Chapter 4:

Qualities of Physical Media Compared with Digital Media

In Chapter 3, I defined a medium as a combination of properties, usability, and appeal. The properties of a medium establish a "world" populated with a particular shape vocabulary (or elements) and tools (or operators) to manipulate those elements. The usability of a medium is determined by its capabilities and limitations. The appeal of a medium influences the designer's level of engagement and contributes to pleasure, inspiration, and motivation. In sum, a medium is a combination of the following traits:

- **Properties** (primitive elements and operators)
- **Usability** (affordances and constraints)
- **Appeal** (sensory and conceptual attractiveness)

However, when a designer works with a medium, he or she does not tend to analyze it into component parts, as in the definition above. Rather, the designer recognizes certain *qualities,* which stand out as particularly unique, appealing, or advantageous in the design process. It is this qualitative experience, gained over time from working with a medium, that helps the designer to ultimately choose how and when to best use a particular medium. This kind of perception identifies what might be a small capability such as "undo" in the digital realm, or an invisible capability such as tactile feedback in the physical realm, and recognizes or the tremendous impact it may have on a design process.

4.1 Qualities

4.1.1 Physical Media

Not many people today are discussing the qualities of physical media to the degree that computers and the digital medium are touted. As described in Chapter 1, the advent of computers has demoted the status of physical media for the past few decades to “old-fashioned” or “legacy.” One must look several decades earlier, when the demise of handicraft to mechanized manufacturing inspired contemplative texts on the process of working with materials by hand. Focillon wrote in the 1930s:

The hand knows that an object has physical bulk, that it is smooth or rough…. The hand’s action defines the cavity of space and the fullness of the objects which occupy it. Surface, volume, density, and weight are not optical phenomenon. Man first learned about them between his fingers and the hollow of his palm [1].

This reference not only brings attention to the material aspects of physical media such as surface, volume, density, and weight, but also emphasizes the importance of the tactile sense in the process of physical form-making. In fact, the most-powerful qualities of physical media may be their direct correlation to our senses; correspondingly, our senses have evolved to allow us to thrive in the physical, material world.

With Focillon’s help, below is my first take on the qualities of physical media, followed by my second take, where I regrouped elements to eliminate redundancies:

Physical media	**Regrouped**
tactile	tactile (texture, density, weight, surface, volume, temperature)
visual	visual (texture, surface, volume, color)
aural	aural (sound)
olfactory	olfactory (odor)
spatial	spatial
ambiguous	ambiguous
persistent	persistent
textured	
dense	
have weight	
have surface	
have volume	
have temperature	
have color	
make sound	
have odor	

This reorganization could have taken another approach, grouping the senses within the material properties such as “surface (tactile and visual)” or “color (visual).” However, these properties do not stand alone as clearly as the senses do. In other words, in the physical world touch can exist without vision, but a surface cannot exist without volume, and a color cannot exist without a surface? However, I kept "spatial" as a separate quality even though it could be considered part of "tactile" and "visual," because it is such a significant advantage of physical media over the digital.

4.1.2 Digital Media

Although I use the term *digital media*, which is a broad term, I am using it here in the context of architecture, so I am really thinking about current CAD systems instead of all things that could be considered digital media. A casual gathering of digital media qualities from some articulate proponents rendered this first list, which I then regrouped into the second list:

Digital media	**Regrouped**
(Sutherland)	
structured	intelligent (structured, procedural, multimedia)
precise	precise
scalable	transformable (scalable)
(Mitchell)	
copyable	copyable (nondegradable)
reworkable	reworkable, undoable (nondegradable)
undoable	
(Negroponte)	
compressible	portable (compressible)
nondegradable	
multimedia	
(Holtzman)	
real-time	fast, *real-time (moved to physical media)*
ephemeral	ephemeral
(Murray)	
procedural	
(others that I added)	
fast	
portable	
transformable	
visual	visual
aural	aural

Sorting out the redundancies from the first list of digital media qualities was more difficult than sorting the list of physical media qualities. The complexity of the technology, its rate of evolution, and the need for an interface all make it more difficult to catagorize. Below I explain some of my thinking.

