Technology: Theory-Driven Experimentation and Combinatorial Salience

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European Economic Review

Special Issue on
"Explaining Technology"

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Abstract
Recombination has long been seen as a central mechanism for explaining technological evolution and economic growth. Yet this view suggests several puzzles. First, the set of potential combinations is astronomically large, raising the question of how humans somehow arrive at useful combinations (amongst indefinite possibilities). And second, just as possible combinations are "unprestatable" in advance, the same goes for the elements or components that might serve as building blocks of combination. The central question, then, is how actors generate salience for useful combinations as well as plausible combinatorial components. We argue that *theory-driven experimentation* generates combinatorial salience by providing a shortcut for brute force search—making the combinatorial explosion analytically tractable. We link our argument to existing approaches to combination and technology, in particular, Koppl et al.'s *Explaining Technology*. We augment long-run, evolutionary explanations of combinatorial technology with a more decision-oriented approach.

Key words: combinatorial innovation, technology, theory, novelty, evolution, experimentation

1 Introduction

Since Schumpeter's (1934) seminal work, combination and recombination are widely regarded as foundational mechanisms for explaining innovation, economic growth, and technological evolution. The central argument is that new knowledge and technologies are built on existing components of knowledge and technology in combinatorial fashion (Arthur, 2009; Weitzman, 1998). Combination and recombination are also frequently studied mechanisms within adjacent domains such as entrepreneurship and innovation (e.g., Fleming and Sorenson, 2001; Harper, 2018; Xiao et al., 2022). Koppl et al. (2023) formalize the combinatorial view of technology in their recent book *Explaining Technology*, highlighting how the accumulation of technologies generates an ever-expanding set of potential combinations. Combinatorial dynamics, they argue, explain the "hockey stick" growth we observe within both biological and economic spheres—offering an explanation of things like the Cambrian explosion and the Industrial Revolution (also see Cazzolla Gatti et al., 2020; Cortes et al., 2025; Devereaux et al., 2024).

The combinatorial view of technological and economic evolution is persuasive. But it leaves some central puzzles open. For example, given an astronomically large set of possible combinations, how are *useful* combinations somehow identified amongst indefinite useless ones? Even a very modest set of 50 elements yields over a quadrillion (1×10^{15}) possible combinations. Evaluating every possible combination—for example, at the speed of one per minute—would require over two billion years. Another challenge for combinatorial theories is that the plausible building blocks for combination are not given or known in advance. In other words, just as combinations are "unprestatable"—as Koppl et al. (2023) rightly emphasize—so too are the building blocks themselves from which combinations and technologies are formed. The central question, then, is: how (and why) do particular combinatorial components and their plausible combinations become salient?

To address this question, we offer a theory of combinatorial salience. We first (briefly) review existing theories of recombination (e.g., Arthur, 2009; Weitzman, 1998), with a particular emphasis on Koppl et al.'s (2023) recent articulation of the combinatorial view of technology in *Explaining Technology*. We revisit their equation and highlight the opportunity to more carefully explain how humans generate salience for combinatorial elements and identify fruitful combinations. We emphasize the role that theory-laden human activity—a form of "practical science"—plays in the emergence of combinatorial technologies. The human capacity for theorizing, and associated causal reasoning and experimentation, can shortcut a mechanistic process that otherwise would require brute force search through indefinite combinations, or some form of random trial and error. In this way, scientific reasoning functions as a generative metatechnology that makes useful combinations possible by, in effect, enabling a meaningful reduction in the search space of the adjacent possible. To make our arguments more concrete, we revisit several of the historical examples raised by Koppl et al. (2023) and others. Our overall goal in this paper is *not* to replace the long-run combinatorial explanation of technological evolution. Rather, we augment these approaches by focusing on more *decision-oriented* explanations of combinatorial technology and evolution.

2 Combinatorial Model(s) of Technology and Economic Evolution

Combinatorial models of technology and innovation have a long history in economics, tracing back to Schumpeter's concept of innovation as the result of "new combinations" of existing resources, processes, and elements. Schumpeter (1934) portrayed entrepreneurship as the creative act of breaking with established routines by recombining existing means of production into new constellations, arguing that "innovation consists in carrying out new combinations" (1939: 88). Nelson and Winter's (1982) influential evolutionary theory puts Schumpeter's notion of new combinations within a historical process, emphasizing how innovation arises through the cumulative recombination and selection of routines that shape the long-run evolution of industries. Subsequently scholars like Weitzman—citing Abbott Payson Usher's *A History of Mechanical Inventions*—further explore this idea, defining invention as "the constructive assimilation of preexisting elements into new syntheses, new patterns, or new configurations of behavior" (1998: 224). The logic of recombination—combining existing components of knowledge and technology—has also influenced fields adjacent to economics. For example, the literatures on innovation, strategy, and entrepreneurship frequently describe innovation as an act of recombination (e.g., Fleming and Sorenson, 2001; Kneeland et al., 2020; for a thorough review, see Xiao et al., 2022). Even work in the sciences—which conceptualizes innovation as a function of the evolution of a collective "cultural brain"—views "serendipity, recombination and incremental improvement" as the main sources of innovation (Muthukrishna and Henrich, 2016: 4).

The idea of technological innovation as recombination has continued to draw parallels across economics and the sciences through the concept of evolution. In his influential book, Arthur (2009) similarly emphasizes that all technologies are fundamentally combinations of other technologies—each component of which may itself be a technology—further emphasizing how innovation draws upon a preexisting technological base. Technological evolution is an iterative, cumulative, and evolutionary process that builds on previous advances, with the potential to essentially harness the past in new and increasingly sophisticated and surprising ways. Arthur's theory of technological recombination draws direct inspiration from biological arguments (cf. Kauffman, 2000), but adapts it to the world of artifacts and technology. Like Darwinian evolution, Arthur emphasizes that novelty emerges through variation and selection. In particular, he emphasizes a close parallel to the biological notion of common descent: just as organisms inherit traits from earlier species, new technologies in effect inherit components from prior ones. Arthur describes this as the "process by which all objects of some class are related by ties of common descent from the whole collection of earlier objects" (2009: 19). He further argues that combinatorial evolution offers a useful analogy to biology's concept of genetic recombination, where novelty arises primarily through the rearrangement of existing genetic material (or, in technology, rearrangement of existing components and modules) rather than through entirely new creation. Arthur also stresses that radical novelty depends on the continual capture and harnessing of natural phenomena (e.g., MRI harnesses the reflection of electromagnetic waves), which serves as raw material for new technological combinations.

