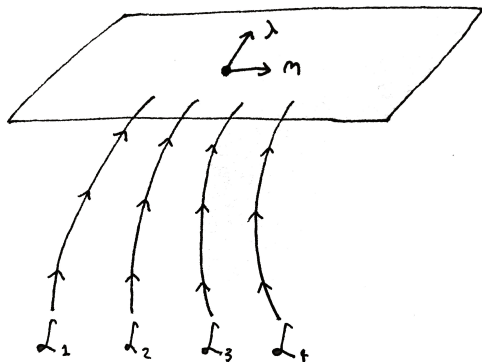
In the case of current quantum field theories it is, but to do so exactly one has to add an infinite number of terms to the “effective” Lagrangian \mathcal{L}' (seems bad but wait...).

The coarse-graining transformation induces a “flow” on a space of theories: studying this flow gives us information about how the low-energy structure of a field theory depends on its high-energy structure.

Result: Universal Low Energy Behaviour

Classes of fundamental theories are attracted to the same finite-dimensional surface.

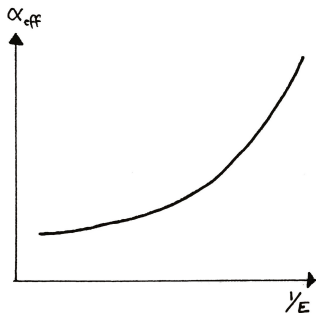
This means that, up to a high level of precision, we can mimic the low energy behaviour of a more fundamental quantum field theory using an effective Lagrangian with a finite number of parameters.



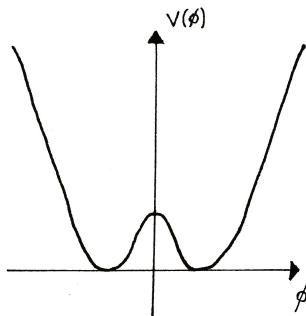
Seperation of Scales

The low-energy behaviour of a quantum field theory is highly insensitive to some aspects of its high-energy structure. This makes qualitatively distinct low-energy behaviour possible.

1. Running couplings



2. Hidden Symmetries



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Challenge

Can we give content to Batterman's claim that non-fundamental theories provide a more natural representation of low-energy/long-length scales?

Can we make sense of the world's nomic structure being described by \mathcal{L} at high energies but better described by \mathcal{L}' at lower energies?

A Naive Non-Humean Attempt

Suppose we take the Lagrangian \mathcal{L} to encode primitive natural modalities, e.g. Armstrong (1986), Adlam (2022).

Problem: Naively, analysing the claim that the world is described by \mathcal{L}' at scale E would mean positing a new set of modal primitives. Seem to either have redundancy or some form of strong emergence.

A Naive Best System Attempt

Could we implement Lewis's best system approach to lawhood on different scales?

- 1 Start with the fundamental Humean mosaic. Determine the best system of laws—hopefully, this is \mathcal{L} .
- 2 Implement some kind of coarse-graining of the Humean mosaic. Now determine the best system describing regularities in quantities below some energy scale E —hopefully, this is \mathcal{L}' .

Problem: Need to introduce a new set of primitive natural properties at each scale in order to implement a syntactic simplicity criteria (there are options here—Gómez Sánchez (2023)).

Sketch for a Metaphysical Model of Scale

On the face of it, traditional accounts of lawhood don't have the resources to express the key insight of the renormalisation group approach: a system is better described by a new Lagrangian at low energies because physics at scale E is only sensitive to some features of the fundamental laws.

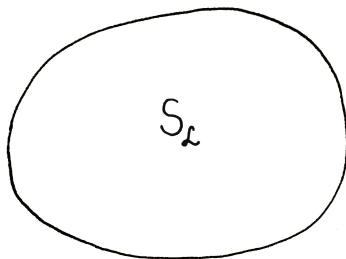
Here is a preliminary attempt to express this in metaphysician speak...

Ingredient 1: Set of Physically Possible Worlds

Assume we have a fundamental quantum field theory with Lagrangian \mathcal{L} which describes arbitrarily high energy scales.

Its solutions correspond to a set of possible worlds $S_{\mathcal{L}}$ in which these fundamental laws hold.

One can adopt a Humean or Non-Humean account of how this set of worlds is generated.



Ingredient 2: Scale-E Equivalence Relation

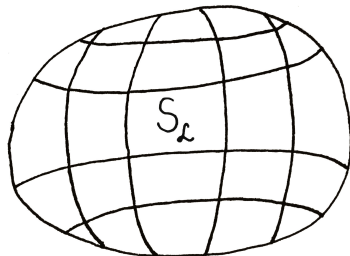
Introduce an equivalence relation between worlds.

Scale- E equivalence: \sim_E

Two worlds W_1 and W_2 are **scale- E equivalent** if they agree on all physical quantities below energy scale E .

