1 Introduction

1.1 Background/historical

1.1.1 Pervasive architecture and functional patterns found in nature

The Greek terms *dendri-, dendrites, dendritic* are root word descriptors for *branching or treelike structures*. These terms describe some of the most pervasive architectural patterns observed on our planet [1]. Before the early 1980s [2–4] all dendritic architectures and networks were known only as naturally occurring structures/entities found either in the abiotic world (e.g. snow crystals, lightning patterns, erosion/tributary river network fractals) or in the biological realm. In biological systems, these dendritic patterns are found at length scales ranging from *meters* (trees), *millimeters/centimeters* (vascular/circulatory systems in plants and animals, Golgi domains (*organelles*), fungi), *microns* (neurons) to *nanometers* (IgM antibodies, amylopectins and proteoglycans) as illustrated in Figure 1.1. Certain randomly branched, dendritic architectures were hypothesized by Nobel Laureate P. Flory as early as the 1940s to describe theoretical polymer intermediates in crosslinking events [5]. However, it was not until the late 1970s that the first examples of such dendritic architecture were intentionally synthesized and rigorously characterized in a laboratory. These first dendritic structures were synthesized both as core-shell-type, small molecules, and macromolecules. The widely recognized terms – *dendrimers/dendrons* (i.e. *dendri* [branched] and *mer* [part of] – were first coined and introduced by Tomalia in 1983 [6] to describe these compositionally broad and diverse categories of precisely defined core-shell, dendritic structures. A typical dendrimer family derived from a core and surrounded by radial shells (i.e. generations) of covalently connected branched monomers is illustrated in Figure 1.1.

It was soon realized that these newly discovered dendritic structures could be synthesized with a very wide range of diverse elemental compositions (i.e. both organic and inorganic). Furthermore, it was found that they could be obtained with unprecedented mono-dispersity and extraordinary structure control as a function of (a) size, (b) shape, (c) surface chemistry, (d) flexibility/rigidity, (e) architecture, and (f) composition. Unlike traditional synthetic polymers, these synthetic macromolecules were routinely synthesized with structure control normally associated only with highly precise biological polymers such as proteins, DNA, and RNA.

Cambridge University Press & Assessment
978-0-521-51580-1 — Dendrimers, Dendrons, and Dendritic Polymers
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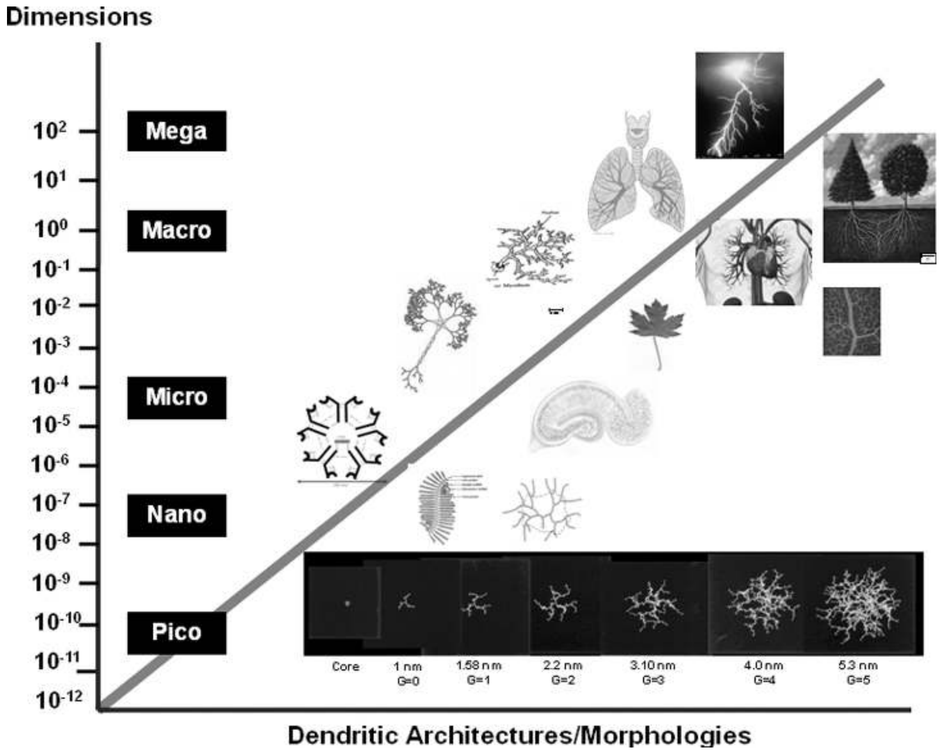

Figure 1.1 Various naturally occurring biological dendritic architectures as a function of dimensions compared to first known synthetic dendritic structures; dendrimers.