Intelligent (structured, procedural, multimedia)

Of interest to architects is the ability to create three-dimensional drawings or digital models and then transform them in various ways. These models are dependent upon computers having the capacity to store numbers and perform procedures on those numbers. Sutherland [2] called drawings derived from data "structured." Murray [3] describes computer environments as inherently "procedural," meaning the computers can execute a series of rules, as when a digital model is scaled or otherwise transformed. Negroponte [4] defines *multimedia* a "commingling of bits," or different media—print, photography, video, animation—sharing a similar storage format. I struggled to find a term that encompasses these capabilities, which all have to do with the common issue of data storage and processing. "Intelligent" may seem to overstate what these capabilities encompass, but no other term is as accurate.

Transformable (scalable)

The term *scalable* does not encompass all the transformations possible with digital representations, which could include such operations as curving straight lines or extruding a two-dimensional shape to three-dimensions. So, I thought of "scalable" as one aspect of "transformable."

Copyable (nondegradable) and Reworkable (undoable, nondegradable)

Copy and Undo are advantageous functions of digital media compared to physical media. The ability to make perfect copies of digital files and the ability to undo a procedure on a file is achieved by the system progressively saving a copy of the previous version. The nondegradable quality of bits when they are copied makes these capabilities possible. Therefore, I considered "nondegradable" as an aspect of both "copyable" and "reworkable." I considered "undoable" as an aspect of "reworkable" because the infinite reworkability of the digital medium is achieved, not just by the Undo function in software, but by the metaphorical undo capability at any level of a digital process by retrieving previously saved files.

Portable (compressible)

Portable can be taken in a relative sense to describe current hardware, which is much smaller and thus more portable than previous generations of hardware. It can also refer to the data—bits—which are inherently small and are compressible by removing redundancies. So, I considered "compressible" as an aspect of "portable."

Fast and Real-time

Computers are faster than humans at numerical calculation. Computers are also faster at reshaping and rescaling digital models than humans are at reshaping and rescaling physical drawings or models. However, using a computer requires a great deal of waiting time to start up, open and process files, connect to networks, print, digitize, and so forth, making computers perceptually slower than physical media in many cases. When computers are described as "real-time," they are behaving at the speed of the real, physical world (which means they are actually processing data very fast). Physical media is inherently real-time, while digital media is perceptually real-time sometimes. They also sometimes seem faster than real-time, and at other times, slower than real-time. Thus, I placed "real-time" on the list of physical media qualities.

4.1.3 Comparisons

PHYSICAL MEDIA	DIGITAL MEDIA
tactile	nontactile
visual	2-D visual
aural	recorded, synthesized aural
olfactory	nonolfactory
spatial	representative of space
ambiguous	explicit
physically transformable	logically transformable
persistent	ephemeral
real-time	faster than real-time
not intelligent	intelligent
inexact	precise
moderately copyable	infinitely copyable
moderately reworkable	infinitely reworkable
physically portable	electronically transferable

Next, I attempted to correlate the lists of physical and digital qualities (shown above). Some qualities on the lists were the same. For example, both lists had "visual" and "aural." Three qualities of digital media were also true enough of physical media to be added to that list: copyable, reworkable, and portable. I added more-descriptive words to distinguish between, for example, the physical "moderately reworkable" and the digital "infinitely reworkable." Some qualities on the lists corresponded well, not necessarily as opposites but as related, such as “real-time” and “fast.” Some had no correspondence, resulting in my adding new, negative qualities to each list to complete the correlation. For example, digital media is simply “nonolfactory” compared to physical media.

Because I was interested in determining the desirable qualities of each realm, having negative qualities served no purpose, so I eliminated them (shown below).

