The traditional approach to building artificially intelligent systems can be characterized as a top-down methodology: creating large complex systems with massive amounts of knowledge dedicated to solving one particular aspect of supposedly intelligent behavior, such as theorem-proving, or playing chess, or understanding natural language. At some point, it is hoped, all of these separate modules can be connected together to create a wholly intelligent system, but until then, we have a collection of idiots savants, who may, for instance, be able to beat all but a handful of the humans on this planet at chess, but lack the ability possessed by even the lowliest housefly to navigate through a crowded room to the chessboard. The failure of three decades of AI research to even match the behavioral repertoire of insects, let alone humans, and a heightened awareness that what it takes to act intelligently in a challenging environment has little to do with game-playing and theorem-proving, has led to the emergence of a new approach to creating intelligent systems, one that starts from the bottom.

This new approach, called the "animat path to AI" by Stewart Wilson at the Rowland Institute for Science, constructs artificial creatures or agents (animats) existing in some environment that begin simple and are gradually made more and more complex, exhibiting more and more complex--and intelligent--behaviors at each step of the way. The key to this bottom-up approach is that each animat system should be an integrated whole, incorporating sensory input, behavior generating, and behavior effecting (e.g. motor) subsystems to act intelligently, and in a way that scales up naturally with the addition of further subsystems. Intelligence here is redefined as adaptive behavior--achieving the goals and satisfying the desires and motivations intrinsic to the individual animat, which goals in turn reflect the actions necessary to survive, and succeed, in the animat's surrounding environment. Thus while we might not consider crossing a busy street to be the epitome of human intelligence, since squirrels and occasionally frogs can do the same, a small robot street-sweeper that satisfied its goals of collecting garbage and not getting crushed by passing cars would be behaving very adaptively, and intelligently, in its specified asphalt environment.

The environment the adaptively-behaving agents exist in can be, as in the street-sweeper example, the real world, which implies that the agents will be physically-instantiated robots. Using the real world as a testbed for intelligent behavior has advantages, when compared to the alternative of using artificial computer-simulated environments: the real world already exists, and it embodies complex features and phenomena, like gravity, friction, the propagation of light and sound, which are difficult and expensive to simulate. Rod Brooks and his lab at MIT have taken advantage of these facts in designing and building a set of sophisticated mobile robots that roll down hallways collecting soda cans, or walk over objects with a six-legged gait, or flock together like birds. The behavioral repertoires of each of these robots was carefully designed in a bottom-up fashion, beginning with a module for collision detection and avoidance, then adding a superordinate module...
for wandering about while avoiding collisions, then adding a next-higher module for directed exploration or following, etc., so that at each step in their development the robots would be able to emit some appropriate behavior, which could gradually be elaborated with the addition of further modules. Brooks's robots furthermore achieve their intelligent behavior without traditional AI techniques such as knowledge representation and symbol processing; they rely on the world to be its own constant representation, to which the behavior modules can refer through the robot's sensors.

But building actual physical robots, with their complex motors, sensory systems, etc., can be very difficult and time-consuming, as Brooks admits; hence the temptation to bring the search for intelligent behavior inside the more-manageable--or at least less physical--world of the computer. The majority of artificial adaptive agents reside in simulated environments, where their simulated bodies behave and respond to simulated sensory cues, often with two-dimensional graphical representations to conjure up real-world analogies to movement, eating, fighting, etc. Sometimes, these agents are completely designed by hand and merely tested out in their environment, but often researchers take cues from biology and leave part or all of the design up to automated processes akin to something in the natural world. Many researchers use evolutionary design processes (most commonly the genetic algorithm developed by John Holland at the University of Michigan), which operate on a population of agents simultaneously through a mechanism much like natural selection. Beginning with a random population of agents that one would like to exhibit adaptive, intelligent behavior in their simulated environment, each individual is tested in that environment and scored according to their behavioral ability. Those that do better, in terms of succeeding at whatever goals the environment presents them with, will have more "offspring" in the next generation. Offspring can be direct copies of the original--that is, agents that will behave in exactly the same manner as the original; copies with slight random mutations--agents that will behave slightly differently; or combinations of two agents from the previous generation--agents that will incorporate some of the behavioral patterns of both "parents". After many generations of agents have been created and evaluated, the behaviors exhibited will tend to become more and more appropriate for the particular environment they inhabit, or in other words, more and more adaptive. In this way, for example, John Grefenstette has evolved agents that pursue and evade one another, and Rob Collins and David Jefferson at UCLA have evolved simulated ants that cooperatively forage and bring food back to a central nest.

