

Functional blueprints: a means of adaptive integration?

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One of the most remarkable facts about animals is that they are not injured by their own growth. An animal is composed of many tightly integrated systems, all interlocking in multiple ways. For example, bones fit together in joints that permit a useful range of motion, muscles attach to the bones in a pattern that allows them to work together effectively to move the body, the circulatory system delivers oxygen and nutrients to every portion of the bones and muscles via an intricate network of vessels, and their waste products are carried away for removal by the kidneys. As the animal grows, from an embryo to a mature adult, all of these systems are constantly adapting in order to remain integrated and fully functional.

This is not generally the case for our current engineered systems. Many artifacts, such as cars and airplanes, have no real capacity for growth at all. In engineered systems that do grow, the growth is often accompanied by significant degradation of function as the existing balance of systems is disrupted and painstakingly reintegrated. Adding an extension to a house means months of dust, being unable to use existing rooms, and electrical and plumbing disruptions. Expanding the road networks of a growing city requires years of detours and traffic disruptions, not to mention economic disruption for businesses nearby the construction. Upgrading the software of a computer often requires a reboot and leaves a trail of incompatibilities and ongoing headaches. Beyond the obvious differences in mechanical and material properties, we simply do not know how to describe our designs in a way that allows for disruption-free growth. We may thus be led to consider languages for adaptable design, both to better understand animal development and also to improve engineered systems.

I propose *functional blueprints* as a new mechanism for specifying an adaptive design. The basic idea is that a system should constantly monitor how well it is satisfying its functional specification, and when its behavior is marginal, it should incrementally adjust its structure towards better satisfaction. A functional blueprint thus consists of four components: 1) A program that provides functional behavior in both normal and stressed conditions. 2) A functionality metric that can determine the degree and direction of stress on the structure. 3) A program for incrementally modifying structure in order to decrease stress. 4) A program for constructing a minimal initial system. Together, these form a feedback mechanism for structural adaptation.

Biology provides us with at least one clear example of functional blueprints, in the regulation of the vascular system. Under normal conditions, sufficient oxygen diffuses through the walls of capillaries into the surrounding tissue. When cells are not receiving enough oxygen, however, they become stressed and emit a chemical signal that causes nearby capillaries to leak. This constitutes a program for behavior in normal and stressed conditions, as well as a functionality metric (the chemical signal).

The vascular system also has an elegant program for regulating its capacity. When a capillary leaks often, a new capillary begins to grow out of the leaky area, increasing the available blood supply to the oxygen-starved region. Blood vessels are elastic, and when they are frequently stretched, the cells divide, increasing the capacity of the vessel; likewise, when frequently contracted, cells die and shrink the vessel. Thus, the vascular system incrementally grows and shrinks to match the demand of the tissues it serves, branching into underserved regions and adjusting the size of vessels to match the flow through them. All that remains is a minimal system specification, which surely must exist.

Others systems might work this way as well. For example, a muscle might be specified to be capable of contracting at a certain speed (and thus flexing the joint it is attached across), and grow new bulk when it does not contract quickly enough. The movements of a developing fetus would then signal its muscles to grow to a strength appropriate to its size, no matter what that might be. Likewise, a kidney might be specified to emit blood of a certain purity, and grow additional filtering capacity when it is unable to do so.

If each system is capable of operating under minor stress and of incrementally adjusting to decrease stress, then feedback between components should allow all the systems comprising an animal to maintain a tight integration as the animal grows, even if their relationship and relative sizes are changing. Moreover, this decoupling of ultimate structure from developmental program could allow phenotypic adaptation to environmental change (simply by continuing to execute morphogenetic programs) and also facilitate evolvability by eliminating the need for coupled mutations.