Chapter 6

Conclusion and Future Directions

This thesis has demonstrated the implementation of molecular machines while formulating an overarching method to program very simple molecules.

We have identified a new class of programmable behaviors that require an energy source external to the system and cannot be implemented on “energetically-incomplete” systems even if the systems are Turing-complete. As we have demonstrated, a sufficiently expressive implementation of an “active” molecular self-assembly approach can achieve these behaviors. Using an external source of fuel solves part of the the problem, so the system is not “energetically incomplete.” But the programmable system needs to have sufficient expressive power to achieve the specified behaviors. Perhaps surprisingly, some of these systems do not even require Turing completeness to be sufficiently expressive, as we proved at the end of Chapter 3.

We have constructed a new computational model for active self-assembly (Chapter 3), the first of its kind to be implemented in DNA molecules (Chapter 4). We have designed and experimentally verified the construction of the first synthetic linear polymer capable of growing exponentially fast and also capable of dividing. Finally, we have characterized the kinetics of the insertional mechanism used to implement our model (Chapter 5).

When visualizing the capabilities of our system, the reader might wonder whether the transformation of information into an active entity is inherently bottlenecked by some linear phase. In biology, all information is stored in the genome whether it be chromosomal or mitochondrial. This information must be transcribed into RNA which is then translated into strings of proteins that fold into their desired shape. We have shown that exponential growth of a polymer is possible, but we have yet to construct a two or three dimensional model or implementation of such a behavior. This thesis also presented a proposed implementation for treadmilling in a linear system by combining an insertion primitive with a division/deletion primitive, but this behavior runs in linear time.

Another open question for future work would be the analysis of the complexity of a system capable of metamorphosis: what is the trade-off between complexity of information inherent in the system and the flexibility of its component molecules?

In the context of nanotechnology and material science this work presents an advance in our ability to manipulate matter. This work is part of a growing push in these fields toward fabricating smart materials that can be programmed and that interact via molecular reactions, thus rendering them capable of being interfaced with biological compounds. Such materials capable of complex behaviors and programs will not run the kinds of programs that computers run (nor should they). Rather these molecules will most likely be used to do what molecules do best: communicate information via shape, structure and interaction. They will be used by future doctors to deploy an army of molecular surgeons like those that Richard Feynman envisioned [1] [Feynman, 1960]. They may be used to reprogram the nano wires in reusable hardware.

These future molecules and the materials they comprise will likely be used to design materials capable of modifying themselves, reusing materials, and adapting or metamorphosing as needs change. In short, they will be used to do what nature and biology and biochemistry do best, but perhaps at the control of a human re-imagining his or her reality. This ultimate goal is one that will be reached at the intersection of several fields that converge on materials, information, biochemistry and physics.

While we have motivated this work by asking how it is that information becomes an active entity, in the process this work touches or creates a small piece of what Jean Baudrillard calls “the hyperreal” [2] [Baudrillard, 1994]. In the larger context of philosophical discourse this is significant

---

[1] In his essay ‘*There’s Plenty of Room at the Bottom*, Feynman writes: “(Albert R. Hibbs) suggests a very interesting possibility for relatively small machines. He says that, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and ‘looks’ around. . . It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately-functioning organ.”

[2] Baudrillard explains this concept as follows: “Today abstraction is no longer that of the map, the double, the mirror, or the concept. Simulation is no longer that of a territory, a referential, or a substance. It is the generation by models of a real without origin or reality: a hyperreal. The territory no longer precedes the map . . . ”

as human society is embarking on an era in which we are no longer building out of the raw materials of the earth, but decomposing those materials into molecules and remaking nature as we see it. While this future technology may enable myriad possibilities, society at large must continue to confront how quickly our bodies, our psychologies, and our cultures will adapt to materials that are evolving thousands of times faster than we are [Toffler, 1984].