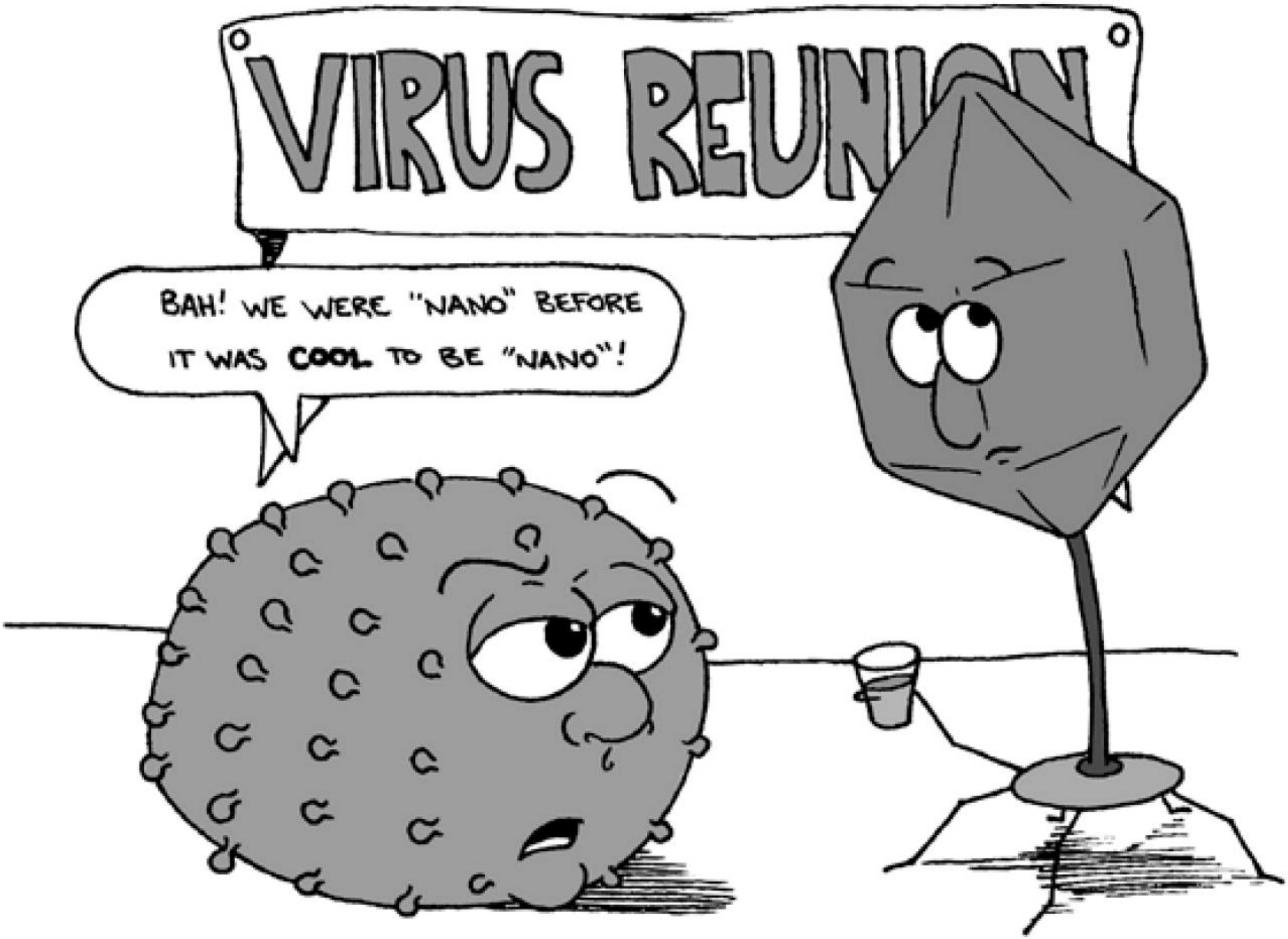

VIRUS REUNI
BAH! WE WERE "NANO" BEFORE IT WAS COOL TO BE "NANO"!

