Search Without a Searcher

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I begin with search as a word from computer science and ask what remains of the idea when there is no searcher in charge. Ant colonies, evolving populations, symbiosis, immunity, and cognition all show forms of organized exploration in which past results change what can be tried next. Some evolutionary processes go farther: one lineage can acquire a solution worked out by another, without retracing the path by which that solution was built. I call this federated evolutionary search. Cognition appears late in the story, when these older processes become internal enough to imagine possibilities before acting on them. The searcher, in other words, is not the cause of search but one of its consequences.

Words That Smuggle Agents

I first encountered the word *search* in something approaching its technical sense in the late 1970s and early 1980s, when I was teaching myself computer science and working through the canonical pairing of sorting and searching. It was an ordinary English word pressed into more precise service. A search procedure did not need curiosity, intention, or even any conception of what it was doing. It required a space or structure containing alternatives, rules governing what would be examined next, some way of evaluating what had been found, and usually some retained state that affected subsequent operations. The ordinary meaning nevertheless

remained attached to the word as a cloud of associations. To search, in English, is usually to be a searcher looking for something, and it is remarkably difficult to use the noun without importing the agent.

Memory carries a similar cloud. In ordinary speech it suggests recollection by a mind, while in a technical description we may require only that an earlier event leave some persistent physical state capable of altering what happens next. A computer register can contain state without remembering breakfast; a chemical trace can preserve information without recollecting anything. Both words are useful in thinking about biology, but only if the ordinary meanings are unpacked rather than allowed to do hidden work. As I write this, both Sapir and Whorf are whispering above my shoulder.

The danger is particularly old in biology because organized function invites purpose almost automatically. In 1802 William Paley asked his reader to imagine finding a watch on a heath. Its coordinated parts and evident function, he argued, implied a watchmaker, and the considerably more intricate organization of living things must therefore imply a designer. Darwin's great achievement was not to deny the appearance of contrivance but to explain how intricate adaptation could arise without an artisan standing behind it. Yet the watchmaker has proved remarkably difficult to evict. Whenever evolutionary change appears directed, economical, inventive, or unexpectedly rapid, an incomplete mechanism leaves room for purpose to be mistaken for explanation.

The usual counter-image is the *drunkard's walk*, borrowed from the mathematical idea of a random walk. Imagine a drunk leaving a tavern and taking successive steps whose directions are locally unpredictable, with no destination governing the next move. After enough steps he may get somewhere interesting, but only because one of the many possible trajectories happened to take him there. In loose evolutionary usage the metaphor becomes mutation supplying undirected steps while natural selection retrospectively preserves the trajectories that happen to work. It is useful because it removes foresight. The trouble begins when absence of foresight is allowed to imply absence of organization in the search itself. Paley was wrong about the watchmaker; it does not follow that the only alternative is a drunkard.

Search Without a Searcher

Ant colonies show why those are not the only choices. No individual ant possesses a map of the surrounding terrain, knows the colony's best route to food, or contains a representation of the colony's overall search strategy. Individual ants respond to local conditions, including trails laid by other ants, according to comparatively simple rules governing movement, pheromone deposition, trail following, persistence, and departure from established routes. The colony nevertheless produces coherent search patterns in which alternatives are explored, productive routes acquire more traffic, poor routes fade, and exploration continues around the resulting network. Different ant species, and colonies operating under slightly different local rules, can produce markedly different branching geometries by altering only a few parameters. There is no blueprint inside the nest corresponding to the global search pattern that appears.

This is *emergence*, a central idea in cybernetics and in the study of biological organization. Interactions among components following local rules can produce organization at a higher level that is neither represented nor specified as such in any component. There is nothing mystical about the higher level; it is embodied in the physical state of the system. The trail network produced by earlier ants changes the local information encountered by later ants, which changes their movement and further modifies the network. A description confined to an isolated ant therefore misses the organized search conducted by the colony, but inventing a Hobbesian queen to serve as the directing sovereign of the nest would explain nothing.