The existing research on combination and recombination is extensive across a number of fields, and reviewing it is beyond the scope of our paper. Good syntheses and reviews of this work can thankfully be found elsewhere (Bresnahan, 2011; Fleming and Sorenson, 2004; Harper, 2018; Kalthaus, 2020; Xiao et al., 2022). Here we instead zero in on Koppl et al.'s (2023) particular generalization and model of combination, and augment their arguments.

2.1 Combination and the TAP Equation

In *Explaining Technology,* Koppl et al. (2023) build on the work of Arthur (2009) and Kauffman (1988) and develop a relatively comprehensive combinatorial theory and model of technological and economic evolution. Their TAP equation succinctly captures combinatorial processes of evolution across biological and economic spheres. Their equation captures central intuition related to combination and growth, and therefore we start by summarizing the central terms of their equation, as they will deeply inform our subsequent discussion.

For convenience, we have reproduced Koppl et al.'s equation here.

$$M_t = M_{t-1} + P \sum_{i=1}^{M_{t-1}} \alpha_i \binom{M_{t-1}}{i}$$

The TAP equation shows that the number of goods M_t at any given time depends on the stock of goods in the previous period, M_{t-1}, plus the new goods generated from combining existing ones. Their model emphasizes how as the stock of existing goods or technologies increases, so do the potential combinations that can be created. Koppl et al. recognize that possible combinations are indefinite, and that "all possible combinations [cannot be] surveyed in each time period" (2023: 16). Therefore, their parameter α_i, limits the scope of combinations by recognizing that only a fraction of all mathematically possible *i*-tuples are ever considered plausible enough to try. And the parameter, P, in turn limits the success of those plausible attempts, representing the probability that a given plausible combination will actually yield a new good. In this way, the equation reflects both the fact that only a subset of combinations are ever imagined or attempted (α_i) and that only some of those succeed in producing new goods (P). In this sense, "perfectly good combinations may go unimagined and untried" (Koppl et al., 2023: 17).

Koppl et al.'s (2023) TAP equation and associated theory of combination certainly provide a plausible account of the emergence of new technologies, goods, and the growth of economies. At a high level, their framework helps explain the "hockey stick" trajectory of growth: economic evolution is cumulative and super-exponential, as new technologies arise out of prior ones and continually expand the overall complexity of the technological system. With each round of recombination, the stock of potential innovations grows larger, creating a "combinatorial explosion"—an accelerating increase in both the number and complexity of technologies. This dynamic underlies periods of rapid industrial and technological change, and also resonates with Mokyr's (1992) characterization of the sudden upturn in economic history's long-run trajectory.

While the TAP equation explains the rapid technological change and 'hockey stick' economic growth observed in innovation processes, its operationalization of the constrained set of attempted combinations does not directly or easily account for variation in which combinations are considered. Particularly, the parameter (α_i) constrains the set of plausible combinations as a function of the *number* of elements in the combination (i). This specification draws on the idea that combining more elements is more complex and difficult, and thus less likely to occur in the set of plausible combinations. However, an unlikely combination of previous elements is not only a function of the *number* of elements in the combination, but also the *nature* of the elements in the combination. Koppl et al. (2023: 16) acknowledge this using the example of the Wright Brothers' discovery of flight, where they did not try the combination of "locomotives, ink pots, and mustard seeds"—a point we'll return to later—but instead they (somehow) perceived and tried more useful combinations. The level of variation of the parameter (α_i) is tied to the number of elements in the combination(i). But this is unlikely to be able to capture the variation in the nature of elements combined. The decision of which elements to combine is, in effect, at a different level of analysis. Thus there is no straightforward modification of the parameter (α_i) that can differentiate between more or less likely combinations of a given size (i) based on how salient they are likely to be to decision makers.

In all, as we explore in greater detail below, the mechanisms discussed by the authors of the TAP equation are highly effective at describing the growth in the number of innovative technologies over time, while leaving open the question of how selection processes operate in determining which combinations are tried.

2.2 Mechanisms of Combination and an Open Question

It is worth pointing out that Koppl et al. argue that "combination is *the key* mechanism of innovation and technological evolution" (2023: 5, *emphasis added*). Beyond focusing on combination as the key mechanism, they also postulate what we might call "sub"-mechanisms related to recombination. For example, they argue "combinatorial evolution proceeds by *trial and error*" and tinkering.

While Koppl et al.'s emphasis on trial and error seems to add further explanatory depth, they also simultaneously emphasize that trial and error is relatively blind, where success is more often driven by "tinkery" and "jury-rigging" rather than any form of deliberate reasoning or thinking (Koppl et al., 2023: 49). As they describe it: "when considering technological change, we should model humans as tinkerers, cobbling together existing elements as well as they can, adjusting, tweaking, and combining in an *unending process of trial and error*" (2023: 55).

Much like the initial recombination explanation, the sub-mechanisms of trial and error and tinkering leave unanswered the question of how and why certain elements, and not others, are chosen for combination. This question is particularly important as the world consists of indefinite combinations, most of which are useless. Koppl et al. (2023: 52) do have brief references to human imagination as a plausible mechanism for selecting combinations—for example, pointing to "imaginative tinkering"—but these leave room for more careful specification and delineation. But given indefinite combinations—most of them useless—how exactly do humans somehow arrive at useful ones?

The emphasis on tinkering and trial and error leaves open the question of *why* particular elements are selected for combination (does this, for example, happen randomly?). And importantly, Koppl et al. explicitly downplay the role of reasoning and thinking, arguing that "progress comes from tinkering, *not thinkering*" (2023: 54). Building on Nelson and Winter's evolutionary theory, they maintain that "reason and foresight" play a smaller role in the historical emergence of technologies and combinations, and "technological advance remains somewhat *blind*" (Nelson and Winter, 1982: 725, *emphasis added*). But again, whether we focus on combination or trial and error, both raise the same question, namely *what*—amongst indefinite combinations—should be tried first?

In a companion piece (Cazzolla Gatti et al., 2020), the authors also emphasize the more delimited role of human thinking in the combinatorial process, offering some simple examples (also see Koppl 2025). While they say that "tinkering is action," they qualify this by pointing out that in none of the key moments of technological advance is the human "actor inventing the technosphere or controlling the whole of it" (Cazzolla Gatti et al., 2020: 117). Their point is that humans are always utilizing pre-existing elements. Humans are "technology takers, not technology makers." The authors illustrate this by focusing on language as a technology, highlighting how even linguistic giants like Shakespeare are "mostly language takers" rather than language makers: "each utterance is a human act that occurs within a language but does not create a language." And importantly, "it is much the same with technology. Every innovation occurs within a larger and pre-given technosphere" (Cazzolla Gatti et al., 2020: 118).

