A Systematic Nomenclature for Codifying Engineered Nanostructures

*Darcy J. Gentleman and Warren C. W. Chan**

***N**anotechnology's growing applications are fueled by the synthesis and engineering of myriad nanostructures, yet there is no systematic naming or classification scheme for such materials. This lack of a coherent nomenclature is confusing the interpretation of data sets and threatens to hamper the pace of progress and risk assessment. A systematic nomenclature that encodes the overall composition, size, shape, core and ligand chemistry, and solubility of nanostructures is presented. A typographic string of minimalist field codes facilitates digital archiving and searches for desired properties. This nomenclature system could also be used for nanomaterial hazard labeling.*

Keywords:
- cataloging
- nanostructures
- nomenclature
- toxicity

1. Introduction

Nanotechnology is a rapidly growing field where the premise of research revolves around the unique size, shape, and compositionally tunable properties of structures in the sub-100-nm size range. These nanostructures are currently being studied and exploited in a wide variety of applications such as biological labeling,[1] drug delivery,[2] catalysis,[3] digital memory storage,[4] solar cells and photovoltaics,[5] cosmetics,[6] and photonic devices.[7] Currently, there is no unified method to name nanostructures and no well-defined schemes to classify them. This has created confusion in interpreting research findings both for guidance of governmental regulations and in assessing patents. For example, currently there are controversies regarding the toxicity of materials such as fullerenes and quantum dots (QDs).[8] Many researchers have concluded that size, shape, and surface chemistry could affect the interactions of such nanostructures with biological systems, and hence influence their toxicity.[9] Despite the fact that not all fullerenes or QDs are the same, researchers still report their findings using the common name without specifying exactly these structural and chemical differences. The lack of a coherent cataloging system can lead to the misinterpretation of data and discoveries. Regulatory and governmental agencies' ability to assess potential health effects could be compromised. Additionally, the patent process for nanomaterials could become confused as virtually identical technologies are redundantly developed. While debating the needlessly introduced controversies between data sets, new discoveries could be delayed for many years. The potential wasting of financial contributions and capital investments could hamper progress in this burgeoning field, both in academic environments and industrial commercialization.

With many young research fields, development of a cataloging strategy is important to the field's advancement. The International Union of Physical and Applied Chemistry (IUPAC) has developed nomenclatures for organic, inorganic, biochemical, and macromolecular chemistries, and the Chemical Abstracts Service (CAS) has developed a cataloging system for reagents and new substances.[10] However, neither of these nomenclature methods are appropriate for nanostructures. We therefore present a hierarchical codification system reminiscent of library classification taxonomies. A string of fields draws on typographic codes addressing composition, size, shape, and physicochemical properties. This format is amenable to writing codification and translation algorithms to facilitate digital archiving and searching. The identity of the nanostructures can be directly read from the code, unlike opaque classification systems such as the Digital Object Identifier (DOI) or the International Standard Book Number (ISBN).

[*] Prof. W. C. W. Chan, Dr. D. J. Gentleman
Institute of Biomaterials and Biomedical Engineering
Terrence Donnelly Centre for Cellular & Biomolecular Research
Department of Materials Science & Engineering
Department of Chemical Engineering
University of Toronto
Toronto, ON (Canada)
E-mail: warren.chan@utoronto.ca

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Table 1. Codification protocols for the nanomaterial classification system.

Chemical Class	Size and Shape	Core Chemistry	Ligand Chemistry	Solubility
XT_1T_2	**$r(r_e)M_1M_{1b}(m_2)M_3M_4M_5$**	**$(Z_1,Z_2,\ldots,Z_n)$**	**$[(f_i,f_e)_1;(f_i,f_e)_2;\ldots;(f_i,f_e)_n]$**	**S[log D(pH)]**
X 1 if organic/ fullerene (contains no metals)	**r** = smallest defining dimension in nm **r_e** = other defining size (if applicable)	**0** if no core	**0** if no ligands	**S** **O** if log D > 1 **W** if log D < −1 **OW** if −1 < log D < 1
2 if inorganic/ organometallic	**M_1** **B** = ball **H** = polyhedron/faceted **R** = rod/wire **P** = plate/disc/well	list core elements in conventional chemical order; dopants can be included if known	**f_i** (see Table 2) functional group on inside/ adsorbed to core **f_e** (see Table 2) outer functional group	indicate log D and pH of measurement (if known)
T_1 outermost chemistry **D** = dendrimer **F** = fullerene **L** = liposome **P** = polymer	**M_{1b}** (M_1 value not nec.) **A** = astral (not after B) **I** = irregular			
	m_2 (omit if unknown) **B(b), b** = # radii: **1** = spheroid; **2** = ellipsoid **H(h), h** = # faces **R(r), r** = # barrel faces, **0** = cylinder **P(p), p** = # sides, **0** = circle **A(a), a** = # arms	/ indicates inter–core boundary, for example (Cd,Se/Zn,S) is a core/shell	/ indicates multilayer structures, for example $[(f_i,f_e)/(f_i,f_e)]$ is a bilayer for nested structures, only indicate outermost shell	
	M_3 L if elongated		bioconjugation $[(f_i,f_e/Bio)]$ or $[(f_i,Bio)]$	
T_2 N = nested	**M_4 T** if teethed/ jagged edges		sheet structure, list twice, for example CNT [(Ful,Ful)]	
	M_5 C if coiled/helical/ twisted			