Structural Virology

Fall 2024

Pavel Plevka

Financováno Evropskou unií NextGenerationEU
NÁRODNÍ PLÁN OBNOVY
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

Class rules

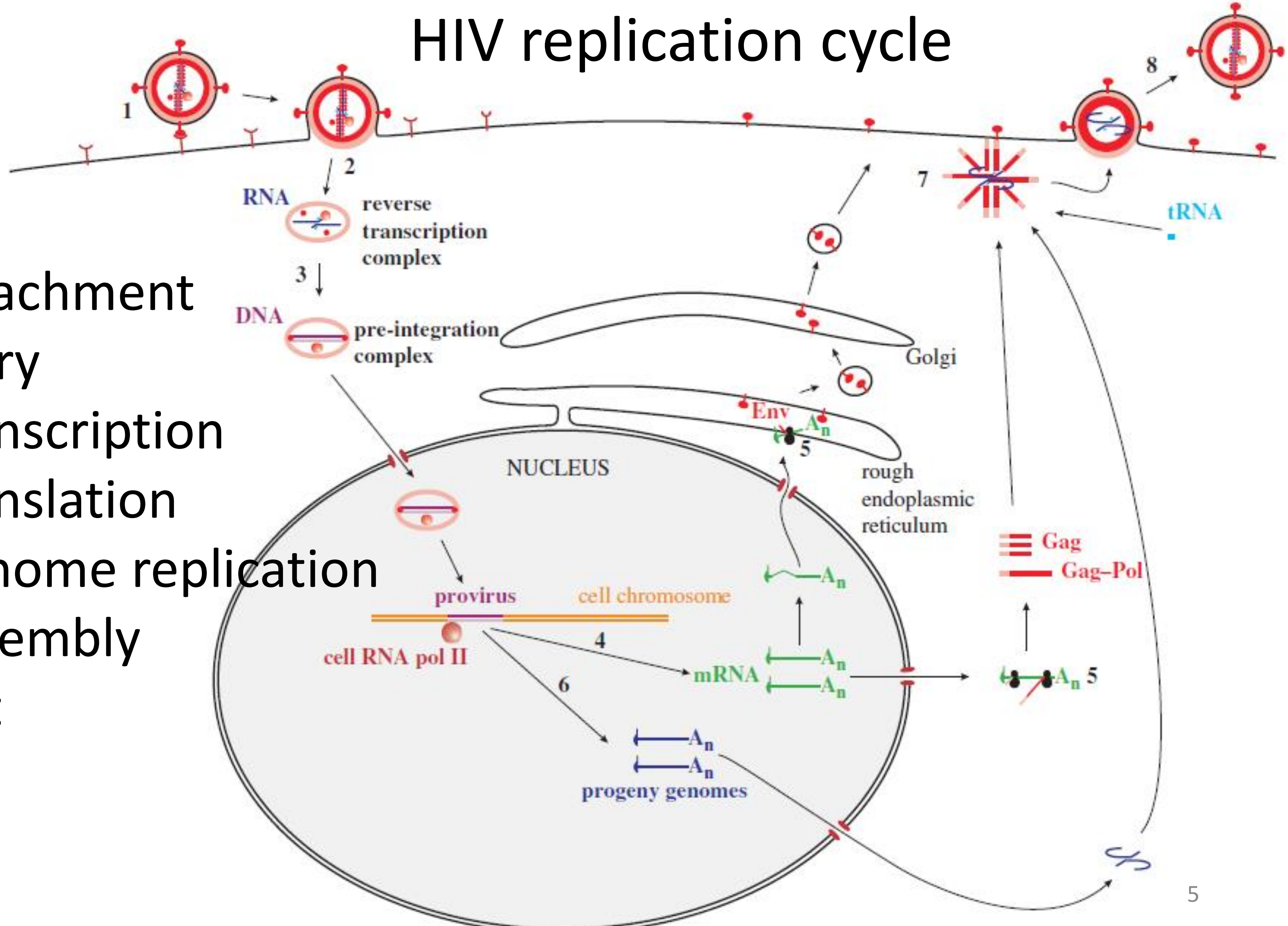
- Turn off anything that beeps or rings.
- Reading any material that is not related to the class, texting, or checking the internet during the class is rude and will not be tolerated.
- Please refrain from eating during class. Having something to drink is fine.
- Ask questions - it will help to clarify the issue not only for you but for your peers as well!
- In class discussions, be respectful of other students' opinions.