The important lesson is that search need not require a searcher in the ordinary English sense. But that claim needs a technical boundary or it becomes trivial. Mere historical dependence is not enough. A river channel is altered by previous flow, and that alteration changes where later water moves, but I would not therefore say that the river is searching for the sea. What matters here is organized exploration in which alternatives are differentially evaluated by their consequences and those consequences feed back to alter the distribution of subsequent exploration. The ant colony explores different routes; routes with useful consequences recruit more subsequent traffic; enough variation remains to test alternatives. Search in this technical

sense consists not merely of movement through a space but of a *feedback* among exploration, evaluation, retention, and further exploration.

Natural selection immediately begins to look search-like under that definition, although only in a minimal sense. Populations generate variants, different variants leave different numbers of descendants, and successful configurations therefore contribute disproportionately to the points from which subsequent variation begins. But simply renaming natural selection *search* would accomplish very little. The more interesting question is whether biological systems alter not only which variants survive, but also the machinery determining what gets tried next, the circumstances in which variants are evaluated, and even the routes by which apparently distant biological states can become accessible.

Landscapes, Seascapes, and Traversal

This brings us to another old metaphor. In the early development of population genetics in the first part of the twentieth century, Sewall Wright asked readers to imagine combinations of genes distributed across an *adaptive* or *fitness landscape*, with hills and valleys whose height corresponded to reproductive success. A population could then be pictured as occupying some region of that terrain, with mutation, recombination, drift, and selection changing its position. Peaks represented combinations that worked well under the specified conditions, valleys combinations that worked poorly.

The important difficulty was not merely climbing a peak. It was getting from one peak to another. A population might sit on a perfectly serviceable local optimum while a much higher peak existed elsewhere. If the only available route consisted of small successive changes, reaching that higher peak could require descending through intermediate forms of lower fitness. Selection would resist the descent, because each step downward would tend to be eliminated in favor of the population already occupying the lower peak. If the intervening states were sufficiently disadvantageous – sterile, nonfunctional, or lethal – the route would be effectively closed; untraversable. Wright's landscape therefore made visible a problem of *accessibility*, not merely optimization. A higher peak is irrelevant if no viable sequence of

intermediate states can connect the population to it.

But biology actually changes the problem more radically than Wright's picture suggests. Some evolutionary mechanisms do not carry a lineage down into the valley at all. Horizontal gene transfer, hybridization, and especially symbiotic acquisition can create a new transition between states that were previously separated by an impassable region. From the recipient lineage's point of view, the *intervening* forms are never instantiated. The analogy is less like crossing the valley than like *quantum tunneling*: a functional configuration appears on the far side because the machinery required to construct it evolved elsewhere.

No quantum mechanism is implied here, and no quantum woo-woo is being smuggled into evolution. The analogy is only geometric. In quantum tunneling, a particle with too little energy to surmount a barrier can nevertheless be detected on the far side; it need not occupy the sequence of classically accessible states that would constitute a *traversal* of the barrier. So here: the recipient lineage never traverses the low-fitness intermediate forms separating one adaptive state from another. It acquires machinery whose evolutionary history was worked out elsewhere, and that accomplishes a jump to another peak.

The fitness-landscape metaphor has lasted because it is good, but it has accumulated rather more furniture than the original landscape can comfortably hold. The relevant space is not merely genetic and is certainly not two-dimensional. Genetic sequence matters, but so do regulation, development, physiology, morphology, behavior, ecological relationships, symbiotic partners, and physical environment, with strong interactions among them. More importantly, three different things tend to disappear into the single word *landscape*: there is the space of possible biological states, there is the mapping from a state to reproductive consequences under particular circumstances, and there are the transition rules determining which new states can actually be reached from the present one. These are not the same object.

Seascape is in some respects a better metaphor. A landscape suggests mountains patiently waiting while populations climb them. A seascape has currents, tides, waves, and storms; a route available under one set of conditions may disappear under another, while the relation between one's

present position and any destination changes as both the water and the traveler move. Biological evolution is stranger still because the inhabitants participate in making the weather. Development changes which phenotypes can be produced from a genotype, behavior changes which environments an organism encounters, and interacting species change the circumstances under which one another survive. Still other mechanisms can change the allowable transitions themselves. Recombination rearranges inherited material, while horizontal gene transfer, hybridization, and symbiosis can create routes between configurations that would be extremely remote if a lineage were restricted to small modifications of what it already possessed.