2. Proposed Nomenclature Scheme

In this nomenclature scheme, five typographic fields comprise the code. Table 1 shows the rules that govern the filling of these fields. The first field, Chemical Class, indicates the general composition and structure. Fullerenes are included with organic for simplicity despite these species' physicochemical properties that challenge the traditional definition of organic. The following two letters of this first field qualify the type of structure. Nested is herein defined as multiwalled structures such as multiwall nanotubes (MWNT) or multilamellar liposomes: core/shell and ligand-capped colloids are not nested. Size and shape are specified in the second field. The intent is to describe the size and shape of the component that results in the structure being considered nanoscopic—possessing size and shape dependent properties. Examples include the diameter of a QD core, the diameter of a nanotube, or the thickness of a quantum well. For nanostructures that have an additional size parameter, such as solvation diameter, length of rods in a monodisperse sample, or the total diameter of a multipod, an optional second size field is included. The morphology fields are designed to capture the present and future diversity of shapes encountered in nanostructures. In this hierarchical listing, the first letter indicates overall shape or dimensionality, while qualifiers and indicators of higher order morphologies follow. Use of the astral descriptor is discussed in the Supporting Information. The third and fourth fields specify core and ligand chemistries. If either of these regions is nonexistent, these fields are assigned a zero so as to maintain five fields for digital archiving consistency. Abbreviations used for the functional groups are listed in Table 2.

As many nanostructures are used in solution, the last field indicates solubility. Taking a cue from pharmacology and environmental science studies, the logarithm of the distribution coefficient,

$$\log \mathrm{D} = \log\left(\frac{[\mathrm{X}]_{\mathrm{oc\,tan\,ol}}}{[\mathrm{X}]_{\mathrm{aqueous}}}\right) \quad (1)$$

is used.[11] Equation 1 is equivalent to log P for non-ionizable species.[12] Lipophilic species have a greater affinity for octanol and render a log D > 0, while hydrophilic species conversely have a log D < 0. We indicate the former with an O and the latter with a W. If −1 < log D < 1, the code OW is used. For species with a known log D, the value is listed along with its requisite pH measurement.

Table 2. Abbreviations for functional groups used in the fourth field.

Functional Group	Abbrev.	Note	AA	Abbrev.
acyl halide	Ach		alanine	Ala
acrylic	Acr		arginine	Arg
alcohol	Alc		asparagine	Asn
aldehyde	Ald		aspartic acid	Asp
alkyl (∼ane, ∼ene, ∼yne)	Alk		cysteine	Cys
amide	Amd	ide = d	glutamic acid	Glu
amine	Amn	ine = n	glutamine	Gln
azide	Azd		glycine	Gly
azo	Azo		histidine	His
phenyl/benzyl	Bnz		isoleucine	Ile
carbonate	Cba	ate = a	leucine	Leu
carboxyl	Cbx		lysine	Lys
cyanide	Cyd		methionine	Met
isocyanide	Icy		phenylalanine	Phe
cyanate	Cya		proline	Pro
isocyanate	Ica		serine	Ser
thiocyanate	Tca		threonine	Thr
isothiocyanate	Itc		tryptophan	Try
disulphide	Dsu		tyrosine	Tyr
(a)ether	Eth		valine	Val
ester	Est			
haloalkane	Hak			
hydroxyperoxide	Hoo			
imine	Imn			
imide	Imd			
ketone	Ket			
nitrate	Nta			
nitrile	Ntl			
nitro	Nto			
nitroso	Nts			
peroxide	Per			
phosphine	Phn			
phosphine oxide	Pox			
phosphodiester	Pde			
phosphate	Pha			
phosphonic acid	Poa			
pyridine	Pyr			
sulphide	Sde			
sulphone	Soo			
sulphonic acid	Soa			
sulphoxide	Sox			
thiol	Thi			
fullerene	Ful			