1.1.2 Importance of architecture at the molecular and macromolecular level

Historically, the subtle yet profound effects of architectural influence on the physico-chemical properties of small molecules have been widely recognized. The seminal work of the nineteenth-century Swedish chemist J. Berzelius [7] clearly demonstrated that minor structural rearrangements of common atoms (i.e. syn/anti-isomers, positional/valence isomerism), let alone major structural rearrangements of common atoms (i.e. linear, bridged, branched types), structural isomers should be expected to dramatically change the physico-chemical properties of compositionally identical, but architecturally differentiated, small molecule structures. Prior to 1978, only three traditional major small molecule architecture types were known, namely: (I) linear, (II) bridged, and (III) branched types. This list was increased to a fourth category by the discovery of type (IV) cascade/dendritic type structures in 1978 [8] as illustrated in Figure 1.2. These four major small molecule architectural types defined essentially all the common sub-nanoscale building blocks used by synthetic chemists during the nineteenth and twentieth centuries. This diversity of carbon-based architectural types was made possible by the three hybridization states of carbon as shown below. These carbon hybridization modes set the stage for the structural synthesis of higher complexity such as traditional polymers [9, 10]

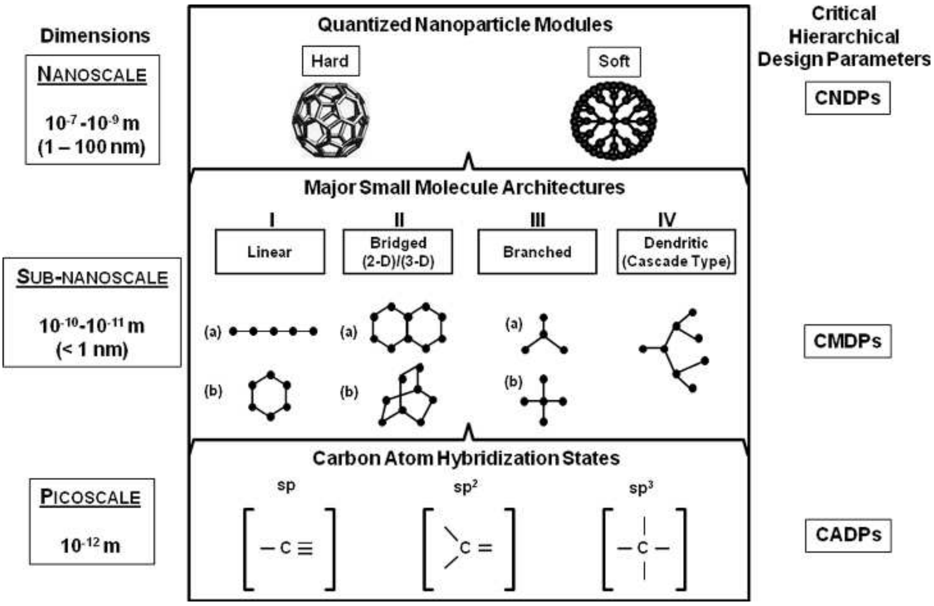

Figure 1.2 Three hybridization states of carbon leading to four major small molecule architectures that provide building blocks to well-defined nanostructures such as fullerenes and dendrimers.

and ultimately at least two important discrete nanoscale building block categories such as buckministerfullerenes and dendrimers shown in Figure 1.2.

The importance of these hard particle (i.e. fullerenes – hard nano-elements) and soft particle (i.e. dendrons/dendrimers – soft nano-elements) nano-building blocks has recently been described [11, 12] in a new periodic system (see Chapter 8). Just as elemental atoms provided the fundamental building blocks for traditional small molecule structures/architectures, so have the small molecule structures/architectural categories in Figure 1.2 functioned as assembly components for the construction of many well-defined, nanoscale building blocks/architectures such as buckminsterfullerenes and dendrimers.