When the Rules of Search Change

The *Baldwin effect* provides an early and unusually clear example of how phenotypic flexibility can redirect evolution without violating Darwinian inheritance. James Mark Baldwin proposed in the nineteenth century that an organism confronting a new circumstance might survive not because inherited variation had already supplied a finished solution, but because learning or developmental plasticity allowed it to accommodate during its own lifetime. The acquired response itself is not inherited. It nevertheless changes which organisms survive and reproduce, and therefore which inherited variants are carried into the next generation. Across generations, variants that make the useful accommodation easier, earlier, cheaper, or more reliable may then be favored. The plastic response need not disappear into genetic fixation; it can persist, increase, or redirect later evolution. The important point is that phenotypic exploration can open an evolutionary path before inherited specialization has discovered it. The genome need not always discover the path first.

Niche construction changes a different part of the loop. Here organisms modify the environment in which selection subsequently takes place. A bird's nest is an intuitive example: nest building alters temperature, humidity, exposure to predators, and the developmental conditions experienced by eggs and chicks. Those altered conditions in turn affect which inherited variants among builders and offspring succeed, while the behavior and morphology of later generations may further alter the nest. The feedback can there-

fore iterate: organisms change an environment; the changed environment changes selection; selected descendants inherit tendencies that may change the environment again. Plants alter soils, burrowing animals alter local hydrology, hosts create internal environments for parasites and symbionts, and predators, prey, flowers, pollinators, and pathogens continually modify one another's selective circumstances. At planetary scale, oxygen-producing microorganisms transformed atmospheric chemistry and thereby created metabolic possibilities unavailable in the previous world. In the language developed here, the Baldwin effect changes which phenotypes can be tried before inherited specialization catches up; niche construction changes the circumstances in which those phenotypes are evaluated. The evolutionary seascape therefore contains accumulated consequences of biological activity as well as geology, climate, catastrophe, and accident.

This suggests a distinction that matters for what follows. Many lineages evolving at the same time constitute *parallel search* in the loose computational analogy: separate populations are exploring different regions of biological possibility. When those lineages interact ecologically and thereby alter one another's selective conditions, their searches become *coupled*. Flower and pollinator are obvious examples; what works for either depends partly on what the other has become. For the stronger case I propose a new coinage: *federated evolutionary search* – a functional result produced along one evolutionary history becomes directly available to another, allowing the recipient to acquire a solution without traversing the sequence of intermediate states by which that solution was originally constructed.

The coinage is deliberate, borrowing *federated* from computation, where partly independent systems remain distinct while making some of their results available across boundaries. Biology has no central server, no common query, and certainly no agreed objective. Nevertheless, horizontal gene transfer can move a useful molecular capability between lineages, hybridization can join far larger bodies of inherited structure, and persistent symbiosis can make the physiology of one organism available to another. What matters is not cooperation but permeability. The receiving lineage has not escaped evolutionary history; it has acquired the product of history that occurred somewhere else.

The Modern Synthesis and the Problem of Merger

The importance of acquisition becomes clearer against the explanatory system that came to dominate evolutionary biology in the middle decades of the twentieth century. Darwin had supplied natural selection but not a workable theory of heredity; Mendelian genetics, rediscovered around 1900, supplied inheritance but at first seemed difficult to reconcile with the gradual variation Darwin had emphasized. During the 1930s and 1940s, population geneticists and evolutionary biologists brought these pieces together in what became known as the *Modern Synthesis*: evolution could be understood as changes in inherited variation within populations, generated principally by mutation and recombination and sorted over generations by selection, drift, and other population processes. In its canonical form, mutation and recombination supply heritable variation without regard to future need, while natural selection subsequently biases the historical path by preserving some variants and eliminating others. In the language used here, the proposal mechanism is largely blind and local; evaluation comes afterward. The drunkard supplies the steps, while selection determines which trails remain populated. Novelty may accumulate rapidly or slowly, under strong developmental constraint or weak, but it ordinarily remains novelty produced by modification within a genealogical lineage.