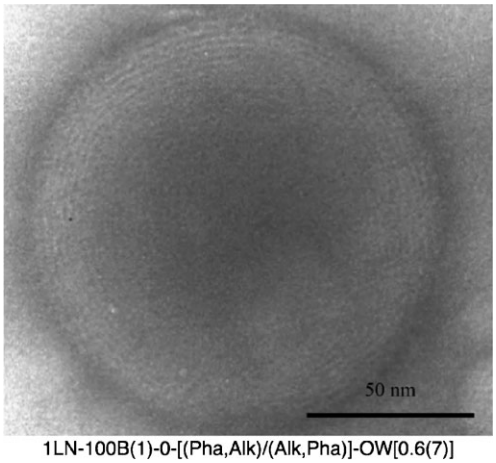


Figure 1. TEM image of a multilamellar liposome. Reproduced with permission from reference [13]. Copyright 2007, Taylor and Francis.

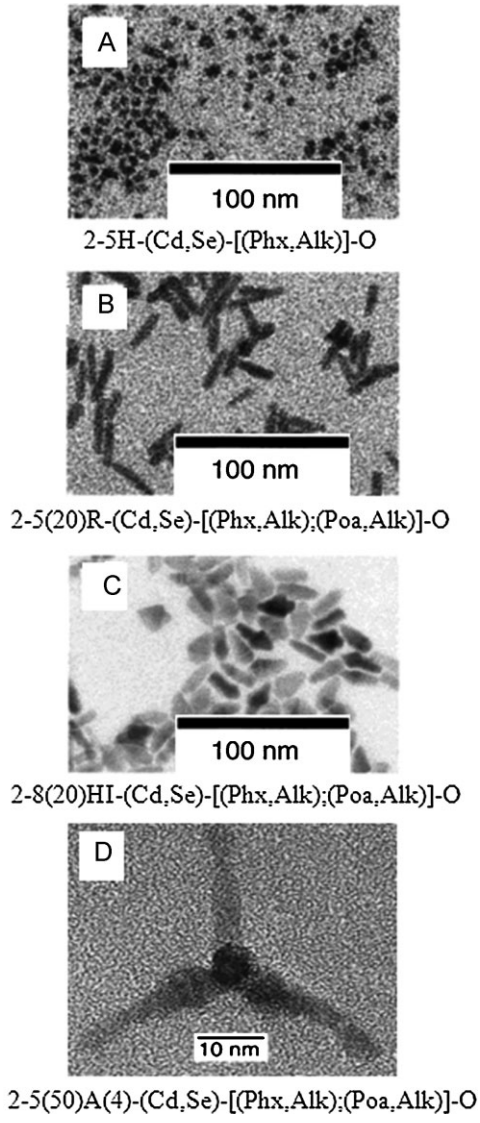


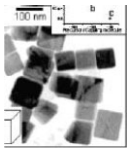
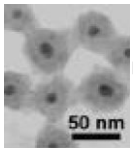
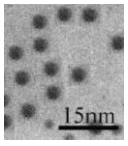
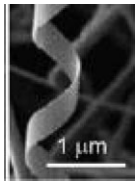
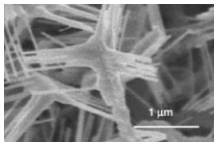
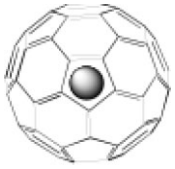
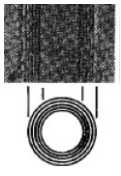
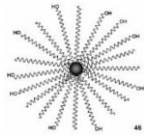
Figure 2. These TEM and HRTEM micrographs show CdSe nanostructure A) quantum dots, B) nanorods (quantum rods), C) irregularly shaped nano-arrows and nano-"trees," and D) a tetrapod. Note how the codes change for the different sizes, morphologies, and ligands. Some sizes are visually estimated from the scale bars indicated. Reproduced with permission from reference [28]. Copyright 2008, American Chemical Society.