To reduce linguistic output to mere language-taking is to miss the creative and indefinite ways that humans are able to combine words to generate and encapsulate meaning. Artificial intelligence is also a language-taker that automatically strings together words, based on training data. But humans engage in the creative use of language that is different from automatic, strictly combinatorial systems (Felin and Holweg, 2024). While Shakespeare did mostly use linguistic material that already existed, he deployed the language in ways that lead us to carefully read and study him to this day. The Shakespeare example is apt, as it provides the basis of the infinite monkey theorem (credited to the mathematician Borel)—that is, the infinitesimally small likelihood that a monkey on a typewriter would type the works of Shakespeare. Yet, even one word is hard to arrive at through a random process.

To illustrate why this question of which combination to try first is particularly important in a combinatorial world of technological innovation, consider the probability of typing the word 'technology' if one randomly presses keys on a 50-key typewriter. Since the word has ten letters, and each letter must be correct in the exact right position, a randomly selecting typist or monkey would need to make ten perfect choices in a row, with each choice having only a one-in-fifty chance of being right. This results in odds of roughly one in 98 quadrillion (9.8×10^{16})—an astronomically tiny probability. In a similar way, random recombination of technological elements would almost never yield functional or valuable outcomes, given all the possibilities. Innovation cannot rely on blind chance alone—or "mostly" blind chance—there must be something that enables the identification of useful combinations. Without such a mechanism of selection, recombination would be overly costly given indefinite possibilities. In all, useful combinations do not simply happen—they require some mechanism of action and selection.

A second important point raised by Koppl et al. is that combinatorial possibilities are "unprestatable" (Kauffman, 2018). That is, they argue that not all possible combinations can be specified or "stated"—recognizing that we do not know ahead of time all the possible ways that technologies and economies can and will evolve. We agree with this point. But an important, logical extension of combinatorial unprestatability is that the *combinatorial elements themselves are also unprestatable*. Yes, there are a fixed number of letters in the English alphabet, which provide the raw material—plausible combinatorial elements—for generating words and sentences. But the building blocks of combination for technologies are indefinite and rapidly growing: there is no stable equivalent of a 26-letter alphabet to capture all possible combinatorial elements. Therefore, not only are combinatorial possibilities unprestatable, but the same assumption necessarily also holds for the very elements that make up the combinations themselves. *Just as asking how many 'things' are in a room leads to an unbounded and shifting list—does the crack in the table or the distance to the window count?—so too the building blocks of technology are indefinite, as what counts as a usable element depends on context, theory, and purpose* (Felin and Kauffman, 2021). Koppl et al.'s equation explicitly assumes that the number of combinatorial elements is given (is stated and known), and the set of possible elements grows as the result of ongoing combinations. In all, the elements themselves require some mechanism of salience.

We acknowledge that treating combinatorial elements as if they can be specified in advance might largely be done for analytical convenience—helpful for the formulation of Koppl et al.'s TAP equation and for illustrating the broader point about combinatorial explosion (Cortes et al., 2025). Yet for us, this assumption opens up a different line of inquiry: the careful development of a theory of salience—that is, a theory of how particular combinations come to stand out in the first place, and how salience is generated for the elements or components that constitute those combinations.

3 Cognitive Foundations: Rationality, Theories, and Salience

Koppl et al. (2023) replace rationality and thinking with 'tinkering' in models of combinatorial innovation, because the information processing needs of the context are not consistent with the deliberative and omniscient choices implied by rationality. While we agree that rational action does not best describe combinatorial innovation, combinatorial selection is also not automatic, and tinkering does not provide a mechanism for how decision makers select combinations from an indefinite set. We suggest that a form of theorizing—which is largely orthogonal to the extremes of omniscience and complete blindness—characterizes human action in contexts of combinatorial innovation, providing a plausible, augmenting mechanism for how actors select combinations from a sea of possibilities.

3.1 Rethinking Rationality

Before delving more directly into our theory of combinatorial salience, the underlying assumptions that are made about rationality—and human nature—are worth carefully considering. As noted by Herbert Simon, "Nothing is more fundamental in setting our research agenda and informing our research methods than our view of the nature of the human beings whose behavior we are studying" (1985: 303). We concur. Here we summarize existing conceptions and offer an alternative, orthogonal view of rationality, specifically focusing on theory-laden human action.

Much of the literature on the combinatorial evolution of technologies and economies does not directly address questions of rationality or human nature. In some sense, it does not need to. For example, mathematical treatments of combinatorial evolution offer seemingly sufficient explanations without requiring any treatment, discussion or even mention of human nature (e.g., Cortes et al., 2025). Combinatorial explanations are in many ways quite straightforward, and therefore, perhaps questions of human rationality and nature can be abstracted away. However, we do think it is useful to recognize the role that human actors play in this process, because combinatorial activity is not automatic. Humans think and intervene in their surroundings in ways that we think can enrich extant explanations of the combinatorial evolution of technology.

It is on this point about "thinking" that we offer an alternative angle—or plausible, additional mechanism—to Koppl et al.'s theory. They equate thinking with what they call standard economic rationality ("if thinking is something close to standard economic rationality", Koppl et al., 2023: 54), and therefore they seek to replace thinking and rationality with "tinkering." They argue that we should not emphasize "Socratic thinkery" but "Darwinian tinkery." The information processing needs of combinatorial innovation and the 'unprestatable' nature of the combinations are not consistent with rationality. We concur. That is, if thinking is indeed equated with some version of omniscient rationality, then the concept ought to be replaced in a context like innovation. However, we think there is an alternative way of thinking about rationality.

Admittedly, discussions of rationality tend toward the extremes. On the one hand, there are omniscience-oriented conceptions which focus on a "representative agent" and make heroic assumptions about economic actors and their ability to process information (Kirman, 1992). And on the other hand, there are bias-oriented conceptions which focus on all the ways that humans make mistakes. For example, Benabou and Tirole (2016: 142-148) summarize existing research on human cognition in economics and argue that the human mind is characterized by such things as "information avoidance" or "biased updating," or where humans more generally display "non-Bayesian behaviors such as not wanting to know, wishful thinking, and reality denial." Gabaix argues that much of the existing work on cognitive biases can be captured by the concept of "behavioral inattention" (Gabaix, 2019; also see Benjamin, 2019): humans miss relevant information, they overweight the wrong things, and so forth. We think both extremes—that agents are omniscient or that humans are riddled with cognitive bias and cannot think—miss the mark (for a review, see Chater et al., 2018; Felin, Koenderink, and Krueger, 2017).