Traditional polymer chemistry has evolved over the past 80 years based on the chemical catenation/bonding of small molecular modules or monomers. Staudinger first initiated macromolecular science in the 1920s [13] by demonstrating that reactive monomers could be used to produce statistical distributions of one-dimensional linear molecules involving as many as 10 000 or more covalent bonds to produce macromolecules possessing very high molecular weights (i.e. $>10^6$ Daltons) [13, 14]. Although traditional macromolecular structures possessing nanoscale dimensions may be readily attained, it is widely recognized that precise structural control of critical macromolecular design parameters such as size, molecular shape, spacial positioning of surface chemistry, and covalent connectivity is difficult. However, it is now recognized that the present four major macromolecular architecture categories (see Figure 1.3) do indeed parallel those of small molecules as described in

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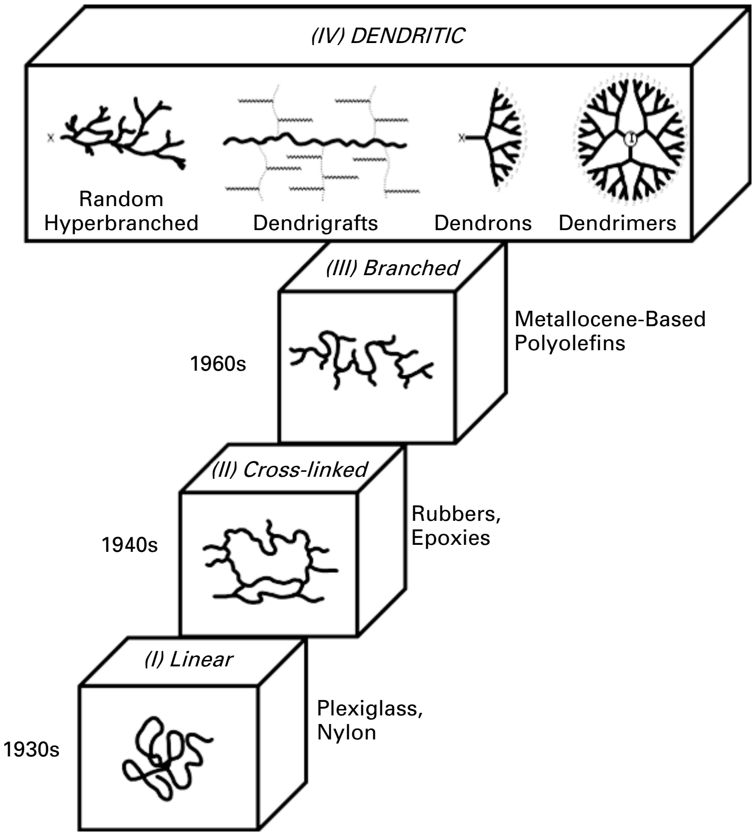


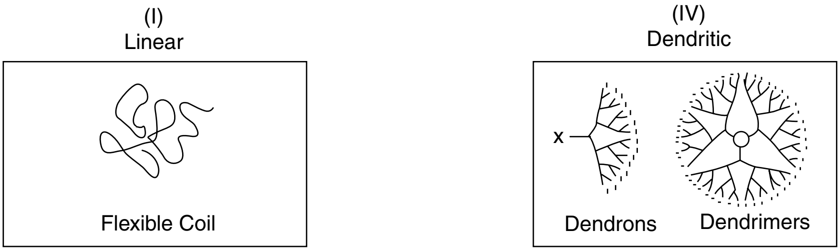
Figure 1.3 Three traditional major classes of macromolecular architecture chronologically leading to dendritic polymers and its four sub-classes: (a) random hyperbranched, (b) dendrigrafts, (c) dendrons, and (d) dendrimers.

Figure 1.2. Furthermore, the profound influence of architecture on small molecule properties is also well recognized for macromolecular systems.

Historically, each time a new macromolecular architecture is discovered, it is usually accompanied by the rapid development of new applications and products based on these new architecturally-driven properties. Such has been the case for the fourth new architectural class of dendritic polymers and will be the focus of later chapters in this book (see Chapter 7). For example, highly differentiated, architecturally-driven properties are apparent when comparing linear polymers to dendritic topologies as described in Figure 1.4. These issues are examined more extensively in Chapter 7.