PHYSICAL MEDIA	DIGITAL MEDIA
tactile	
visual	2-D visual
aural	recorded, synthesized aural
olfactory	
spatial	representative of space
ambiguous	explicit
physically transformable	logically transformable
persistent	ephemeral
real-time	faster than real-time
	intelligent
	precise
moderately copyable	infinitely copyable
moderately reworkable	infinitely reworkable
physically portable	electronically transferable

I then created a table (Table 1) with one column of all the qualities, and two columns where I could rate each quality within the physical and digital realms as present (+) or not present (–). Because qualities can be present but in a lesser form, I also used an in-between rating (0).

Qualities	Physical	Digital
tactile	+	-
olfactory	+	-
spatial	+	-
ambiguous	+	-
persistent	+	-
real-time	+	0
physically transformable	+	-
logically transformable	-	+
ephemeral	-	+
explicit	0	+
representative of space	0	+
fast	0	+
intelligent	-	+
precise	0	+
visual	+	+
aural	+	+
reworkable	0	+
copyable	0	+
portable	0	+
(totals balance out)	6	6

Table 1: Qualities of physical and digital media, each rated as present (+), not present (-), or in between (0).

4.2 The Qualities Discussed

4.2.1 Tactile

Place a ball of clay in front of just about anyone, young or old, and they will soon begin to knead it. It is irresistible, as are many physical media. Clay, wood, paper, stone, paint—all are appealing, intriguing, and satisfying to touch. We get pleasure from touching things. Touch is the oldest sense and the most important one psychologically. As stated earlier, it is so crucial that if we didn't enjoy touching and being touched, we would probably never reproduce, and our species would die out. We have touch receptors all over our body, although in some parts they are more dense. Hands and fingertips, in particular, have some of the most sensitivity [5].

Manipulating a physical medium by hand enables us to determine its malleability, weight, temperature, and tolerances for stability. With practice, we can develop motor skills specific to that medium, which enables us to become more facile with it. The more facile we become with a medium, the more effortlessly we can work. Touch provides information to the brain so that we are able to manipulate objects in three-dimensional space [6]. The hand works in two ways: It can manipulate, and it can receive feedback. This two-way channel has direct bearing on our ability to develop motor control [7]. Adding vision and hearing to touch makes us efficient at understanding and manipulating objects in space.

Tactile input is said to be ten times more influential than verbal input is to the brain [8]. We can also feel things that we cannot see; a tiny sliver can often be felt with a fingertip even if it cannot be seen with the naked eye. Designers use the sensitivity of touch unconsciously. They often begin a drawing by quickly running their hands over the surface, smoothing but also determining the “tooth” and hardness or softness of the paper. Designers also use the sense of touch to manipulate and orient tools and materials, to better understand by tracing with their fingers, and to gesture at drawings and models or in space.

The digital medium has no inherent tactile qualities beyond what the interface provides. Most architects use CAD with a standard GUI with a keyboard and mouse. Adding virtual tactile properties to GUIs has proved to be complex and expensive. The hardware necessary to synthesize tactile feedback often utilizes tiny sensors and mechanical parts. So far, these prototype systems lack verisimilitude, feeling mechanical because they have limited feedback compared to real, physical feedback [9]. Although satisfactory solutions may eventually be developed, virtual tactility may be desirable only when size, as in computer-assisted surgery, or distance, as in space exploration, require it.

Efficiency for understanding and manipulating forms in three-dimensional space is diminished without the tactile component in a CAD environment. This can add cognitive overload, as the user attempts to process objects in space through a single sense-channel, the visual. Also lost is a sense of weight, material, and surface texture, although these may not be important to a digital model where the form itself is primary and the material or texture can be unspecified. But also missing is the pleasure that is normally derived from touching physical materials and textures.