Aims of the course

- learn elementary molecular virology
- appreciate role of structural information in understanding of biological processes
- learn to read and evaluate scientific papers
- learn history of some fundamental discoveries in biology
- be able to evaluate what is an important research question

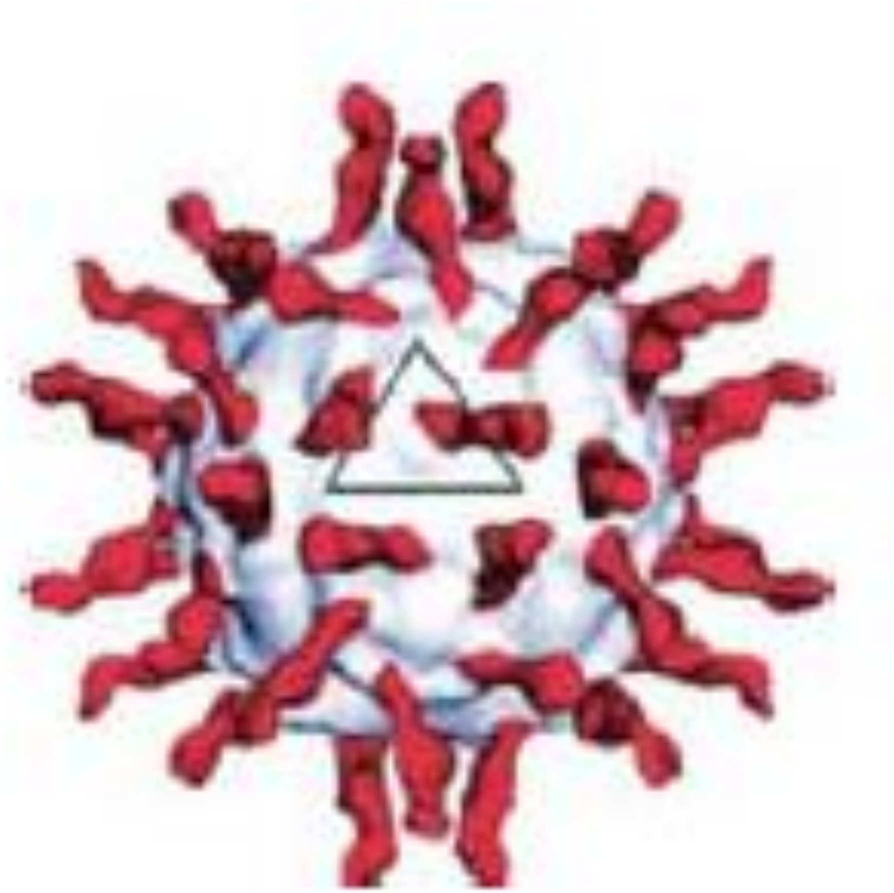
Elementary molecular virology

HIV replication cycle

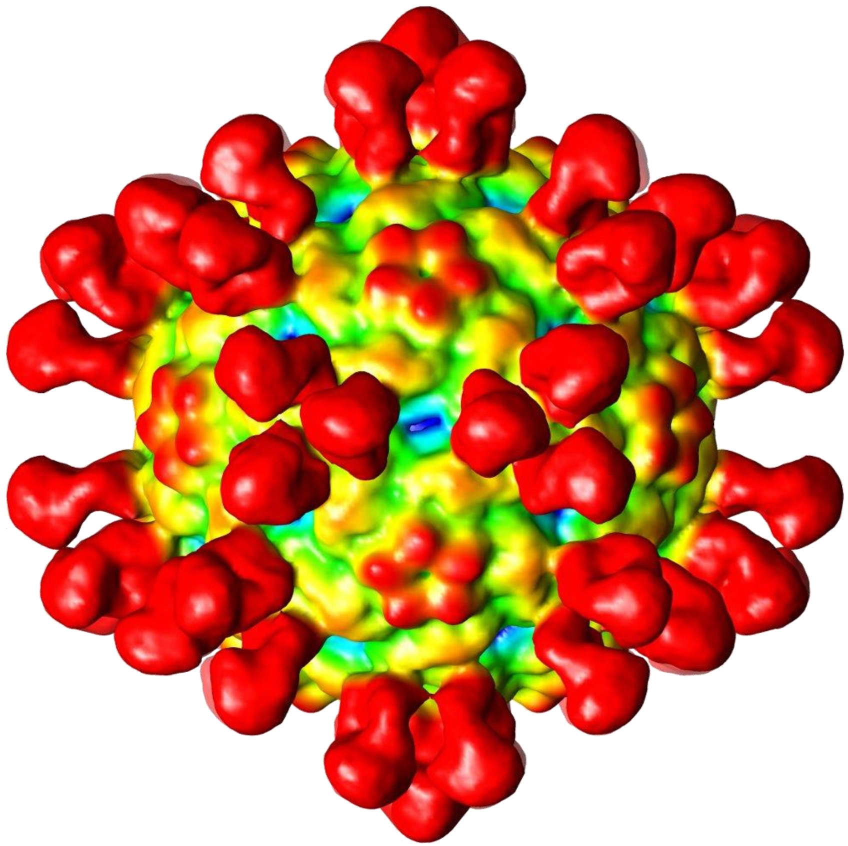


1. **A**ttachment
2. **E**ntry
3. **T**ranscription
4. **T**ranslation
5. **G**enome replication
6. **A**ssembly
7. **E**xit