1.1.3 Quantized building blocks – key to higher complexity

The importance of quantized building blocks as a key to higher complexity is summed up in the following comment by Nobel Laureate R. Feynman:



Linear

1. Random coil configurations
2. Semicrystalline/crystalline materials
   -higher glass temperatures
3. Lower solubility
   -decreases as with Mwt.
4. Intrinsic viscosity follows logarithmic
   -increase with Mwt.
5. Entanglement directed rheological properties
   -shear sensitivity
6. Mobility by reptation
   -segmental and molecular mobility
7. Anisotropic electronic conductivity

Dendritic

1. Predictable shape changes as function of Mwt. and core ①
   -robust spheroids; breathing deformability
2. Non-crystalline, amorphous materials
   -lower glass temperatures
3. Increased solubility
   -increases with Mwt.
4. Exhibits viscosity maximum and minimum plateau with Mwt.
   -low viscosities
5. Newtonian-type rheolgy
   -no shear sensitivity, considerably lower viscosity
6. Mobility involving whole dendrimer as the kinetic flow unit
   -virtually no reptation
7. Isotropic electronic conductivity

Figure 1.4 A comparison of architecturally differentiated properties observed for traditional (I) linear polymers and (IV) dendritic polymers, respectively.

If all scientific knowledge were lost in a cataclysm, what single statement would preserve the most information for the next generation of creatures? How would we best pass on our understanding of the world? [*I might propose:*] *"All things are made of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another." In that one sentence, you will see there is an enormous amount of information about the world, if just a little imagination and thinking are applied.* (*Richard P. Feynman* [*B.Pullman, "The Atom in the History of Human Thought," Oxford University Press, New York (1998)*]).

Nature clearly describes an effective strategy to higher level biological complexity. This strategy involves an elegant continuum of well-defined building blocks. This continuum begins at the picoscale with elemental atoms, proceeding through small sub-nanoscale molecules to precise biological nanostructures and on to micron scale biological cells and finally to meter sized organisms as shown in Figure 1.5.

A well-defined continuum for describing a synthetic abiotic hierarchy is less apparent. However, one may be theoretically constructed by assembling a hypothetical dendritic hydrocarbon series beginning with a single tetravalent carbon atom as the origin. As such, the fundamental concept of dendritic growth and amplification may be captured in its most exquisite and rudimentary forms by utilizing tetrahedral valent carbon atoms as monomeric building blocks. Synthetically, such a sequence would be expected to produce well-defined and discrete higher