That explanatory system has a characteristic geometry – descent with modification through branching lineages, with natural selection shaping which variants persist. Darwin's tree branches. Descendants inherit material from ancestors, modify it, and diverge. In the Modern Synthesis, mutation and recombination supply much of the variation on which that process acts. Even substantial novelty is ordinarily explained by a sequence of changes along a branch, and the fitness landscape fits that picture naturally: a population moves among nearby states, selection biases which moves persist, and difficult innovations are difficult because the lineage must somehow reach them through whatever intermediate states are available. The source of novelty remains principally local modification of what the lineage already has.

By the late twentieth century, however, some of the most interesting evolutionary theorists were already dismantling parts of this tidy picture.

Stephen Jay Gould was among the most prominent. With Niles Eldredge he challenged the expectation that evolutionary change should normally appear as smooth phyletic gradualism; with Richard Lewontin he attacked the habit of treating every biological feature as though natural selection must have optimized it for its present function; elsewhere Gould emphasized constraint, contingency, hierarchy, and the historical structure of evolutionary change. He was therefore not a simple defender of the Modern Synthesis. Much of his career was spent arguing that its explanatory habits were too narrow.

That is precisely why his treatment of symbiogenesis matters. Gould revised the tempo of evolutionary change, challenged the universality of adaptationist explanation, and broadened the levels at which evolutionary causation might operate. Yet those revisions largely preserved a deeper *lineage-internal grammar of novelty*. The evolutionary walker might move episodically rather than smoothly, its possible steps might be heavily constrained, and selection might operate at more than one level; but the new organization still ordinarily arose by transformation along genealogical lines. In the terminology of this essay, Gould revised important parts of the evaluation function and the dynamics of movement without comparably revising the transition architecture itself. His own acknowledgment that his end-of-career over-arching synthesis *The Structure of Evolutionary Theory* remained largely within a selection-centered Darwinian tradition and did not adequately encompass genuinely alternative mechanisms is unusually revealing here.

Symbiogenesis alters precisely that deeper assumption. A lineage can acquire a complex biological system whose construction occurred on another evolutionary branch. The recipient does not traverse the sequence of intermediate states that produced it; those states belong to somebody else's history. Branches that the ordinary tree depicts as separate can join, and the resulting association can become a new evolutionary individual. In the language of search, this is not merely a different result produced by the old proposal mechanism. It is a different *transition operator*.

One obvious objection is that none of this is news. Evolutionary biology has long recognized horizontal gene transfer, hybridization, and endosymbiosis; why not simply regard them as additional sources of heritable varia-

tion and leave the larger architecture untouched? Because that description collapses the distinction the fitness landscape made visible. Mutation and recombination generally propose modifications within the inherited structure of a lineage. Transfer and acquisition can instead make available a functional system whose construction occurred elsewhere, without the recipient lineage traversing the sequence of states by which it was built. The issue is not whether non-vertical inheritance exists. It is what non-vertical inheritance does to the geometry of possible transitions. It changes what counts as adjacent.

At this point Lynn Margulis enters the argument naturally, because she made precisely this kind of merger central to evolutionary explanation. Her proposals were not all of equal quality. Her argument for the bacterial origins of mitochondria and plastids acquired overwhelming support; her proposed symbiotic origin for eukaryotic flagellar machinery did not. A useful intellectual history has to separate the claims rather than sanctify or dismiss Margulis's ideas as a package.

That, in turn, makes Gould's treatment in his massive tome *The Structure of Evolutionary Theory* especially revealing. Published in 2002, it was an enormous attempt to reconsider the architecture of Darwinian theory, yet Margulis does not appear by name or in its bibliography, and the word *symbiogenesis* does not occur anywhere. More importantly, Gould does acknowledge that the origin of cellular organelles from symbiotic prokaryotes violates a cleanly nested genealogy; he then classifies the case as historically "frozen" – something that happened once upon a time in deep time, an exception that need not alter his larger architecture. In effect, the extraordinary merger that helped construct the eukaryotic cell could be acknowledged as history and then placed outside the machinery explaining ordinary evolutionary novelty.

That move makes far more sense once its explanatory setting is visible. If symbiogenesis was a singular event confined to the remote construction of the eukaryotic cell, the basic lineage-internal grammar could remain untouched thereafter. Variation would again be supplied principally by mutation and recombination within lineages, with selection shaping the resulting paths. The exception would be real but safely historical – a hole in the map encountered once upon a time and fenced off thereafter.