Physical tools and materials enable two-handed interaction, compared with a GUI where much of the activity of drawing is strictly one-handed (and one task at a time). With the GUI, even though one hand is needed to activate function keys while the other is using the mouse, the kind of interaction where both hands perform continuous tasks in concert does not exist. Two hands working together can perform the same activity simultaneously, such as mold clay. Two hands can also work asynchronously, such as one holding a ruler and the other marking with a pencil. Buxton asserts that "GUIs can be greatly improved through incorporation of this class of input." [10]

4.2.2 Visual

Vision has been called the most important sense for modern humans, because vision is the sense most related to alphabetic culture and abstract thinking [11]. Print media has dominated Western culture for centuries. Developing and communicating ideas, particularly in science, requires text explanations supported by visualizations such as diagrams, charts, and graphs.

Vision can also illicit visceral responses. Certain kinds of visual stimulus related to color, symmetry, and light produce universally pleasurable responses in humans [12]. These responses are the basis for the visual appeal of natural landscapes, animals, and other humans. Physical media are visually appealing on many levels, not only because of color and texture but also because of other qualities such as transparency, opacity, and the ability of many materials to capture and transform light.

Vision also provides information that is basic to everyday functioning. Alone or in combination with hearing, vision allows us to detect things at a distance. Vision, touch, and hearing work hand in hand to enable us to excel at understanding and manipulating objects in three-dimensional space. Focus and peripheral vision are qualities of vision that are useful in survival but are also of value to the creative process of design. Seeing a proposed design with peripheral vision or out of focus reveals the basic form more acutely. Although these qualities of vision may be used with computer displays, they are more flexible and powerful in three-dimensional space.

Visual representation is where the digital medium excels for designers. McCullough confirms that: "…the computer has become a visual medium." [13] Interactive graphic simulations, digital movies, hyper-real renderings, and heads-up displays are a few of the extra-visual capabilities of computers. CAD environments provide simultaneous multiple views, wire-frame or rendered views, panning, and zooming. The discipline of information display has experienced enormous advancements with the high-resolution, dynamic, interactive graphic capability of digital media. However, even though computation affords these tremendous extra advantages in representation, they don't replace the sensitivity of human vision in a three-dimensional space.

4.2.3 Aural

Sounds can be pleasurable—the squish of wet clay being shaped on a potter's wheel—or painful—a table saw cutting through a chunk of wood—although both can be satisfying. This is because sound, like other sensory input, provides us with both information and pleasure. Music gives us pleasure. as do a number of natural sounds, such as bird songs, cricket chirps, and falling rain. Working with a physical medium may provide a more subtle aural pleasure. The scratching of a pencil or pen on paper, the rustling of paper, and an X-Acto blade cutting cardboard all reinforce the quiet rhythm and flow of work.

Like the tactile sense, sounds also provide clues as to the nature of tools and materials. If you heard absolutely nothing as you were cutting wood with an electric saw, you would have much less of a sense of whether the saw was straining and you were in for a potentially dangerous snag. The sound that a material makes can sometimes reveal its nature better than seeing or touching it can. A hard, clear material may look and feel like glass, but the sound made by tapping on it will reveal that it is plastic. Hearing is also spatial. Sound resonates off of walls and objects, revealing or reinforcing spatial arrangements. In combination with our tactile and visual sense, hearing assists in efficient understanding and manipulation of objects in three-dimensional space.

Virtual sounds may not be appropriate in a CAD environment, beyond interface cues such as beeps to inform that a requested procedure is complete. The rhythm of work is appropriately accompanied by the clicking of mouse and keyboard. What is the sound of mathematically defined forms in a void, anyway? Material-related sounds, such as those used in children's paint software or the spatial audio currently used in virtual reality systems, are difficult to achieve without seeming comical or annoying.

4.2.4 Olfactory

Smells are memorable. A smell can vividly bring back a past experience initiating an emotional response in us such as relaxation, excitement, or anxiety. For example, the aroma of freshly cut grass can give many adults a momentary carefree feeling of their childhood in a quiet suburb. Smells play an important role in our attraction to each other, making them significant to species survival. Women's hormonal cycles can change by olfactory stimulation. Most parents can recognize their own children just by smell. Smells can even stimulate learning and retention. It was found that children who were given olfactory stimulation along with a list of words were better at recalling the list than when given the list without olfactory clues [14].