But there is an alternative conception of rationality and thinking which does *not* require us to make heroic assumptions about the capacity of humans to process information, nor does this alternative require us to jump straight to relatively blind forms of trial and error either. We think this alternative conception of rationality and thinking—including its extensions into technological combination—can also be directly linked to less-emphasized but important points about the role of reasoning and thinking in the combinatorial evolution of technology.

3.2 Theory-Laden Human Action

So what precisely is the alternative? So far, we have only foreshadowed our argument that *human theory-laden action* provides a useful way of thinking about decision making as it relates to combinatorial technology. Next, we delineate the central aspects of what theorizing actually means and then discuss the implications of this for combinatorial technology and evolution.

We argue that thinking and reasoning are a natural human endowment, grounded in the human capacity to theorize. Psychologists and cognitive scientists have highlighted—and empirically shown—how even young infants engage in theorizing, causal reasoning, and associated experimentation as they interact with and learn about their surroundings (Gopnik et al., 1999; Spelke et al., 1996; for a review see Baillargeon et al., 2016). To provide a brief example, experiments show that when infants drop objects from a highchair repeatedly, they are not acting randomly or merely playing but actively theorizing and testing hypotheses about gravity, solidity, and cause–effect relations. Note that while the importance of insights from "experiments with children" have been emphasized in the context of economics (for a review, see List et al., 2024), surprisingly, this crucial insight—*that humans theorize and reason causally*—has not been meaningfully recognized or incorporated into economics. The role of human theorizing and causal reasoning by economic actors has relatively recently been further developed in economics-adjacent disciplines like strategy and entrepreneurship through theoretical and empirical work in the so-called "theory-based view" (e.g., Camuffo et al., 2020; Coali et al., 2024; Felin and Zenger, 2017; for a recent review, see Felin, Gambardella, and Zenger, 2024).

That theorizing is a broad human endowment—and not just the privilege of science and scientists—is also a basic premise of pragmatism. Pragmatism holds that theorizing is a universal aspect of human engagement with the world (Dewey, 1916). Dewey describes "science as a practical art" (1916: 413)—scientific reasoning is a cognitive tool that all humans (can) use and have at their disposal as they interact with and seek to solve problems in the world. To offer a trivial example, when driving we constantly generate theories and engage in causal reasoning: about what other drivers are likely to do (whether the car ahead will merge, whether a pedestrian will step off the curb), and about our own alternatives (whether switching lanes will shorten travel time or taking a different route will avoid traffic). This form of everyday theorizing involves thinking about causal connections—if I do x, then y is likely to follow—and illustrates how theorizing and causal reasoning together can guide moment-to-moment decisions in ordinary activity. This form of theorizing is not abstract, it has practical utility. Practical theorizing shapes what we see and decide to do. While theorizing and scientific reasoning are often elevated to some kind of special status—separate from lay or folk reasoning—it is a human endowment that practically helps us navigate even our everyday surroundings. We similarly think that "theorizing [is] on a par with all other practical activities" (Toulmin, 2003: 439). The capacity to theorize is fundamental to any human activity, including—as we discuss below—combinatorial innovation.

We argue that the human capacity to theorize—think and reason—offers a mechanism for explaining how humans intervene in their surroundings: why they see what they see and why they take the actions they take (Felin and Koenderink, 2022). Aspects of this human capacity to theorize have also been discussed by others. For example, Mises argues: "Thinking and acting are inseparable. Every action is always based on a definite idea about causal relations. He who thinks a causal relation thinks a theorem. Action without thinking, practice without theory are unimaginable." (1949: 177).

It is worth pointing out that economists implicitly agree that they as scientists theorize and intervene in their surroundings (consider the typical RCT), but often do not grant this ability to the human subjects they model and study. This of course is not just a problem in economics. Scientists readily grant themselves the ability to think and theorize—to engage in causal reasoning and experimentation—while at the same time portraying human subjects as biased, deficient, or hopelessly bound by cognitive limitations. Or lay persons are seen as possessing naïve "folk" theories, when compared to more fully fleshed-out forms of thought and theorizing by scientists themselves. This double standard is precisely what Edith Penrose criticized in her response to Armen Alchian in *American Economic Review*: "For the life of me I can't see why it is reasonable (on grounds other than professional pride) to endow the economist with this 'unreasonable degree of omniscience and prescience' and not entrepreneurs" (1952: 813). Penrose's intuition highlights the need for increased symmetry when it comes to our assumptions about human nature *tout court*—recognizing that the same faculties of thought that scientists themselves prize are also surely operative among the humans and economic actors we study (Felin and Zenger, 2017).[1]

That said, recognizing that all economic actors (can and do) think and theorize does *not* mean they are omniscient or infallible, or that they somehow arrive at identical expectations or beliefs (for an excellent discussion of the "common prior" assumption in economics, see Morris, 1995). Quite the contrary: different actors have different theories, and different theories lead to different actions, different forms of

[1] Koppl's (2021; also see Koppl, 2018) critique of expertism echoes Penrose's intuition by rejecting the asymmetry that grants experts or policymakers superior rationality while denying it to ordinary actors. Like Penrose, Koppl insists on epistemic symmetry. However, his central point is that experts—like scientists—are subject to the same biases and limitations as the entrepreneurs and humans they presume to direct. Our emphasis, by contrast, is on *epistemic parity in the other direction*: the theoretical reasoning available to scientific experts is likewise available to lay persons, technologists, entrepreneurs, and others.

experimentation, and different decisions. *And naturally, theories can be—in fact often are—wrong.* The efficacy of a theory can be judged, over time, by the outcomes it produces. And during intermediate time frames, theories can direct humans toward the types of interventions and experimentation that might enable the realization of something novel and useful—including novel and useful combinations.

3.3 Using Theories to Generate (Combinatorial) Salience

So far we have argued that human action is theory-laden. But we have yet to fully work out what this means for combinatorial technologies and evolution. Next, we discuss the role theories play in generating salience—first, salience in general, and then more specifically, salience for combinatorial elements and combinations. While salience certainly has been discussed in economics (Bordalo et al., 2022; Kahneman, 2003), we focus on a different way of thinking about it. Particularly, we emphasize how human or economic actors generate salience through theories which spotlight certain combinatorial elements and combinations as plausible for innovation and how this enables us to explain combinatorial evolution in a way that is consistent with the observed human behavior that generates innovation.

A central starting point for any discussion of salience is that we are never able to *fully, exhaustively* observe or account for our surroundings, let alone the world. The world teems with possible things that we might attend to or become aware of, and only a small subset is visible or salient at any one moment. So, why are some objects salient—visible and noticed—while others are not?