A difficulty is that Gould, in the same discussion, was willing to contemplate lateral gene transfer among prokaryotes as sufficiently extensive to disrupt the conventional tree of descent. Genealogical mixture was therefore not conceptually unavailable to him. He admitted its architectural significance when the process was ongoing and then withheld the same significance from symbiogenesis because the canonical organelle-forming events were "frozen." The distinction substitutes present frequency for causal architecture. The Cambrian explosion, the origin of multicellularity, and many of Gould's own central historical cases are equally frozen in the relevant sense. A process does not cease to matter to evolutionary theory merely because it happened only once. But, as we will see below, this one happened more than once, across evolutionary history – *and is still happening*.

This is not an accusation of bad faith. It is an accusation of bad *epistemic hygiene*. Gould accepted the evidence, recognized that it violated the geometry of a cleanly branching genealogy, and then classified the violation as an exception rather than allowing it to reorganize the explanatory system. The evidence was not denied; it was quarantined. That is quite precisely an epistemic failure – acknowledging an anomaly while preventing it from becoming load-bearing.

The biological evidence available now makes the category of symbiogenetic acquisition impossible to quarantine in a remote past. The canonical mitochondrion and plastid were already separate incorporations. More strikingly, photosynthetic amoebae of the genus *Paulinella* acquired a cyanobacterium independently of the ancient plastid event, roughly a hundred million years ago. The resulting photosynthetic compartment, called a *chromatophore*, has undergone substantial genome reduction and depends increasingly on functions supplied by the host. Because the event occurred independently and vastly later than the canonical plastid acquisition, *Paulinella* gives us something that appears to be a second evolutionary development of primary photosynthetic organellogenesis with many of the seams still visible.

A still different case broadens the point beyond photosynthesis. The marine alga *Braarudosphaera bigelowii* contains a cyanobacterial partner, UCYN-A, specialized for nitrogen fixation – the conversion of atmospheric nitrogen into chemically usable forms. The association has become suf-

ficiently integrated, with coordinated growth and division and extensive dependence on proteins supplied by the host, that the structure is now described as a *nitroplast*, a nitrogen-fixing organelle. Complete organellogenesis remains rare, which is itself important. But "rare" is quite different from "once upon a time."

The history becomes still more elaborate with *secondary endosymbiosis*. In a primary event, a eukaryotic host incorporates a bacterium, as in the origin of ordinary plastids or independently in *Paulinella*. In a secondary event, a eukaryotic host incorporates another eukaryotic cell that already contains a plastid inherited from an earlier bacterial acquisition. Some descendants retain a tiny remnant of the swallowed alga's nucleus, called a *nucleomorph*, so that what appears to be one cell carries the genetic residue of several formerly independent organisms. The result begins to resemble a biological matryoshka – one evolutionary history nested inside another, which is itself nested inside another. Higher-order events repeat the pattern.

The conservative conclusion is therefore straightforward. Complete organellogenesis remains unusual; acquisition and progressive integration do not. What can no longer be sustained is the larger inference that symbiogenesis belongs to a unique formative episode in the remote construction of the eukaryotic cell. The observable biology instead presents a range of acquisitions, partial integrations, metabolic dependencies, transfers, and occasional mergers, with completed organelles at the rare far end of a recurrent family of processes.

Federated Evolution

Kleptoplasty shows a particularly vivid transient case. The word refers to the retention of chloroplasts taken from algal prey by an organism that digests much of the prey while keeping the stolen plastids – kleptoplasts – structurally intact and photosynthetically useful. In some *Mesodinium* ciliates, the theft extends beyond the chloroplasts: the predator also retains a transcriptionally active prey nucleus, a *kleptokaryon*, which continues supplying functions needed to maintain the captured photosynthetic apparatus. The recipient has not evolved photosynthesis along its own lineage. It has changed the problem from constructing photosynthesis to recognizing,

capturing, maintaining, regulating, and exploiting machinery constructed elsewhere.