Although smell has little or no direct bearing on the efficiency with which we physically manipulate objects, as does touch, vision, and hearing, smell plays an emotional role in the use of physical media. Physical materials have distinct smells, ranging from appealing (natural clay, wood, linseed oil) to toxic (some metals and plastics). An appealing smell likely increases the appeal of a medium. A smell may create a mood in the designer that promotes creativity. Isen [15] has found that even a small increase in the feeling of happiness can increase creativity.

The digital medium has no smell, which could be perceived as either positive (safe and nontoxic) or negative (sterile). Having no smell may diminish our emotional response to it.

4.2.5 Spatial and Representative of Space

The *somatosensory* system makes up most of our experience of three-dimensional physical space [16]. Touch is the most familiar of the somatic senses, which also include *proprioception,* the sense of the position of the limbs, and *kinesthesis,* the sense of the movement of the limbs. Our sense of space is supplemented by vision, hearing, and our sense of balance centered in the inner ear. It is a misconception that a two-dimensional visual representation of a three-dimensional space can be as easily comprehended, navigated, and remembered without the benefit of proprioception and kinesthesis.

There is a great efficiency in representing physical structures with physical media. Such models differ only in scale or material from the final outcome of a design. Physical models offer the user an intuitive understanding of complex geometries and physical relationships that are difficult or impossible to describe in any other way. After observing engineering students solving a design problem, Brereton and McGarry [17] concluded that design thinking is heavily dependent upon references to physical objects and that designers seek out physical props to help them think through design problems and communicate design ideas.

There is even much value in working with physical two-dimensional representations, such as drawings in a three-dimensional space. Easy rearrangements such as juxtaposition, sequencing, and overlapping support exploration necessary to the creative process. Trace paper, for example, allows progressive sketching upon a base drawing without disturbing the integrity of the base drawing. Trace layers can be stacked, reordered, or reoriented to new positions. Viewing from varied distances by pinning up on a wall provides a new perspective on a drawing or permits easy comparisons among a group of drawings.

Physical materials in three-dimensional space support communication by enabling pointing and gesturing in three-dimensional space. Harrison and Minneman [18] studied designers at work and report that objects are an integral part of design communications and form a body of representations that are drawn upon by other designers. In a three-dimensional space, designers can gather around drawings and models and feel an engagement with the other designers and the materials themselves. That same level of engagement does not occur when a group gathers around a computer screen because of the size and because all are focusing forward toward the screen.

The two-dimensional environment of a standard computer screen never feels large enough. Juggling multiple windows to juxtapose, sequence, pan, zoom, and shrink can be tedious. Cognitive overload can occur as the user mentally translates two-dimensional representations into three-dimensional forms.

However, there are advantages to these two-dimensional representations of space. They can contain a multitude of information linked to the representation, such as measurements and material specifications. They can be see-through to reveal internal structures by use of a wire-frame or they can specify a view at a particular slice of a digital model. They can be dynamic, running what-if scenarios that would be too costly to construct with real materials, such as trying out particular layouts, lighting, colors, and so forth. Virtual walk-throughs can be made from digital models to provide a limited sense of space and pathways. Although these simulations do not replace the use of physical mock-ups, they can be helpful in providing more varied representations as aids for solving a complex design problem. Clients and other consultants also can benefit by supplemental visualizations of proposed designs.