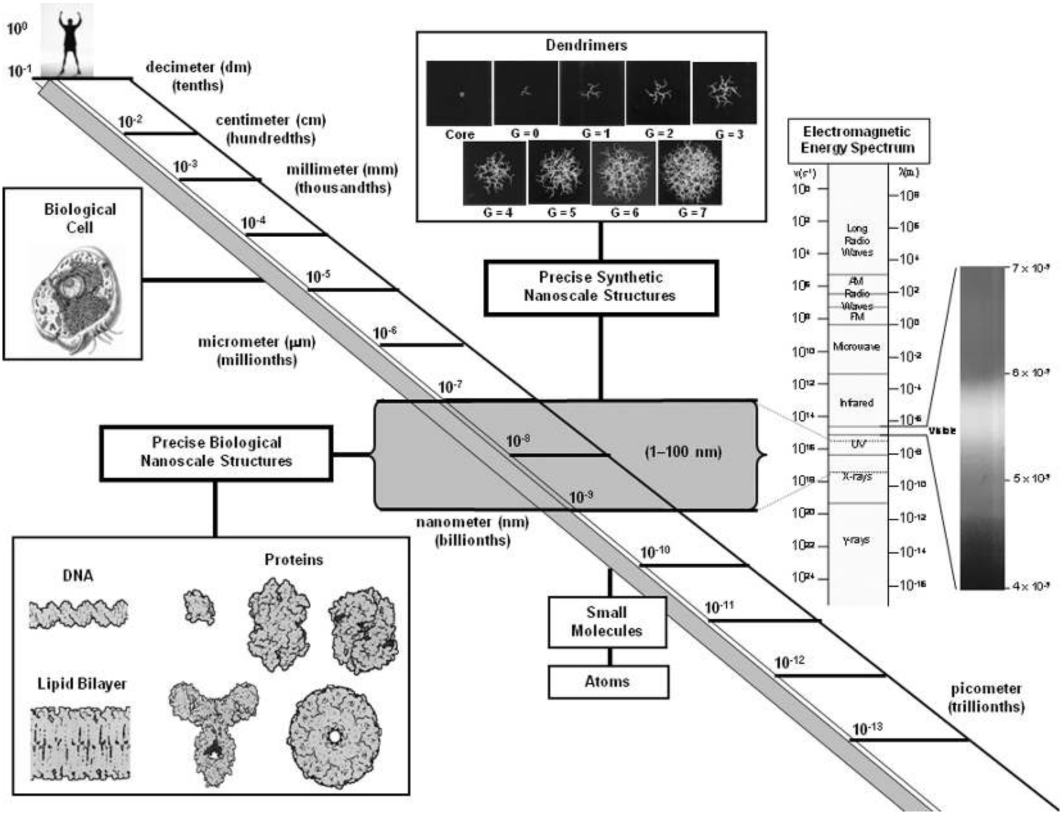


Figure 1.5 A continuum of natural and synthetic building blocks from atoms, (picoscale), small molecules, (sub-nanoscale), macromolecular, (nanoscale), biological cells (micron scale) to organisms (macroscale). Reprinted from reference [95]. Copyright (2005) with permission from Elsevier.

complexity, as shown in Figures 1.6 and 1.7. More specifically, using a single carbon atom core, one can build concentric shells (i.e. generations) of carbon atoms covalently tethered to the core by following the sequential dendritic amplification operations as described in (a-c): (a) begin with methane as core, (b) covalently attach methane moieties to each tetrahedral carbon bond site (i.e. each hydrogen site on the core). This produces the first member of a hydrocarbon dendrimer series that follows the empirical formula; C_nH_{2n+2}. This core-shell, hydrocarbon dendrimer structure consists of one core carbon atom, four shell carbon atoms and 12 terminal surface hydrogens, referred to as G = 1. Finally, (c) covalent attachment of 12 methane moieties via sp^3 hybridized carbon atoms to the G = 1 terminal hydrogen sites leads to a hydrocarbon dendrimer, $C_{17}H_{36}$, which is referred to as G = 2, shown in Figure 1.6 below.

Continued iterative growth of concentric shells around this well-defined collection of carbon atoms (i.e. G = 2) to produce higher shell levels according to their periodic carbon/hydrogen stoichiometry, space filling features, and dimensions is

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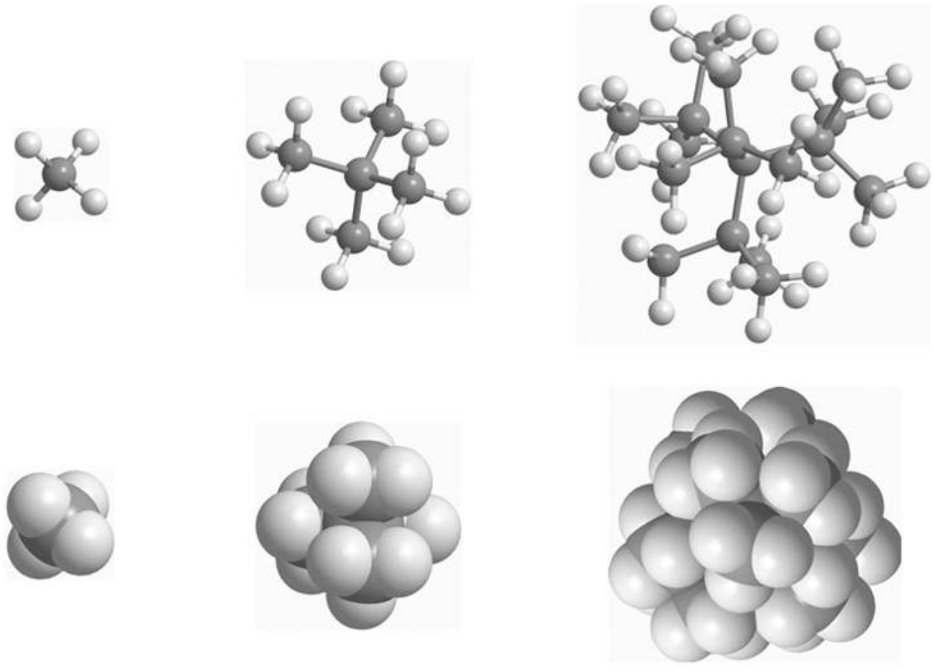

methane 2,2-dimethylpropane tetra-*t*-butylmethane ($C_{17}H_{36}$)

