In addition to the laws of physics, several other factors limit in practice the complexity of man-made

systems; among them are cost, reliability, performance, and functionality. Assembling reliable systems

from unreliable components is quite challenging; as the number of components grows, the mean time

to failure (MTTF) of the entire system becomes smaller and smaller. As the number of components

increases, so does the complexity of coordination; then the fraction of system resources dedicated to

coordination increases and limits the performance.

Modularity allows us to develop individual system components independently and then assemble

them into more complex structures. Inmany instances the laws of physics place a limit on the composition

process; for example, the number of gates in a solid-state circuit is limited by the ability to remove the

heat generated during switching. A new technology could extend these limits until other physical laws,

e.g., the finite speed of light, expose a new limit.

Computing and communication systems have a unique characteristic: the physical limitations of

composability can be pushed further and further as the software allows us to overcome the physical

limitations of the hardware. For example, though there are limits on the number of cores on a chip, the

software allows us to build multiprocessor systems in which each processor has multiple cores. Such

systems can then be interconnected using networking hardware under the control of another layer of

software to form a computer cluster; in turn, multiple clusters can be interconnected to build a computer

cloud controlled by the next layer of software, and so on.

Our limited understanding of system complexity and the highly abstract concepts developed in the

context of natural sciences do not lend themselves to straightforward development of design principles

for modern computing and communication systems. Nevertheless, the physical nature and the physical

properties of computing and communication systems must be well understood because the system

design must obey the laws of physics.

Some of the specific factors affecting the complexity of computing and communication systems

are [2]:

• The behavior of the systems is controlled by phenomena that occur at multiple scales or levels. As

levels form or disintegrate, phase transitions and/or chaotic phenomena may occur.

• Systems have no predefined bottom level; it is never known when a lower-level phenomenon will

affect how the system works.

• Abstractions of the system that are useful for a particular aspect of the design may have unwanted

consequences at another level.

• Systems are entangled with their environment. A system depends on its environment for its persistence;

therefore, it is far from equilibrium. The environment is man-made and the selection required

by the evolution can either result in innovation or generate unintended consequences, or both.

• Systems are expected to function simultaneously as individual systems and as groups of systems

(systems of systems).

• Typically, computing and communication systems are both deployed and under development at the

same time.

A number of factors contribute to the complexity of modern computing and communication systems,

as shown in Figure 10.1. Some of these factors are:

• The rapid pace of technological developments and the availability of relatively cheap and efficient

new system components such as multicore processors, sensors, retina displays, and high-density

storage devices.

• The development of new applications that take advantage of the new technological developments.

• The ubiquitous use of the systems in virtually every area of human endeavor, which, in turn, demands

a faster pace for hardware and software development.

• The need for interconnectivity and the support for mobility.

• The need to optimize the resource consumption.

• The constraints imposed by the laws of physics, such as heat dissipation and finite speed of light.

Each one of these factors could have side effects. For example, the very large number of transistors

on a chip allows hiding of hardware trojan horses (HTH),4 malignant circuits that are extremely hard

to detect. Wireless communication creates new challenges for system security, and increased security

demands more complex software.

These factors will continue to demand changes in the way we engineer and manage computing and

communication systems. They may require paradigm shifts in many areas, including hardware design,

software engineering, and new strategies for systems integration.