4.2.6 Ambiguous and Explicit

Ambiguity is nourishment for creativity. Minsky [19] defines creativity as a process of "re-representation." Ambiguous representations enable re-representations. Take the example of sketching with pencil on paper. In a sketch, a line that is drawn as the edge of a wall can be reinterpreted to be a column or wire. The designer or other designers opportunistically discover new ideas based on misinterpretations or reinterpretations of the sketch. In observations of designers sketching, Schon [20] found a process of negotiation between designer and sketch. The designer draws, then interprets his or her own sketch, then continues or redraws the sketch in a process that yields a progressively more refined design. In empirical studies of designers, Goel [21] and Bilda [22] found that sketching facilitates design idea generation while CAD does not. Goel's evidence suggests that sketching supports design thinking because it is a "dense and ambiguous symbol system."

The fluid process of sketching and the ambiguity of the sketched representation have analogies to physical prototyping. Physical "sketch models" can be interpreted in multiple ways; they too are ambiguous and, like sketches, facilitate re-representation.

Physical materials such as pencil on paper and clay, lend themselves to sketching. They record gestures easily whether they begin as blobs or blocks in a subtractive process (e.g., carving) or as strokes in an additive one (e.g., drawing). When a designer wants to transform a raw material into an explicit representation, it can be challenging. Compare the difference in effort between making a rough sketch with pencil on paper and making a realistic-looking rendering.

Explicit means “leaving no doubt as to the intended meaning.” It is possible to be explicit with a physical medium, but it requires skill and effort. The tools and techniques that are available, in combination with the material itself, influence the effort required. However, the skill of the designer may have the most influence here. A gesture can be ambiguous, but it can also be an explicit expression of an emotion, which brings to light an important point. An explicit representation can convey a specific emotion or it can convey an exact form. Physical media are good at recording gestures (expressing emotion) and somewhat good at mechanical, emotionless representations (conveying information).

CAD behaves in an opposite way to most physical media. It is not easy to record gestures with CAD, but it is easy to create mechanical, emotionless representations. Into a void, the designer enters forms by specifying their exact measurements. Even if the intent of the designer is to gesture an approximate form, the computer responds in a similar way, mechanically recording vertices. Free-form, curvy shapes simply require more vertices. Capturing other aspects of gesture, such as speed and pressure, is not possible at this time with standard systems.

4.2.7 Precise

Precision is required in any design process. Once a concept and preliminary design are set, based on rough measurements and analysis, the need for precision increases as the design process progresses, culminating in the construction drawings. The smaller the project, the more a contractor or fabricator could be depended on to compensate for vague specifications as part of the building process. Large, more complex projects have many more variables and details that must be specified, and building costs must be accurately estimated in advance to avoid expensive overruns.

Tools and materials determine how easy or difficult it is to achieve accuracy. For instance, if you needed to draw a plan of a building to scale, you would probably use a sharp pencil on smooth paper with a professional scale, as opposed to charcoal on rough paper with a child’s ruler. In other words, the granularity or fineness of materials, combined with the accuracy of measuring tools, affects the precision with which a drawing or model can be made.

Computers excel at precision. Bits have no granularity. Their precision is limited only by processing power and memory, which already far exceeds the precision that can be achieved with physical media. All forms are mathematically defined. The numbers produce the drawing. As a result, CAD has made construction drawings more accurate, which has made the construction process more manageable. Architecture plans act like a contract between the client and the builder. The more precise and explicit they are, the more accurate are the expectations of costs and the fulfillment of the final product.

Computers have also increased the analysis capabilities of designers. Architects have always needed to address impacts to their proposed projects, such as how wind might affect a tall building or if drainage patterns on a property will create erosion over time. Before computers, this task was done intuitively in combination with calculations by hand. Computer analysis programs can take into account many more variables in a much shorter time than a human can. Effects that can be easily quantified and require many calculations are well suited to computer analysis. However, the analysis is only as good as the algorithms in the software or the interpretation of the results.