Figure 1.6 Dendritic growth and amplification to produce a core-shell dendrimer hydrocarbon series (i.e., [core: sp^3 carbon]; (G = 1–3); *dendri*-poly(methylene)-$(H)_z$ dendrimers using tetravalent methane as the building block monomer.

described in Table 1.1. This is a hypothetical hydrocarbon dendrimer series possessing tetravalent (sp^3) carbon atom core (i.e. core multiplicity of $N_c = 4$) and concentric shells consisting of (sp^3) carbon atom branch cells (i.e. branch cell multiplicities of $N_b = 3$), wherein the number of terminal hydrogen atoms (Z) at any generation level may be calculated (predicted) according to $Z = N_c N_b^G$. It is readily apparent that such controlled dendritic growth rapidly advances these structures from the small molecule level (i.e. < 1 nm) to the nanoscale level upon the completion of 4–5 shells (generations) by enhancing the spherical diameter of the structure to >1 nm. It is noteworthy that only the first two hydrocarbons in this series (i.e. the methane core) and 2,2-dimethyl propane; G = 1) have been successfully synthesized. The hydrocarbon; tetra-*t*-butylmethane or more accurately 3,3-di-*t*-butyl-2,2,4,4-tetramethylpentane; G = 2; $C_{17}H_{36}$) remains to be synthesized. If this structure or other higher generation structures are ever produced experimentally, they will constitute one of the most minimalistic examples of a dendrimer family. Structures in this dendrimer family would be expected to be severely strained and congested. This is clearly a consequence of the unique tethering of all four branched attachments to the core. Many of these and other interesting issues may be visualized by introspection of the hydrocarbon series in Table 1.1. For example, it is