The apparent jump through evolutionary space is therefore real from the perspective of the recipient but is not history-free. The history happened somewhere else. *Dinophysis* makes the nesting stranger because some species obtain their photosynthetic machinery by consuming *Mesodinium*, which itself obtained the plastids from algal prey. The same functional apparatus can thus pass through successive ecological relationships before being put to work by its current host. Kleptoplasty does not imply an inevitable escalator toward permanent organellogenesis; most such associations may never proceed farther. It does show, however, that capture, partial integration, and metabolic appropriation are contemporary biological processes rather than hypothetical conveniences invented solely to explain ancient organelles.

This is what makes *federated search* more than a decorative metaphor. If photosynthesis occupies a distant functional region for a heterotrophic lineage, a purely local search would require some viable sequence of intermediate states through the immense biochemical and regulatory machinery needed to produce it. Acquisition changes the transition operator: instead of traversing that sequence, the recipient begins with machinery whose difficult construction was completed along another evolutionary trajectory. Selection then acts on a different problem – whether the acquired system can be maintained, regulated, transmitted, and integrated into its new biological setting.

Such acquisitions will usually fail. The imported machinery arrives entangled in membranes, regulation, protein targeting, replication, metabolism, and conflicts of interest, none of which is obliged to fit its new host. But when an acquisition does persist, evolution begins working from the new starting point. The recipient has not escaped evolutionary history; it has inherited the result of history conducted elsewhere.

Seen in the geometry of the fitness landscape, this is where the tunneling analogy earns its keep. The low-fitness valley is not crossed because its intermediate states are never traversed by the receiving lineage. The new functional state arrives carrying an evolutionary history of its own. The recipient may still face an arduous adaptive problem – compatibility, control, transmission, regulation – but it does not have to replay the sequence

by which the acquired machinery originally came into existence.

Distance in evolutionary space therefore depends on the available moves. Two functional configurations may be fantastically remote if the only permitted transitions are incremental modifications within one lineage, yet much closer if horizontal transfer, hybridization, or endosymbiotic incorporation becomes possible. To say that evolution "jumps across the fitness landscape" captures the visual effect but not the more important change. The topology of possible transitions has been altered: a new edge now connects regions that, under the previous rules, were effectively unreachable from one another.

Ecology broadens the picture without requiring material transfer. The products of one lineage's history can become conditions, opportunities, or constraints for another. Oxygenic photosynthesis changed planetary chemistry; flowering plants created new ecological possibilities subsequently explored by insects, whose evolution then altered the possibilities available to plants; hosts constitute elaborate environments for parasites and microbial communities; reef builders manufacture physical structures within which other evolutionary trajectories proceed. These are better described as coupled searches than federated ones because the result need not cross into another lineage as a transferable component. But the larger implication is the same: the biosphere consists not of independent walkers on a common surface but of many evolutionary processes continually changing one another's available problems and opportunities.

The resulting architecture is extraordinarily unlike a single optimizer. There is no global objective, and evolutionary interests frequently conflict. Parasite success can be host disaster; an adaptation useful today can become a liability when climate or competitors change. Yet the biosphere nevertheless contains an enormous asynchronous collection of searches proceeding in parallel, coupled through ecology and occasionally federated through the actual transfer or incorporation of biological results. The output of one search can become the environment of another, the component of another, or the machinery by which another search subsequently proceeds.

The ant colony again helps clarify why none of this requires an evolutionary planner. Change a few local ant rules and a different global search geometry emerges. Evolutionary lineages likewise need not acquire some

explicit facility called "better search." Changes in mutation bias, DNA repair, recombination, developmental organization, dispersal, mate choice, cellular uptake, or tolerance of intracellular partners may spread for immediate local reasons while profoundly altering what kinds of descendants can subsequently be generated. The long-term consequence for evolvability need not be what selection originally favored. Local rules change; the branching statistics of future exploration change with them.

Search Moves Inside

There are biological systems in which the word *search* becomes still harder to avoid. The vertebrate adaptive immune system must generate molecular receptors capable of recognizing targets that the inherited genome cannot enumerate individually in advance. In specialized structures called germinal centers, B-cell lineages undergo repeated cycles in which antibody genes are varied and cells producing receptors with better antigen-binding performance are preferentially expanded. Partial success changes where subsequent molecular exploration is concentrated, while successful solutions can be preserved even as related variants continue to be tested.