4.2.8 Persistent and Ephemeral

Something that exists for a long time is persistent. Most physical media—stone, wood, paper, and so on—are persistent by our perception of time. The Great Sphinx at Giza in Egypt was carved from a solid outcropping of rock some 3,500 years ago. When it was excavated by archaeologists in the late 1800s, from the sand that buried most of its body, it was still recognizable as a sphinx, even after all that time and after having sustained cannon fire from various armies in recent history. A more malleable medium like paper doesn’t last that long; four or five hundred years will reduce most to crumbles.

Unlike a drawing on paper, media such as dance or music is described as time-based, meaning it must be experienced over a length of time. They are dynamic rather than static like a drawing. Electricity introduces a new twist on time-based. An electronic medium is only active while it is plugged in to a power source, which is why it is described as transitory or ephemeral. Video must have electricity to “play,” or to be worked (recorded and edited). Computers present another variation on ephemeral that is more akin to “alive” than the “playing” of a videotape. Electricity gives life to a computer allowing it to respond to input, or at least that is our experience of interactivity.

Digital media are not purely ephemeral. A soap bubble is ephemeral. Digital data that defines an image or a three-dimensional model is stored on a disk, even when the power is off. The visual representation is ephemeral but the data stays put, even if we can’t sense it. Little doses of persistence have value in the digital realm. The state of your computer desktop luckily remains the same from your last session and doesn’t revert back to some default state. Web pages are relatively persistent: servers are kept on all the time but pages are often updated.

Although persistence has its advantages—not tethered to a power source, stable, and bonded to sensory qualities—ephemeral media can be dynamic and alive-seeming.

4.2.9 Physically and Logically Transformable

What makes the digital medium such a powerful aid to design is the combination of being ephemeral *and* able to store models as data and run procedures on those models. Digital models are logically transformable by running mathematical procedures on the data that define the model. Transformations can include scaling, skewing, distorting, extruding, adding curvature, giving perspective, and so on.

Physical media can be physically transformed, by hand or with tools. One must contend with the properties of the raw material. Clay can be molded into freeform shapes, but it will not stand up if molded too thin. Wood is much harder to shape and has a grain. It requires much more effort to shape than pliable clay, but it has more strength and can hold its shape even if cut thin.

4.2.10 Fast and Real-time

Speed can be measured only in comparison to something—fast compared to what? Computers are defined as fast machines because they can perform certain types of procedures faster than humans. But on a practical level for a designer, this translates to advantages as well as disadvantages. To do some rough sketching, nothing exceeds the speed of pencil on paper. Consider the time it takes to start up a computer, start up the software, open a new document, name it, and save it compared with the time it takes to open a sketchbook and lift a pencil. If the end result must be hard copy, factor in the time to print a computer file.

To do a measured drawing, a CAD environment is likely to be more efficient. With a large set of construction documents, there will inevitably be numerous changes to them over the course of design finalization, approvals, and construction. Although the initial drawing set could take roughly the same amount of time whether done by hand or by CAD, changes done in a CAD environment are much faster. One correction to the digital model makes the correction on all subsequently printed drawings. By hand, this could involve correcting many individual drawings.

While a design is being worked on in the early phases by hand, performing rough assessments by eye, such as shade effects of a tall building, can happen seamlessly in a few minutes. Here, a human with a sketch can work quickly. When more detailed and accurate analyses are required, such as studies showing sun/shadow progression through the day or seasons, and the designer must do some numerical calculations, the process takes more time. When complex analysis is required on a project, it is more efficient to use analysis software, because computers can accomplish a large number of calculations faster than a human can. However, to do the analysis, the computer must have a digital model to work with.

Much of the slowness of using digital media is related to the input and output of data from analog to digital and back to analog. These tedious transfer steps are labor-intensive and prone to frustrating hardware and software complications.

When software is attempting to simulate a real event, like walking through a virtual building (using VR or GUI), it is described as real-time if system has no delays in its response time. The real world is always real-time, while computer systems achieve it some of the time.