The utility of using log D to codify nanostructures with respect to assessing toxicities and/or potential environmental mobility is discussed below.

3. Nomenclature Example

To demonstrate the use of this codification system, we provide an example using a liposome. Figure 1 shows a multilamellar spherical liposome consisting of concentric phospholipid bilayer shells, recently reported by Mura et al.[13] The first field is thus **1LN**, and the scale bar indicates that the second field is **100B(1)**. Note that B(1) denotes a

Table 3. Codification of reported nanostructures.

Structure	Description	Code
 [a]	≈90-nm wide PbS nanocubes aminoalkane cap	**2-90H(6)-(Pb,S)-[(Amn,Alk)]-O**
 [b]	57-nm diameter silica-coated Au NPs; poly(DMAEMA) cap biofunctionalized	**2-57B(1)-(Au/Si,O)-P[(Amn,Acr/Bio)]-W**
 [c]	4-nm diameter CdSe NC capped with PAMAM dendrimer	**2D-4H-(Cd,Se)-[(Amn,Amn)-O**
 [d]	20-nm thick ZnO nanohelices, no cap	**2-20P(4)LT-(Zn,O)-0-W**
 [e]	50-nm diameter ZnO elongated nanorod trefoil barbing, no cap	**2-50RA(3)L-(Zn,O)-0-W**
 [f]	Gd atom inside hydroxylated buckyball [Gd@$C_{82}(OH)_{16}$]	**2F-1B(1)-(Gd)-[(Ful,Ful);(Ful,Alc)]-O**
 [g]	7-nm diameter fullerene MWNT	**1FN-7RL-0-[(Ful,Ful)]-O**
 [h]	r-nm diameter star polymer 50% alkyl, 50% hydroxyl	**1P-rA-(C)-[(Bnz,Alk);(Bnz,Alc)]-O**

[a] Reproduced with permission from reference [14]. Copyright 2002, American Chemical Society. [b] Reproduced with permission from reference [17]. Copyright 2006, Institute of Physics. [c] Reproduced with permission from reference [18]. Copyright 2006, Elsevier. [d] Reproduced with permission from reference [19]. Copyright 2005, American Association for the Advancement of Science. [e] Reproduced with permission from reference [20]. Copyright 2007, Elsevier. [f] Reproduced with permission from reference [21]. Copyright 2007, Springer. [g] Reproduced with permission from reference [22]. Copyright 1991, McMillan. [h] Reproduced with permission from reference [23]. Copyright 2003, American Chemical Society.

Table 4. Cataloging for property comparison.

Searching for attainment of quantum confinement in CdE QDs		
Code	Filter Field 3	Filter Field 2
2-3H-(Cd,S)-[(Phx,Alk)]-O[a]	(**Cd**,**E** = **S**)	**r** < **6**
2-3H-(Cd,Se)-[(Phx,Alk)]-O[a]	(**Cd**,**E** = **Se**)	**r** < **6**
2-3H-(Cd,Te)-[(Phx,Alk)]-O[a]	(**Cd**,**E** = **Te**)	**r** < **6**
Bioconjugation of Au nanoparticles		
Code	Filter Field 3	Filter Field 4
2-13B(1)-(Au)-[(Thi,Bio)]-W[b]	(**Au**)	[(Thi,**Bio**)]
2-57B(1)-(Au/Si,O)-[(Amn,Acr/Bio)]-W[c]	(**Au**/Si,O)	[(Amn,Acr/**Bio**)]
2-14R-(Au)-[(Amn,Bio)]-W[d]	(**Au**)	[(Amn,**Bio**)]
Diversity of fullerenes		
Code	Filter Field 1	Conventional Name
2F-1B(1)-(Gd)-[(Ful,Ful);(Ful,Alc)]-O[e]	2**F**	buckyball/fullerene cage
1F-1RL-0-[(Ful,Ful)]-O[f]	1**F**	CNT – SWNT graphene nanotube, quantum wire
1FN-7RL-0-[(Ful,Ful)]-O[g]	1**FN**	CNT – MWNT

[a] Coded for structure in reference [24]. [b] Coded for structure in reference [25]. [c] Coded for structure in reference [17]. [d] Coded for structure in reference [26]. [e] Coded for structure in reference [21]. [f] Coded for structure in reference [27]. [g] Coded for structure in reference [22].