Most treatments of salience emphasize the so-called "bottom-up" nature of salience, rooted in the psychophysics tradition, where the properties of objects themselves determine whether they are observed. For example, Kahneman (2003) and subsequent work in behavioral economics argues that what becomes salient in judgment is largely determined by the physical or statistical properties of stimuli—such as intensity, contrast, or frequency. More recently, Bordalo, Gennaioli, and Shleifer (2022) summarize and build on this tradition. They argue that things are salient when "a stimulus attracts the decision maker's attention bottom up, automatically and involuntarily"—and this salience is a driven by such things as the "high contrast with surroundings," "surprising nature" or "prominence" of stimuli. This builds on psychophysical studies where focal stimuli are seen and noticed when they have certain characteristics, such as being loud, large or somehow comparatively different (for a review of this work, see Felin and Koenderink, 2022). To provide a brief example: studies in visual search show that a red "T" target among blue "L" distractors is detected almost instantly, regardless of how many distractors are added—the classic "pop-out" effect (Wolfe and Horowitz, 2017). Applying this type of logic to economics, Bordalo et al. (2022) highlight how decision makers can overweight attributes that stand out due to contrast, surprise, or prominence, while underweighting less striking features. For example, a highly contrasting price or payoff "pops out" for a decision maker, biasing choice even when normatively irrelevant. Most of the emphasis in economics has been on how *object characteristics* shape what is salient. Overall, salience in economics has been largely framed as an automatic process (Kahneman, 2003), and the emphasis has largely been made on the mistakes humans make as the result of paying attention to the wrong things (Gabaix, 2019).

By contrast, we emphasize top-down salience: how theories generate and enable economic actors to see objects (Felin and Koenderink, 2022). As Einstein famously noted, "whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed" (quoted in Polanyi, 1971: 604).

In the context of technology and innovation, this means that theories enable a form of top-down salience for some kind of objective or end—in particular, for solving a problem that has been formulated. In this way, top-down salience both includes the observation of particular objects and the solution for which the objects might be used. A theory proposes both solutions that would be acceptable for a particular problem and objects that may help us arrive at those solutions. Without a theory, the relevant objects or solutions would simply not be salient. Theories serve as a powerful spotlight of sorts, directing awareness toward new uses and features of the world, amongst indefinite things we might attend to or become aware of. To offer a mundane example, if you open a window in your office and the wind blows papers off your desk, your mobile phone might become salient—not because of its shape or color or even size, but because the problem (stopping the papers from flying) and your theory (any relatively heavy object can anchor them) reframes its possible use (cf. Felin, Kauffman, and Zenger, 2023). This hypothesizing and theorizing thus brings certain things—anything heavy enough to stop papers from flying—into focal awareness. From this perspective, problems and theories are not independent cognitive processes but part of the same reasoning loop: problems direct attention and motivate search, while theories frame which objects and solutions become visible as potential answers. In this sense, problem-driven theorizing is precisely the mechanism through which actors generate salience for otherwise hidden possibilities. In all, whether an object or solution is salient and visible—whether it "pops out" or not—depends on the associated theory and problem formulation we humans bring to any encounter with the world.

Now, returning to Koppl et al.'s (2023) argument: how does the idea that theories generate salience relate to their argument about technology? We first argue that theories provide a different way of conceptualizing the constraint on plausible combinations, which becomes not only a function of the number of objects combined, but also the salience for those objects, and potential combinations, as given by human theorizing.*** Thereafter, in the next section, we revisit some of the technology examples discussed in the existing literature, and highlight how top-down theories enable combinatorial salience.

Evolutionary history has many examples for why top-down, and not bottom-up, theorizing is likely to be key in innovation. Felin and Kauffman (2023)—building on Liebenberg (1990; also see Pastoors and Lenssen-Erz, 2021)—highlight how activities like tracking and hunting in evolutionary history illustrate a form of "proto-scientific" theorizing and experimentation that guides what becomes salient. Theorizing, and the salience this created for objects and clues in one's surroundings, were essential to the success of ancestral hunters. To illustrate, there is no way to generate salience for animal spoor bottom-up, as bottom-up salience offers no mechanism for knowing what to look for or what any given piece of evidence (like a small broken twig) might *mean*. Meaning is generated top-down. Salience for relevant clues emerges through the process of forming hypotheses in an effort to reconstruct the unseen movements of animals and potential prey. Hunters learn to look for and treat inconspicuous and seemingly irrelevant stimuli—the angle of a broken twig, moisture in dung, the brushing of dew from grass, or even the silence of birds—as salient clues, each interpretable only against a "plot" or theory of the animal's likely movement and behavior. By projecting themselves into the position of animals, trackers can infer hidden behaviors, anticipate where an animal might be headed, and test these conjectures against subtle signs in the environment. Nonobvious, small or even seemingly hidden things in the landscape can "pop out" as relevant and useful, only if one has a theory in mind (Felin and Koenderink, 2022). What would otherwise remain unnoticed background becomes meaningful evidence, enabling the reconstruction of unseen actions and the pursuit of prey that is out of sight. A hunter might also formulate problems—for example, an animal they are tracking might smell humans due to wind direction—and generate novel solutions like hunting downwind from the animal or disguising their own odor (with smoke, herbs or tree sap). Notice, again, that salience was not given by what is there, but rather by the proto-scientific theorizing and problem solving of the hunters. This form of causal reasoning turned abstract inference into practical survival.

In much the same way, technological recombination depends *not* on the inherent visibility of components, but on theories and problem formulations that render certain elements salient as promising building blocks—amongst innumerable possibilities. Our point here is that even the stock of elements (or components) available for combination is not necessarily salient without some kind of guiding theory—as we illustrate below. What matters is the power of theories to generate new uses and affordances, enabling actors to perceive possibilities that are not immediately given.

Technologies often emerge from re-seeing mundane things in new ways. For instance, Felin and Kauffman (2023) provide another, ancestral example where the ground—ordinarily a surface for walking, running or building—became a technology when hunters invented pitfalls, allowing them to trap large prey rather than risk close combat. Similarly, in evolutionary history, "desert kites" exploited natural contours and low stone walls to funnel animals into enclosures, sometimes even laying foundations for domestication (e.g., Crassard et al., 2022; Svizzero and Tisdell, 2018). Such cases illustrate how evolutionary history is replete with examples where ordinary materials or features of the landscape were recombined into and utilized as technologies. These were not mere strokes of luck but reflected the capacity of theorizing to render the overlooked salient (Felin and Kauffman, 2023), transforming the familiar into instruments of survival and innovation.