4.2.11 Intelligent

Sutherland may have misrepresented physical drawing by calling it "just dirty marks on paper," but he was right about the value of CAD when he suggested that "CAD is useful because the model can be used for more than just producing a picture." [23] CAD drawings are structured; they contain information beyond just the pictures that can be derived from them. A CAD model is a database. Mathematical procedures can transform the digital model in scale, shape, and orientation. Much information can be derived from the database, including materials lists, floor-area calculations, and numerous analysis results such as energy use and structural viability.

A digital model can be used as a database that is fed to analysis and simulation software to get results of such assessments as heating and cooling efficiency or room acoustics. Knowledge-base applications go a step further in attempting to perform evaluations on digital models for such things as code adherence, facilities planning requirements, and even style consistency. So far, the robustness of these types of applications has not been high.

4.2.12 Reworkable

Physical media have different tolerances for reworking. Watercolor, for example, has low tolerance for reworking. Once paint is placed on paper, it cannot be removed completely. Any attempts at reworking a painted area can result in muddied colors and irreparable damage to the paper. You can't put pieces of wood or stone back together after they are cut, without the consequences of gluing or joints. Plasticine, which never dries out, can be reworked repeatedly. However, it will pick up debris and dirt from the work environment and look discolored.

Time-based media, such as music, dance and theater, is infinitely reworkable with no permanent consequences to the sound waves or the piece itself. The digital medium is also infinitely reworkable, subject only to the limitations of a software package or degradation by hardware glitches. Negroponte [24] describes bits as "nondegradable" which allows them to be copied infinitely with out any loss of quality. "Undo," a powerful capability of the digital medium, is enabled by this quality of bits.

4.2.13 Copyable

A work created by hand with a medium such as paint or pencil is one of a kind. Reproduction methods such as photography or photocopying produce a copy in a different medium. Copying in the original medium, by hand, can never produce an exact copy, although it may be difficult to distinguish the two. Goodman makes the distinction between autographic, a piece that is one of a kind, and allographic, a piece that can be performed or reproduced many times. He defines a work as autographic, "if and only if the distinction between the original and forgery of it is significant; or better, if and only if even the most exact duplication of it does not thereby count as genuine." [25]

Goodman asserts that perhaps initially all arts are autographic. "Where works are transitory, like music, or require the work of more than one person, like architecture, a notation may be devised in order to transcend the limitations of time and the individual." [26] The digital media may change this assertion. A digital file can be copied infinitely with no degradation to the original or the copy. Is a digital file ever autographic? It may be considered so if printed only once in a physical form, and if the only copy of the digital file is subsequently destroyed.

In the same way that bits can be reworked with no degradation, they can be copied exactly, in part or in whole, with no degradation to the bits, and the copy is indistinguishable from the original.

In the analog world of tape recording, a copy is always inferior to the original. With a video recording, for example, the copy is a *generation* away from the original. Each generation results in a loss of quality. In the case of one-of-a-kind, handmade work, a copy must be made by hand. Copies require as much, or more, work as the original and depend to a great extent on the skill of the copier. It is not humanly possible to make a handmade copy *exactly* like the original.

4.2.14 Portable

The raw material of the digital medium—data—is tiny and weightless. It can be sent electronically or carried on lightweight, hand-size disks. Data processors and associated hardware continue to shrink. A laptop is more portable than a physical desk with its associated tools, and the laptop offers a comparable drafting capability. The current generation of tablet computers attempt to be even more lightweight. A workstation or desktop PC compares quite equally to the physical desk, both being nonportable. Digital portability excels when a large set of construction documents can be saved on a few Zip disks or e-mailed in minutes around the globe.

Physical tools and materials have mass and weight, which renders many of them not very portable. But there are those few items, like a small sketchbook, with which the computer cannot yet compete. They are not only small but convenient and appropriate to the serendipitous act of sketching.

4.3 Summary

Qualities of a medium are defined by our experience of that medium and by how we might apply it to a task at hand. Physical media possess sensory richness in comparison to digital media, which excels at fluidly transformable, ephemeral representations.