Structural biology in understanding virus infection



Virus binding to receptor



Binding of antibodies to virus particle

Read and evaluate scientific papers

CHALLENGES IN IRREPRODUCIBLE RESEARCH:

- **more than 50% of drug-related research articles in high profile journals contain irreproducible data**

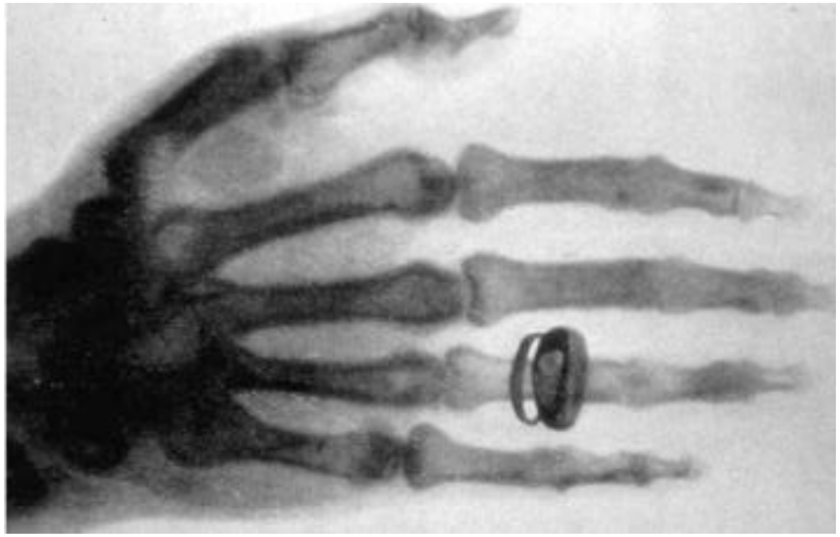
Reasons for irreproducibility:

- Under supervised students and post-docs
- "Publish or Perish" threat
- wrong design of experiments – "know your statistics"

History of fundamental discoveries

WILHELM CONRAD RÖNTGEN (1845-1923)

- **1901 Nobel Laureate in Physics**
  discovery of the remarkable rays subsequently named after him



What is important research question?

Interesting X Important

1. *It asks about something other people care about*
2. *It builds on what you and others already know*
3. *It allows you to learn something you don't already know*

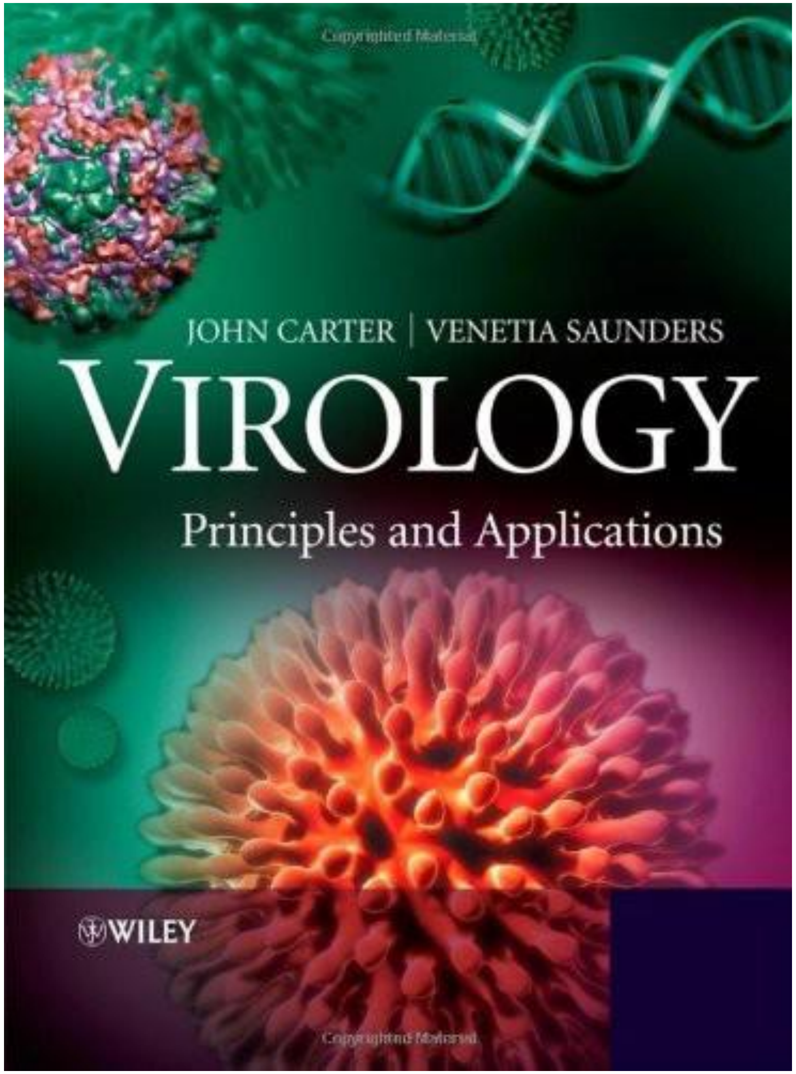
What are evolutionary relationships of anaerobic protists?
What is the probability that current Ebola epidemics is going to spread outside of Africa?