No B cell knows the antibody it is trying to discover. Yet the system generates alternatives, subjects them to differential consequences, retains and expands partial successes, and changes the distribution of subsequent exploration around those successes. Natural selection has produced within the organism a compact evolutionary mechanism whose biological function *is* search. This is an existence proof of some importance because it separates search from nervous systems. Cognition is *not* required for a generate–evaluate–retain–reexplore architecture.

The next examples push toward sensing. Warnowiid dinoflagellates are single-celled marine eukaryotes that contain an extraordinary subcellular structure called an *ocelloid*. It is sufficiently eye-like to contain structures functionally analogous to a focusing lens and receptor field, yet it is assembled inside one cell from cellular machinery with still deeper evolutionary histories. The ocelloid incorporates components derived from mitochondria and plastids – organelles that themselves descend from

ancient endosymbiotic acquisitions. The eye-like apparatus is therefore built partly from the domesticated descendants of organisms that once lived independently.

This example is almost indecently elegant. Something acquired in ancient symbiogenesis as cellular metabolism eventually becomes raw material for constructing an optical sensor. Paley would presumably have enjoyed the eye; he might have been less pleased to discover that part of the watch had once been another watch.

The story improves with *Erythropsidinium*, a warnowiid possessing both an ocelloid and a remarkable contractile structure called a piston. Its ocelloid can rotate within the cell, often before the cell swims, and its lenses concentrate incident light. The behavioral function of that rotation is not established well enough to claim that the organism deliberately aims its eye at a prospective target, but the physical architecture permits directional sampling rather than mere passive reception. A single cell has acquired something recognizably closer to active looking than simply being struck by light.

That distinction matters. A system responding only to whatever stimulus happens to arrive is organized differently from one capable of acting so as to *change* what information it receives *next*. Active sensing introduces a loop in which information-gathering behavior influences the subsequent information available for action. One should not infer a tiny contemplative mind inside *Erythropsidinium*; there is already enough marvel without supplying one. What matters is the accumulation of machinery for sampling, retaining state, and directing behavior before anything like a conventional nervous system appears.

The recursion is striking. Ancient symbiotic acquisitions become organelles; organelles are later repurposed into components of sensory machinery; sensory machinery affects how an organism samples its environment; the acquired information changes later behavior; and behavior changes which conditions are subsequently encountered by the organism and potentially by its descendants. The products of previous search become machinery for later search, and under federation they may be products of somebody else's search.

Futures That Never Occur

This still does not give us *counterfactual search*. A bacterium can embody temporal regularities in regulatory circuitry, and a unicellular eukaryote can retain state or change its sampling behavior according to what recently happened, without internally representing several incompatible future trajectories. That distinction is worth guarding because some nervous systems eventually introduce something genuinely different.

In at least some animals, possible futures can be represented before any one of them is enacted. At a decision point, neural activity can transiently represent alternative trajectories through the environment, allowing action selection to depend on states that have not yet occurred. The important transition is not simply that search becomes faster. The candidate itself has changed status: it can now exist as *a representation of a possible state* rather than as the corresponding state of the external world.

Eventually some organisms can run models of *futures that never occur*.

That marks a distinct change in organization. Population-level evolution often pays for exploration by constructing whole organisms and allowing some of them to fail. Developmental plasticity can test phenotypic alternatives without first altering inherited sequence, overt behavior permits one animal to explore several possibilities during its lifetime, and the immune system compresses rapid evolutionary exploration into competing cell lineages. A sufficiently capable nervous system goes farther because some candidate trajectories can be generated, evaluated, and discarded without ever being physically executed. Search has moved partly into representational space.

Cognition is not the origin of search. It is what happens when much older architectures of exploration, differential evaluation, historical retention, and biased re-exploration become increasingly internalized. An ant colony performs much of its search in moving bodies and pheromone-modified terrain, an evolving population in differential reproduction across generations, and an immune system in rapidly varying molecular lineages inside one body. Some nervous systems make it possible to search among transient representations of alternatives. These processes are not identical, and forcing them into a single mechanism would destroy the argument rather than strengthen it. The continuity lies in what progressively becomes

possible: more of the cost of exploration can be paid in temporary internal states rather than in failed bodies, failed lineages, or failed actions.