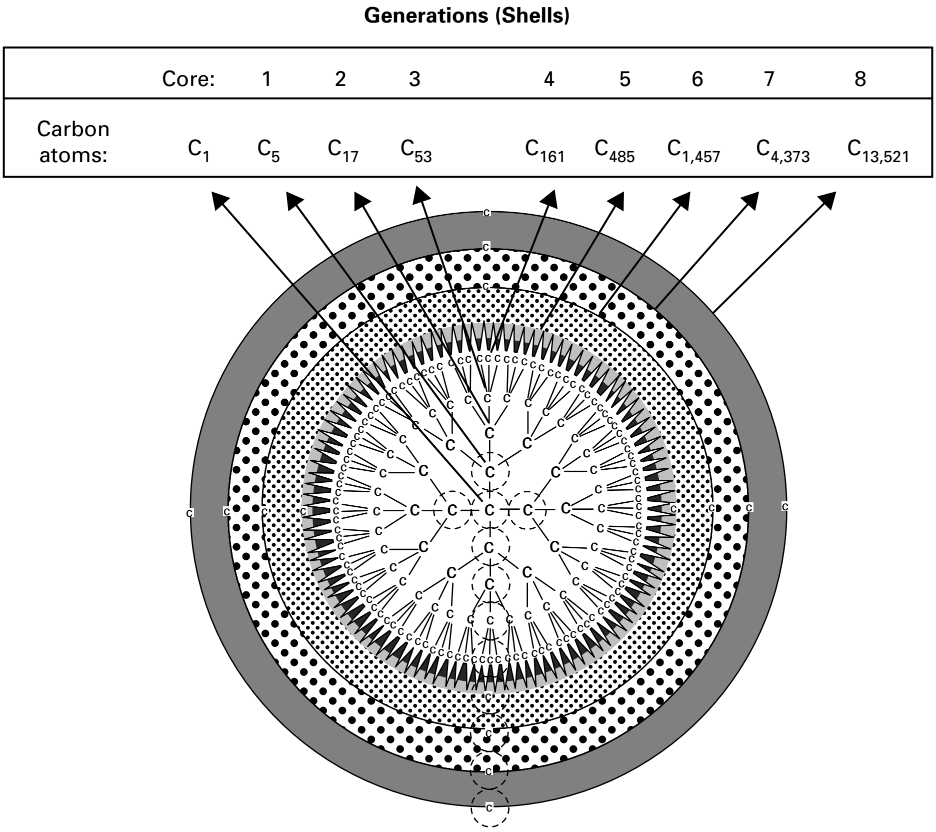

Figure 1.7 Two dimensional illustration of the core-shell structure of a [core: sp^3 carbon]; (G = 1–8); *dendri*-poly(methylene)-$(H)_z$ dendrimer series showing the amplification of carbon atoms at each generation level according to mathematically defined dendritic branching principles; $Z = N_c N_b^G$, where; Z = # of terminal hydrogens, N_c = core multiplicity, N_b = branch cell multiplicity and G = generation. Reprinted with permission from reference [15]. Copyright 1989 American Chemical Society.

well known that bottom-up assembly of 60 (sp^2)-hybridized carbon atoms produces the familiar hollow, conjugated spheroidal buckminsterfullerene architecture with nanoscale dimensions of ~ 0.9–1.0 nm. By comparison, the core-shell, dendritic assembly of 53 to 161 (sp^3)-hybridized carbon atoms produces a totally different tree-like architecture of C_nH_{2n+2} hydrocarbon dendrimers. It should be noted that G = 3–4 exhibits similar dimensions to buckminsterfullerenes with diameters of ~0.7–0.9 nm (Table 1.1). This comparison clearly demonstrates the profound role that architecture can play at the picoscale level by changing the shape of the carbon atom hybridization state. From this minimalistic model, one can clearly visualize a smooth continuum of core-shell, sp^3-hybridized all-carbon dendrimer structures with well-defined diameters that range from small molecule to nanoscale dimensions. Finally, tethered structural amplification clearly leads to congestion. This

Table 1.1 Mathematical values calculated for the dendritic growth and amplification of the [core: sp^3 carbon]; (4⟶3); *dendri*-{poly(methylene)-(H)$_z$}; (G = 1–8 dendrimer series) [15].

Generation	Formula	Outer edge of carbon shell radius units	Vol. of sphere of carbons units	Vol./ C atom units	Radius to surface of sphere at distance of H atoms units	Area of the H atom sphere units	Area/H atom units
Core	C_1H_4	0.5	0.524	0.524	1	12.57	3.14
1	C_5H_{12}	1.5	14.14	2.83	2	50.26	4.19
2	$C_{17}H_{36}$	2.5	65.45	3.85	3	113.1	3.14
3	$C_{53}H_{108}$	3.5	179.59	3.39	4	201.06	1.86
4	$C_{161}H_{324}$	4.5	381.7	2.37	5	314.16	0.970
5	$C_{485}H_{972}$	5.5	696.9	1.44	6	452.39	0.465
6	$C_{1457}H_{2916}$	6.5	1150.4	0.790	7	615.75	0.211
7	$C_{4373}H_{8748}$	7.5	1767.2	0.404	8	804.25	0.0919
8	$C_{13121}H_{26244}$	8.5	2572.4	0.196	9	1017.8	0.0388

is readily visualized from space filling 2-dimensional projections of the core-shell structures (Figure 1.7), as well as the calculated space and surface area available for the interior carbon and surface hydrogen atoms (Table 1.1) [15]. These issues are discussed in the context of de Gennes type dense packing and nanoscale-sterically induced stoichiometries (N-SIS) in later chapters.

1.2 Birth of a new macromolecular chemistry concept

1.2.1 Inspirations from nature, academia, and industry

To describe the many elaborate shape patterns observed for plant and animal growth, mathematicians have used dendritic branching rules to describe the evolutionary complexity of various emerging morphologies [16, 17]. Invoking simple mathematical rules related to branch angles, branch lengths, and branching multiplicity, it is possible to produce an evolutionary continuum of morphologies. With mathematically-driven iterative schemes, it is possible to simulate the same dendritic amplification and growth patterns manifested in the **[core: sp^3 carbon]; (4⟶3); *dendri*-{poly(methylene)-(H)$_z$};(G = 1–8)** dendrimer series described above (Figure 1.7). An enormous range of dendritic shapes is possible through the iteration and variation of only four critical parameters, namely: (a) core multiplicity, (b) branching multiplicity, (c) branching arm length, and (d) branching angle (see Figure 1.8). Many of these shapes and morphologies are strikingly familiar and similar to those found in Nature [17].