Equivalence Classes on $S_{\mathcal{L}}$

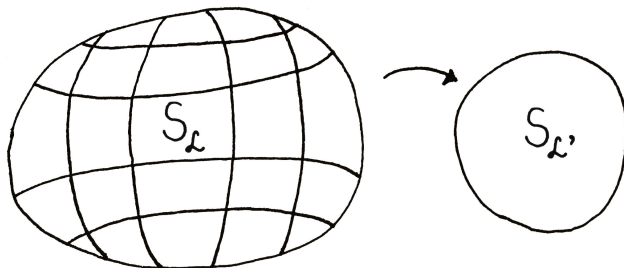
Question: does this equivalence relation group multiple worlds in $S_{\mathcal{L}}$ into equivalence classes?



The existence of equivalence classes represents the fact that only some of the modal content of $S_{\mathcal{L}}$ is relevant at scale E .

Quotient Set $S_{\mathcal{L}} / \sim_E$

Idea: The solutions of an effective theory with Lagrangian \mathcal{L}' stand in one-to-one correspondence with the quotient set $S_{\mathcal{L}} / \sim_E$.



Approximation and Precision

A **necessary correction**: we will only get agreement on low energy quantities up to a finite level of precision, $\pm P$.

Introduce a modified equivalence relation:

Scale- E equivalence: $\sim_{E,P}$

Two worlds W_1 and W_2 are **scale- E -precision- P equivalent** if they agree on all physical quantities below energy scale E up to precision P .

More corrections will likely be needed...

Different Scales, Different Lagrangians

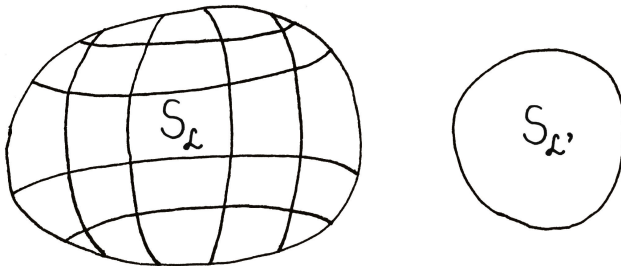
Proposal

An effective theory with Lagrangian \mathcal{L}' provides a “natural” representation of physics at scale E (precision P) if each element of $S_{\mathcal{L}'}$ stand in one-to-one correspondence with elements of the quotient set $S_{\mathcal{L}} / \sim_{E,P}$.

Intuition: $S_{\mathcal{L}}$ describes the possibility space at scale E with redundancy. $S_{\mathcal{L}'}$ captures the possibility space at scale E without redundancy (inspiration from Strevens (2011)).

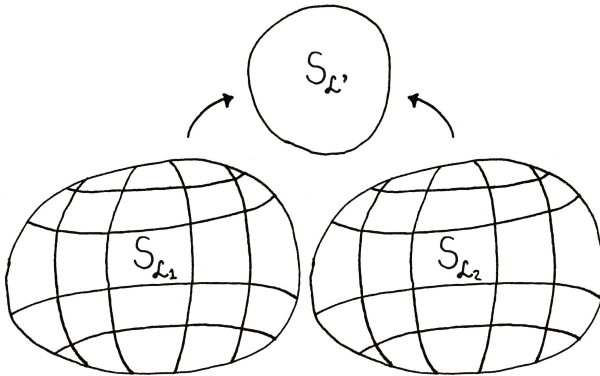
Supervenience

If two worlds differ with respect their their $\sim_{E,P}$ equivalence class then they differ with respect to their fundamental field configuration.



Multiple Realisability

Can characterise multiple realisability as a situation where the $\sim_{E,P}$ quotient set of different theories coincides.



Objectivity?

Does the introduction of a level of precision into the equivalence relation compromise objectivity (McKenzie 2024)?

Once an equivalence relation has been specified the question of whether it induces a quotient set on the space of physically possible worlds seems to be a perfectly objective one.

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Two views:

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Invariably, both apply.

Special Science Laws: Proof of Principle

Fodor (1997): “Why is there anything except physics?” How are special science laws possible?

Why is there anything except fundamental physics? How is it possible for physical systems to display different lawlike behaviour at different scales?

Answer: Because the low-energy/long-length scale physics is only sensitive to some aspects of its high-energy/small-length physics.

References

- Adlam, E. (2022). "Laws of nature as constraints." *Foundations of Physics*, 52(1), 28.
- Armstrong, D. M. (1986). *What is a Law of Nature?*. Cambridge University Press.
- Batterman, R. W. (2021). *A middle way: A non-fundamental approach to many-body physics*, Oxford University Press.
- Fodor, J. (1997). "Special sciences: Still autonomous after all these years." *Philosophical perspectives*, 11, 149-163.
- Gómez Sánchez, V, (2023). "Naturalness by law." *Noûs* 57 (1):100-127.
- Lewis, D. (1983). "New work for a theory of universals." *Australasian journal of philosophy*, 61(4), 343-377.

References

- McKenzie, K. (2024). “No grounds for effective theories.” Draft
- Koberinski, A., and Smeenk, C. (2023). “ Λ and the limits of effective field theory.” *Philosophy of Science*, 90(2), 454-474.
- Strevens, M. (2011). *Depth: An account of scientific explanation*. Harvard University Press.
- Wilson, A. (2024) “Metaphysical emergence as higher-level naturalness.” Draft
- Wilson, J. M. (2021). *Metaphysical emergence*. Oxford University Press.
- Woodward, J. (2016). “The problem of variable choice.” *Synthese*, 193, 1047-1072.