All that said, we do acknowledge that some truly accidental discoveries are possible. But seemingly lucky encounters only become intelligible against the backdrop of a theory or problem frame that renders them meaningful. Edison, for instance, could recognize the potential of the carbon filament not simply because it appeared by chance in his lab, but because he was already theorizing about the problem of durable illumination. Likewise, Fleming's recognition of penicillin was not merely an accident of a contaminated petri dish, but the result of seeing its relevance for the broader problem of bacterial infection. What might appear to others as noise or irrelevance is instead recognized as a clue or candidate solution, precisely because the actor is oriented toward a particular end. In this way, serendipity is less a matter of chance alone and more a function of interpretive preparedness, where theory creates the conditions for noticing, re-purposing, and exploiting what would otherwise remain hidden in plain sight.

4 Pulling It All Together: Combinatorial Salience Through Theories

Next we pull together the above arguments by revisiting or reinterpreting several examples of combinatorial technology and evolution (raised by Koppl et al., 2023 and others). We specifically use flight and wireless telegraphy as our examples. Our purpose here is to highlight how theories and causal reasoning—and associated experimentation—guide entrepreneurs and technologists in their efforts to identify useful components and combinations. Our goal here—it bears repeating—is to offer our theory of combinatorial salience as an augmenting complement to, rather than replacement of, existing theories of technological combination.

Our goal with these brief illustrations is *not* to reify the actors involved with these technologies—the Wright brothers and Marconi—or to point to them as unique geniuses. Quite the opposite. In briefly revisiting these cases, our aim is to show how the more general mechanisms of theorizing and experimentation can direct human awareness toward useful combinations. We recognize that both the Wright brothers and Marconi were operating in distinctive historical and technological contexts, and in that sense, every example is unique. But this does not diminish the broader principles that cases like this can illustrate: innovation often hinges on the ability of actors—whether canonical figures or anyone else engaging in innovation—to formulate problems, develop theories, and experiment in ways that render particular combinations salient. Our use of these examples is thus illustrative of underlying processes, rather than an effort exceptionalize particular individuals.

4.1 Powered Flight as Brief Illustration

Perhaps a useful starting point is Koppl et al.'s (2023: 16) off-hand remark that the Wright brothers "did not try to combine locomotives, ink pots, and mustard seeds" to create their flying machine. This cuts to the crux of the issue, namely: what did the Wright brothers choose to combine and why? How did the relevant materials and combinations become salient to enable them to generate human powered flight? Koppl et al. (2023: 16) argue that "the Wright brothers knew what to combine." But the question is—how? How did the right actions, experiments, and combinatorial elements become salient to them?

We argue that the Wright brothers engaged in theory-driven experimentation to solve the problem of flight. We recognize that one can rightly worry that recounting the Wright brothers' case risks being a retrospective "just-so" story, one where we select only those details that fit our narrative. But this concern is largely mitigated by the unusually rich empirical record that survives. The relevant records include years of extensive correspondence with scientists and fellow technologists, and most importantly, the Wright brothers' own notes and data from their extensive experimentation (Wright and Wright archive, 1880-1940; also see Anderson, 2004; Crouch, 2002; Jakab, 1997; McCullough; 2015). These highly detailed records and archives provide a window into not only how the Wright brothers made decisions, but also why they performed the experiments they did. Our treatment therefore is not an ex post rationalization but a window into how the Wright brothers theorized and created salience for relevant components and combinations.

The Wright brothers were extremely systematic and scientific in their approach to flight. In 1899 they began what they called "a *systematic study* of the subject in preparation for practical work" (Wright and Wright). This initiated a *four and a half-year process* of study, careful analysis of data, systematic experimentation and building—before their eventual success. By 1901 they had formulated three problems that they needed to solve—lift, propulsion, and steering—in order to successfully arrive at flight. It is hard to fully capture what the Wright brothers did under the label of tinkering because they were extremely deliberate in reasoning through and systematically experimenting with combinations that related to their three problems.

To illustrate, consider how the Wright brothers tackled the problem of lift. First they carefully analyzed the data of Otto Lilienthal, one of the early aviation pioneers. They found that Lilienthal's coefficients for lift were wrong and inconsistent with their own glider experiments. The discrepancy between Lilienthal's data and their own experiments was not dismissed as error but treated as a scientific problem to be explained and solved. As experimentation with lift was inherently dangerous (Lilienthal died during one of his flight experiments, in 1896), the Wright brothers reasoned that they could more systematically understand and carefully study the principles of lift by building their own wind tunnel. They were not the first to build a wind tunnel. But they certainly were pioneers in generating reliable aerodynamic data through extensive experimentation and meticulous recordkeeping. In their wind tunnel experiments, the Wright brothers systematically varied things like the curvature of the airfoil, aspect ratio, and angle of attack. They tested around 200 different wing surfaces. They also experimented with different planforms and biplane configurations in carefully controlled experiments, measuring lift and drag to develop reliable aerodynamic data for their (eventual) aircraft designs. Again, this is hard to label as tinkering (at least fully), given the careful deliberation and engineering that was involved.

Of course, many of the combinatorial elements used by the Wright brothers pre-existed in one form or another: including wind tunnels, gliders, engines and even their constituent parts (i.e. propulsion system elements like a propeller blade made of wood and a steel bicycle chain). But this hides the fact that the Wright brothers engaged in a number of years of—essentially—careful R&D. Therefore, merely listing the materials (and their combinations) used in the final product does not account for the experimentation and hard-earned *knowledge* that led to the testing and selection of these materials. Furthermore, an accounting of the combinatorial materials does not capture critically important pieces of knowledge like the needed size and shape of the wings, essential for flight. These details are not incidental, they were a fundamental component for enabling flight.

Also, an important addition here is that some of the components utilized by the Wright brothers *were not readymade*—ready to immediately be combined with other components. Many of the underlying components had to be significantly modified or made and manufactured. Take the Wright brothers engine, for example. While combustion engines existed, the Wright brothers were not able to convince existing engine manufacturers to create a lightweight, custom engine for them. They therefore manufactured their own engine (out of aluminum), with the right power-to-weight ratio. And beyond the engine, the Wright brothers engaged in novel causal reasoning and experimentation in relation to other components as well, such as the propeller. Off-the-shelf marine propeller designs could not simply be fitted onto the airplane. The Wright brothers applied their aerodynamic insights (based on hundreds of experiments), treating the *propeller as a rotating wing*—a concept unheard of at the time. Through systematic experimentation they tested various shapes, angles, and pitches, using data from their wind tunnel studies of wing designs. This process enabled them to generate *new* evidence about how a rotating airfoil could efficiently move air to generate thrust, overcoming the limitations of marine propellers designed for water. The Wright brothers designed and hand-carved their own propellers (from spruce), allowing them to fine-tune the design for maximum efficiency. Their careful craftsmanship and experimentation culminated in two propellers positioned behind the wings, balancing thrust and stability in a way that was essential for controlled flight.