Many of these shapes and branching patterns have been firmly integrated into the life of one of the authors [16] through his lifelong passion for horticulture and tree farming. The many branch and root morphologies observed for various tree species prompted

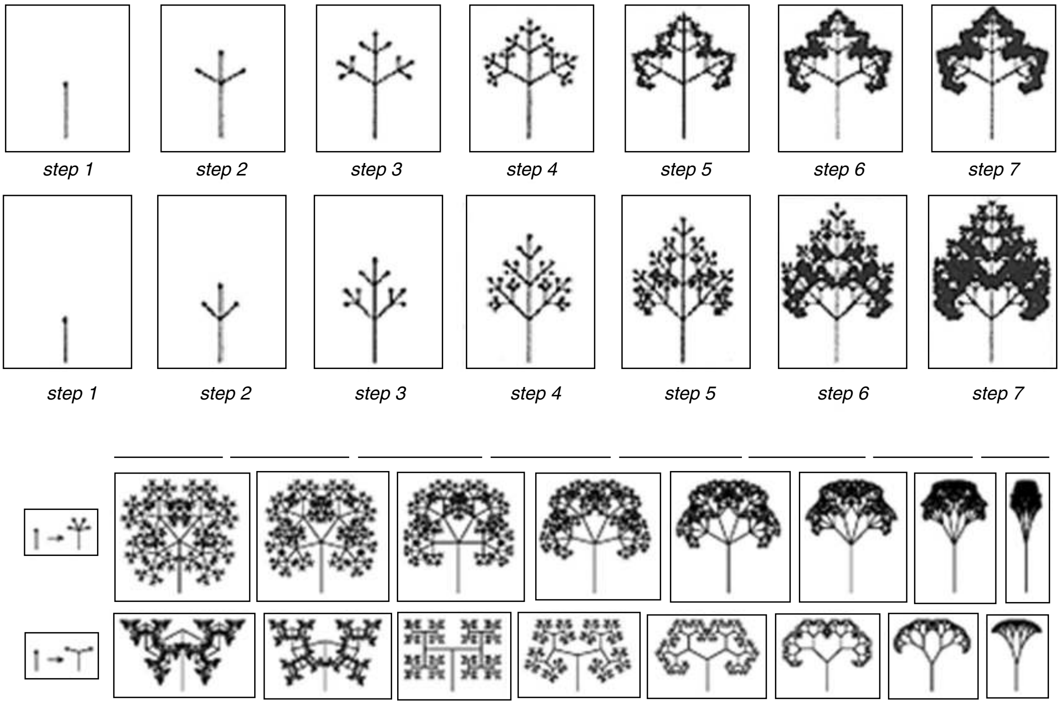

Figure 1.8 Mathematical iteration of several different branch cells possessing various branch lengths and branch angles through eight (iterations) generations of dendritic amplification (growth). With permission from Wolfram Research, Inc. [17].

the natural curiosity of a chemist. *Why did Nature choose this pervasive dendritic architectural scheme throughout the long and extensive evolutionary period leading to present tree morphologies?* To a curious scientist with a peripheral interest in Darwinian evolutionary principles, there appeared to be a strong message in these lifetime observations. It was compelling to ponder the possibly of mimicking tree growth at the molecular level. This was accomplished first by synthesizing simple sapling-type structures, followed by larger, precisely defined, tree-like structures via an iterative process involving covalent attachment of “branch upon branch” to some original core. This concept leading to such regularly branched molecular structures was immediately appealing for both theoretical and practical reasons. During the 1960–70s, the entire repertoire of polymeric architecture consisted only of Type I-linear and Type II-crosslinked morphologies. Type III-branched architectures were just beginning to emerge (see Figure 1.3). Consequentially, many very pessimistic opinions were expressed by some of the best polymer scientists, as well as the general scientific community concerning practical synthesis of such dendritic molecular structures. The prevailing opinion was that any such concept would ultimately lead only to bridging-type processes to produce Type II- crosslinked polymeric architectures. Despite this consensus, the concept was finally demonstrated in the Dow Laboratories near the end of the 1970s [16].