Another process by which adaptive behavior can emerge automatically is learning. If creatures or agents can pick up key features of their environment and figure out what to do about them, that is, learn how to behave adaptively, then much less of their behavioral repertoire has to be built-in or "hard-wired" ahead of time either by hand or through an evolutionary process. The recent explosion of neural network and parallel distributed processing (PDP) techniques has contributed a broad palette of learning mechanisms to research into intelligent behavior. Reinforcement learning methods like those explored by Rich Sutton at GTE Labs, for example, can allow agents to explore and build up cognitive maps of complicated environments, which can later be used to navigate fluently through passages and around obstacles. Wilson used a similar learning technique known as classifier systems to develop animats that could move around a simulated forest-world and discover food. But just what and when to learn must still be determined and itself hardwired into the "brain" of the agents, which opens up the way for fruitful exploration of the interactions of
evolutionary and learning methods together, as Peter Todd and Geoffrey Miller at Stanford and David Ackley and Michael Littman at Bellcore have shown.

While it is natural to focus on the behavior-generating abilities of the agents themselves as the source of intelligent behavior, the importance of the environment must not be underestimated. Even simple creatures in complex environments can exhibit correspondingly complex behaviors in response to the environment. Valentino Braitenberg demonstrated this, and the fallacy of imputing complex behavior to complex internal mechanisms, in a set of simple agents he called "vehicles" which were wired up in various ways to approach or avoid lights, circle beacons, etc. When the vehicles themselves are adorned with lights and beacons, a variety of complex "social" behaviors can emerge. Realizing the importance of the environment also implies that we must not take effectors and sensors--the agents' links to their environment--for granted, and must instead also investigate THEIR design and evolution, as a few researchers in this area have now begun to do.

Throughout this work, the notion of emergent behavior and effects keeps popping up--largely unpredicted and unexpected phenomena exhibited by a system that are more than merely the sum of the effects of the system's parts. Such emergent behavior can occur whenever populations of nonlinear dynamic subcomponents interact, whether they are populations of neurons, whole agents, or societies; and a large part of the bottom-up search for intelligent adaptive behavior is based on the emergence of such population effects when simple components are combined. Much of this research is only now becoming possible, in fact, because of the increasing availability of powerful parallel computers whose structure is well-suited to eliciting such emergent behavior, through the large numbers of simultaneous interactions they allow. As we increase the complexity of our simulations and the questions we want to explore, to look at food webs and ecologies, social systems, communication, and culture, sexual selection and evolutionary arms races, and the formation of new species, we will continue to stretch at the bounds of what we can achieve computationally.

But the rewards will be great, and even now are beginning to emerge. Robots that can perform real-world tasks and adaptively alter their behavior when their situation and surroundings change will be much more useful than the brittle and easily-confused automata we have today. Intelligent adaptive agents that roam the information environment of enormous computer databases searching for relevant material for their human masters, as Pattie Maes and her students at the MIT Media Lab have begun to explore, will be the only way to keep up with the continuing information explosion. Neural-network-controlled pets that accompany us through virtual-reality adventures and react like our true-reality animals do--and which we can further evolve to our own specifications--will be an important aspect of the next entertainment industry. And all of this will emerge, incrementally, as the animats of today are designed, evolved, and trained toward more and more adaptive, and intelligent, behavior.

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