This returns us to the semantic cloud around *memory*. Pheromone concentration, inherited sequence, developmental state, ecological modification, clonal composition, and neural activity retain different sorts of information over radically different timescales. Calling them all "memory" without qualification would conceal more than it reveals. Their common property for the present argument is narrower: earlier events leave physical states that alter the probabilities of later exploration. Cognitive memory is one highly elaborated member of that family, not the definition by which all the others must be judged.

The same restraint must apply to *search*. Evolution has no equivalent of a single food source toward which an ant colony's foraging system has been shaped, no stable global objective function, and no assurance that today's success will remain tomorrow's success. Fitness is conditional and often frequency-dependent, while organisms continually modify the circumstances in which they and other organisms are evaluated. The ant colony therefore does not show that evolution is secretly pursuing a goal. It shows something more useful: organized search can emerge from local processes without a central representation of the search strategy, and changes in those local processes can change the branching geometry of subsequent search.

The old fitness landscape is therefore not wrong so much as insufficient. A better picture is a distributed branching process moving through a high-dimensional and mutable seascape in which the state space, the circumstances of evaluation, and the available transitions are all historically contingent. Previous outcomes alter where later variants originate; plasticity and behavior change which phenotypes and environments become available for selection; ecological coupling causes searches conducted by different lineages to reshape one another; federation allows results constructed in one lineage to enter another; symbiogenesis can turn formerly independent searches into a new evolutionary individual; and changes in local biological rules alter the branching statistics of future exploration. At no point need the process contain a representation of where it is going. There is no goal state toward which the system is steering; trajectory emerges from the dif-

ferential survival, retention, recombination, and reuse of what has already occurred. The trajectory is real; the destination is not specified in advance.

The Searcher Emerges

Paley's mistake was to recognize organization and infer an organizer standing outside it. The drunkard's walk risks the opposite mistake by assuming that removing the organizer must also remove organization from the search itself. Emergence supplies the missing possibility. Local interactions can generate global search architectures, and the results of those searches can alter the local rules and environments within which subsequent searches occur. Independently evolving lineages can couple their trajectories ecologically, occasionally exchange or appropriate one another's results, and sometimes merge so thoroughly that yesterday's independent organism becomes today's cellular machinery.

The deeper continuity is therefore not between blind chance and hidden purpose, but among increasingly powerful ways of generating, evaluating, retaining, combining, and reusing possibilities. Search, in the technical sense with which I first encountered it in sorting and searching, does not require a searcher. Yet evolution eventually produces nervous systems in which search becomes prospective and partly internal. Birds search, dogs search, and an animal seeking food, a route home, shelter, prey, or a companion can represent something of what it seeks before it finds it. At that point the ordinary English meaning of *search* begins to reappear inside the technical one.

Human cognition adds another turn to the recursion. We can search not only for objects and routes but for structures that cannot be directly seen, for causes buried in deep time, and for the meaning of the processes by which we search. Four centuries of science have progressively extended what can be made visible: instruments brought cells and microorganisms into view, geology opened depths of time unavailable to ordinary memory, genetics exposed histories written into living matter, and computation gave us new ways to explore structures too large or too abstract to inspect unaided. The biological eye acquired lenses of glass, then instruments, mathematics, algorithms, and a collective record sufficiently durable to reconstruct events

billions of years older than the observer.

Paley found a watch and inferred a watchmaker. We have since opened the watch and found bacteria incorporated into cells, bacteria transformed into organelles, organelles recruited into something remarkably like an eye, and nervous systems capable of constructing models of futures that never occur. No watchmaker has so far presented himself. What *did* eventually appear was a searcher, in the form of human curiosity and our persistent yearning to understand what all this means.

That is what I find myself doing here, half a century after encountering *search* as an operation in computer science: following the word downward through ants, cells, stolen chloroplasts, symbiogenesis, and the coupled and federated searches of ecologies, then upward again through eyes and nervous systems to the peculiar animal now doing the searching. We did not become the purpose of that history, whatever comfort Dr. Pangloss might have taken from the suggestion. We did, however, become capable of looking back into realms that were unseen until science taught us how to see them. The searcher was not concealed behind the process as its cause. It emerged from the process as one of its consequences – and has now acquired the slightly impertinent habit of searching for the meaning, machinery, and reach of search itself.