spherical architecture given the presence of one geometrical axis, while B(2) indicates an ellipsoid's two unique axes. As liposomes can house solutions and/or smaller molecules, they are hollow. Therefore the third field is void and takes a value of **0**. To represent the bilayer of the outermost shell, the fourth field is **[(Pha,Alk)/(Alk,Pha)]**. Mura et al report a log D of ≈0.6 at pH ≈ 7,[13] so the fifth field is **OW[0.6(7)]**. Therefore the codification of Figure 1 is **1LN-100B(1)-0-[(Pha,Alk)/(Alk,Pha)]-OW[0.6(7)]**. Additional examples of other nanostructures are found in Figure 2 and Tables 3 and 4. If any information on the nanostructure is missing, one can place an **Unk** in its place.

It is important to stress with this example that while the liposome does include cholesterol and dicetyl phosphate for stabilization, only the representational ligands are listed for simplicity. This nanostructure nomenclature system is designed to capture the minimum information necessary to distinguish the structure from others. Just as a CAS number on a reagent bottle is not indicative of purity, here too the structure's entire chemistry is not reported. A good classification system should permit quick determination of identity, and interested parties can then interrogate specification documents as needed.

4. Application of Nomenclature System

A huge advantage of this system is the ability to quickly discern similarities of properties or distinguish highly nanoscale-relevant parameters of structures possessing identical compositions. Table 4 shows examples of the relative ease that one can sort the attainment of quantum confinement in cadmium chalcogenide (CdE) QDs, the presence of bioconjugation, or the morphological differences of several fullerene species. This will greatly accelerate the ability of researchers and regulatory agencies to seek out nanostructures of interest in vast digital archives. Even if CAS or IUPAC were expanded to address nanostructures, the quasi-opaque coding of the former requires memorization of arbitrary digits of interest and the latter is too ungainly for complex structures.

Another applicability of this system regards the labeling of nanomaterials for hazard maintenance. As noted above, the size, shape, and surface chemistry of nanostructures are proving important parameters where their toxicity and potential bioavailability/environmental mobility are concerned. If, for example, polyhedral nanocrystals are found to be more bioavailable than nanorods, all substances with an H in the second field can be earmarked for more stringent toxicity assessment. The so-called Lipinski–Pfizer ''rule of 5'' states

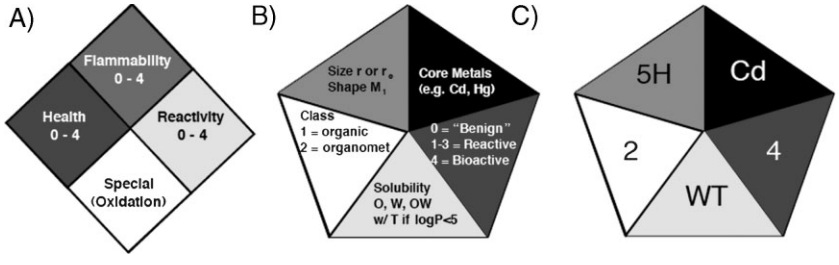


Figure 3. A) The National Fire Protection Association has introduced a widely used ''hazard diamond'' information label found on many chemical products. B) As nanomaterials' potential hazards and toxicity are assessed, the nomenclature system proposed herein could be simplified for hazard labels. C) An example using the ''nanohazard pentagon'' for a CdE nanocrystal with ligands such as mercaptoacetic acid: 2-3H-(Cd,Se)-[(Thi,Cbx)]-W. Figure in (A) after ''hazard diamond'' described in NFPA 704 policy document (2007).[29,30]

that a log $P < 5$ is associated with an increased oral bioavailability.[15,16] If this holds true for nanostructures, the fifth field can also help in segregating potentially hazardous materials. Once these more coarse filters are applied, perhaps by non-specialist technicians, researchers can be guided by the chemical information found in fields three and four to accelerate the risk assessment process. Figure 3 shows how workplace and storage hazard labeling of nanomaterials could exploit the information in this five-field codification system.

5. Conclusions

We described for the first time a universal classification system for nanotechnologies. This nomenclature thus affords transparent communication between regulatory bodies and researchers so as to best develop risk assessment and reporting protocols. The patent process will also benefit from such transparency, as non-specialists can more easily discern the factors affecting potential technological exploitation. The nanostructure codification system proposed herein is not only unrivalled in its breadth of applicability, but can potentially unify the field.

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