Now, Koppl et al. rightly note that "both gliders and internal combustion engines had to exist before the Wright brothers and others could begin experimenting with ways to cobble them together" (2023: 55). This is true. But just because some components pre-exist does not guarantee that they would be recognized as relevant, or that they were readymade for combination, or even rendered salient to the problem of flight at all. The historical record is littered with unused, misunderstood, or misapplied technologies that never find their way into meaningful applications. What mattered in the case of the Wright brothers was not simply the presence of gliders and engines in the technological environment, but the theorizing and causal reasoning that oriented them toward treating these as potential complements, identifying the specific problems to solve, and experimenting in a way that converted mere availability into genuine possibility. In other words, components alone do not explain technological breakthroughs; it is human theory-laden action and experimentation that turns components into candidates for successful combination.

4.2 Wireless Telegraphy as Brief Illustration

If the Wright brothers provide a paradigmatic illustration of practical theorizing and experimentation in the pursuit of flight, then Marconi's work on wireless telegraphy serves as a complementary example in the realm of communication. Authoritative sources point to parallel mechanisms for explaining the emergence of wireless telegraphy (Hong, 2001; Raboy, 2016). Both the case of flight and wireless telegraphy highlight that technological advance is not just a matter of the presence of available components waiting to be combined—*though this of course is also important*. Examining how these technologies emerged, through the actions of the actors involved, provides a plausible window into how practical theorizing renders certain actions, experiments and material combinations salient. Like the Wright brothers, Marconi was extremely detailed in his deliberation. By 1899, he had already compiled a 147-page unpublished manuscript that not only documented his early experimental work but also situated it within a broader narrative of communication history and the potential for global wireless connectivity.

Marconi's achievement in wireless telegraphy is especially instructive because it unfolded in the face of strong scientific skepticism. As Raboy emphasizes, "in 1901, science insisted that it was impossible to communicate across the Atlantic because Hertzian waves were thought to travel in straight lines" (2016: 176). Based on then-dominant theories of electromagnetic propagation, most scientists concluded that any attempt to transmit signals across larger distances would be futile. Most scientists believed that the curvature of the earth created an insurmountable barrier to long-distance wireless communication, since electromagnetic waves were thought to travel only in straight lines—making a transatlantic signal seem physically impossible, regardless of amplification. Marconi disagreed and committed himself to trying to understand and generate practical applications for wireless communication. What was perhaps even more interesting is that—unlike Hertz and others who emphasized the physics of electrical transmission—Marconi's focus was on practically harnessing these phenomena for wireless telegraphy and global communication.

Like the Wright brothers, Marconi's achievement can be seen as a process of combining existing knowledge and components. After all, inductors, capacitors, transmitters, coherer detectors, and spark-gap oscillators all pre-existed Marconi's work. Yet Marconi did not simply inherit these parts—he refined them through careful experimentation. For example, he tested 300 to 400 different metallic filings before finding that a mixture of nickel and silver filings (with a drop of mercury) produced the most reliable coherer (Hong, 2001). It was scarcely evident what the right combinatorial "bundle" of components would be to enable wireless communication.
And beyond the components themselves, of course the knowledge of Hertzian waves was available. But most scientists thought that electromagnetic waves were of scientific interest, and of little to no practical relevance (Raboy, 2016). And even if one thought there was practical utility, many if not most of the devices associated with early radio were not standardized or readymade for integration into a transatlantic signaling system.

Marconi, however, believed that a wireless communication device was feasible. To arrive at this, he essentially broke the endeavor down into three tractable problems that needed to be solved (cf. Hong, 2001). Specifically, the three interrelated problems that became the focus of his experimentation were: signal strength, range, and selectivity (Raboy, 2016). First, how could signals be generated with sufficient strength to travel great distances? Second, how could that energy be preserved over range, rather than dissipating into noise and interference? And third, how could signals be tuned and discriminated so that a receiver could isolate a specific transmission amidst the electromagnetic clutter?

Consider the first problem, signal strength. Conventional wisdom held that the weak signals generated by spark-gap transmitters could only travel short distances. Marconi's insight was to treat the antenna not as an incidental feature but as a central component in amplifying and projecting waves. By systematically experimenting with long vertical wires, elevated masts, and grounding techniques, he improved transmission efficiency. Each adjustment represented a small but cumulative theoretical refinement about how energy could be coupled into the surrounding environment. It is crucial to note that these antenna experiments were not guided by an accepted scientific theory of radiation. Instead, they were guided by Marconi's conviction—against much expert opinion—that antennas could be engineered to harness and direct energy in ways not captured by existing formulas.

The second problem, range, had to do with the earth's curvature. If electromagnetic waves propagated strictly in straight lines, as most physicists maintained, then long-distance wireless communication was categorically impossible—even hills might be insurmountable. Yet Marconi reasoned differently. He hypothesized that waves might, under certain conditions, follow the earth's surface or be reflected back down from the atmosphere. Lacking the detailed ionospheric theory that would only emerge decades later, he nonetheless treated these possibilities as conjectures worth testing experimentally. Marconi's transatlantic experiment in 1901 was therefore not a reckless gamble but the culmination of a line of reasoning. By deploying large aerials in Cornwall and Newfoundland, he designed an experiment to test the very boundary of contemporary theory. The faint but real reception of the Morse letter "S" across the Atlantic was the outcome of years of experimentation. It was the result of a deliberate attempt to generate new evidence, challenging the reigning belief that long-distance signaling was impossible.

The third problem, selectivity, emerged as wireless systems proliferated. Without a means of tuning, all receivers would indiscriminately pick up all transmissions, resulting in chaos. Marconi recognized that for wireless telegraphy to become a practical technology, signals had to be isolated and addressed. This led to his work on resonance and tuning circuits, in which transmitters and receivers were carefully adjusted to the same frequency. Again, existing components were necessary but insufficient. The crucial advance lay in reconceptualizing the system as one of matched oscillatory circuits, an insight that drew on but also extended contemporary physics.

In this way, Marconi's work exemplifies the role that persistent reasoning and theorizing enable the generation of fruitful combinations to solve the problems he had formulated—related to both the technology and its commercialization. There is no question he was the beneficiary of existing knowledge and technologies. But Marconi framed the problem differently, refused to take expert consensus as final, and used relentless experimentation to probe the limits of accepted theory and practical application (Hong, 2001; Raboy, 2016).

5 Discussion: Science as Metatechnology and Proximate Explanation

In this discussion section we emphasize two related points. First, we highlight how the theory-laden nature of human action is not simply another combinatorial component but what might be called a "metatechnology" behind combination. Second, we argue for the importance of distinguishing levels of explanation, as well as their complementarity. That is, we highlight that combination offers a useful long-run, aggregate explanation of technological evolution (Koppl et al., 2023), but this explanation can also be augmented with more proximate mechanisms related to actor-level decision making. Thus, *our goal in this paper is not to supplant combinatorial explanations of technological evolution, but rather to highlight more decision-oriented mechanisms*.

First, we recognize that our point about human action being theory-laden—and scientific reasoning as method or process—could be treated as just another combinatorial element in the long-run evolution of technological change. One might say that the scientific method—systematic observation, hypothesis formation, and experimentation—was already "in the pool" of available practices long before the Wright brothers took flight or before Marconi developed and commercialized wireless telegraphy. But from our perspective, this misses something important. Namely, scientific investigation is not just another element: it is a metatechnology that orients actors toward what might count as relevant and useful elements in the first place. Theorizing and causal reasoning direct attention to particular problems, and problem formulations render certain actions and materials salient, and further guide experimentation toward useful combinations.

In this sense, theorizing is broadly generative rather than merely combinatorial. It does not simply enter into combinations alongside other components—it actively frames, structures, and creates salience for plausible elements and combinations. For the Wright brothers, "science as metatechnology" allowed them to discern flaws in existing data, to generate new evidence through wind-tunnel experiments, and to reconfigure materials into workable airfoils and propulsion systems. It allowed Marconi to treat the transmission of signals across distance not as a matter of simply tinkering with coils and sparks, but as a set of specific theoretical and experimental problems to be solved—signal strength, range, and tuning frequencies. Rather than seeing wireless telegraphy as the haphazard combination of existing electrical components, he framed it as a scientific challenge in which causal reasoning and experimentation would decide what elements and configurations were even worth pursuing. This orientation led him to design systematic trials, to refine aerials and receivers in light of theoretical predictions, and to extend the feasible range of wireless communication far beyond what experts thought possible.

In this way, science as metatechnology does not merely enlarge the pool of combinatorial options, but furnishes the very criteria of relevance and plausibility that can guide experimentation. Without this type of meta-level reasoning, the vast combinatorial landscape of possible components and combinations would have remained inert. Seen in this way, science exemplifies the broader point of this paper: that theory-laden action is not reducible to recombination, but is a central process through which recombination becomes tractable, directed, and capable of producing novelty. In other words: science as a metatechnology is less a "part" of technological evolution than the enabling condition that allows certain parts to become visible, salient, and combined in new ways.

Of course, there is variance in the extent to which the tool is utilized and how it is wielded. At certain times—including in the case of our examples—seemingly naïve technologists were more systematic in wielding this metatechnology, as is evident from their systematic deliberation and careful experimentation. Both the Wright brothers and Marconi upended scientific dogmas, and their discoveries in turn also led to discoveries in science (e.g., the discovery of the ionosphere, which accounted for why electromagnetic waves seemingly could bend). That said, the use of scientific reasoning is never perfect: scientists and entrepreneurs can misjudge and be biased, inadvertently follow false leads, or prematurely close off unlikely-sounding possibilities. But theorizing and associated experimentation, as tools, are available to all, extending to lay individuals who can (at times) display more open-ended and genuinely scientific reasoning than scientific experts. As these practices of systematic observation, causal reasoning, and experimentation became institutionalized and taught, they can amplify the effectiveness of both individuals and organizations in navigating the combinatorial landscape (cf. Camuffo, 2020). In this way, the broad diffusion of science across professional and everyday domains has made humans progressively better at identifying promising problems, discarding unfruitful paths, and harnessing materials in novel ways—thereby accelerating the pace of technological evolution.

Second, our emphasis on theory-laden human action and associated experimentation—when it comes to explaining combinatorial technology and evolution—need not be seen as some kind of knockdown critique of combination as a key mechanism. At the level of hundreds of years, and even evolutionary time, combination certainly offers a powerful way of thinking about and explaining technology.

We think that, in many ways, recombination and theorizing can be seen as complementary rather than competing explanations. As Nagel (1961) and others have emphasized (see also Mitchell, 2003), explanatory mechanisms can differ—and even appear contradictory—across time scales and levels of analysis. Explanatory pluralism is therefore not only unavoidable but desirable: different levels and time windows yield different causal stories. In biology, for instance, one can distinguish between long-run evolutionary explanations of why a trait persists in a population and proximate mechanistic accounts of how particular genes and regulatory pathways produce that trait in an individual organism (Mayr, 1961; Tinbergen, 1963). In a similar sense, we might say that combination—and sub-mechanisms like trial and error or tinkering—captures the long-run, aggregate patterns of evolution, while theory-laden action and experimentation focus on the more proximate, actor-level decisions and processes through which new possibilities are generated and pursued. A similar distinction appears in economics. Growth theory and other macroeconomic frameworks focus on long-run trends, but they obscure the proximate mechanisms of decision making by households, firms, and individuals. Aggregate models can be useful for identifying general trajectories, yet they often collapse heterogeneity into a representative agent and thus miss the actor-specific processes through which new value is envisioned and created. At this proximate level, theory-laden action becomes indispensable: it accounts for how entrepreneurs, engineers, and scientists frame problems, generate hypotheses, and design experiments that yield new data and open up novel technological pathways.

While recombination accounts for patterns of growth that emerge over long horizons, insights can also be gained by zeroing in on the more theory-driven and decision-oriented reasoning of actors as they seek to bring forth useful combinations and generate technologies to solve problems. Without this level of explanation, the apparent "mechanism" of combination risks becoming a post hoc description of outcomes rather than a genuine account of how possibilities are generated and realized in practice. We think the complementarity of levels—aggregate, long-run recombination and more proximate theorizing and decision making—can provide a fuller picture of combinatorial technology and evolution, recognizing both the long-run patterns and the short-run, decision-oriented processes through which novelty actually enters the world.

6 Conclusion

In conclusion, this paper argues that while long-run combinatorial accounts of technological evolution illuminate the vast space of potential novelty, they leave unexplained the decision-related mechanisms by which particular combinations and components become salient. We propose a theory of combinatorial salience, emphasizing that theory-laden human action—through causal reasoning, problem formulation, and experimentation—guides actors toward fruitful paths that would otherwise remain hidden in an astronomically large search space. Historical cases such as flight and wireless telegraphy offer a window into combinatorial technologies and how actors generate salience through problem formulation and associated experimentation. By foregrounding the generative role of theory and theorizing as a metatechnology, we augment evolutionary explanations of recombination with a decision-oriented account that highlights the active, situated processes through which economic actors create novelty.

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