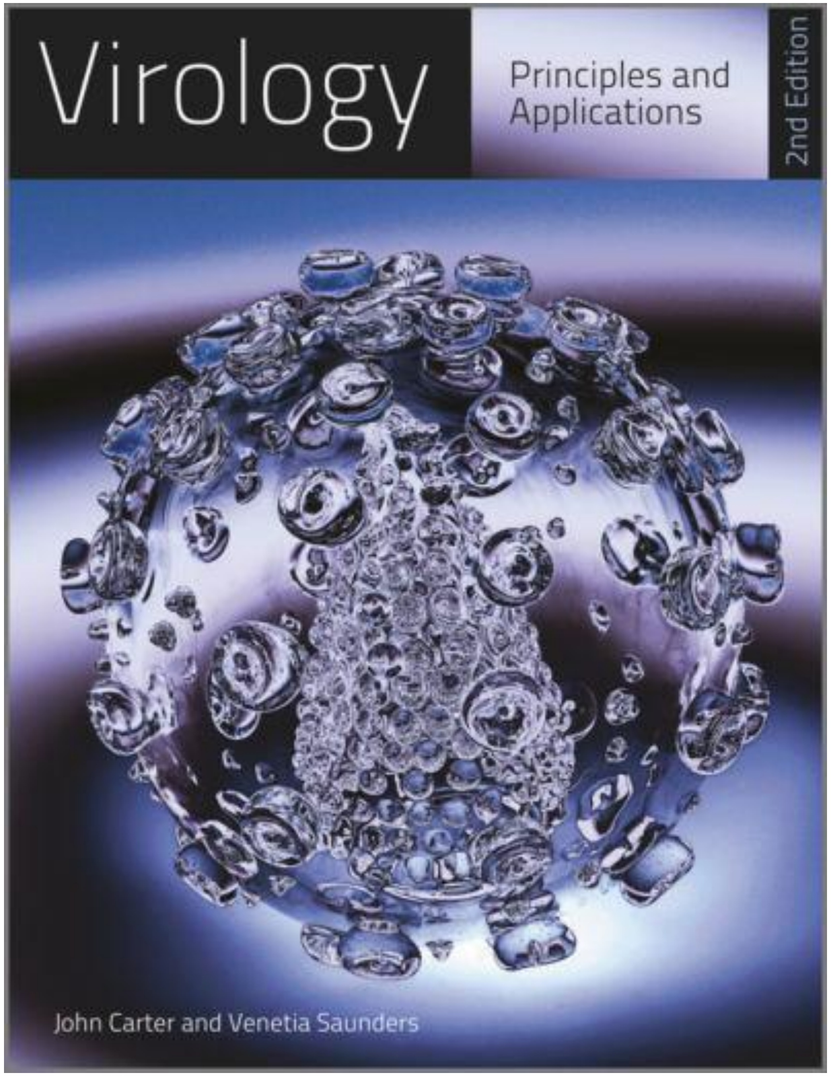
What is asked of you:

- Read assigned readings *before* the day for which they are assigned
- Bring five-sentence essay describing the importance of a scientific paper to each lecture
- Participate in discussions
- Submit two mini-assignments
- I am here to help, learning is up to you!

Course textbook:

14 copies are available in campus library





Viruses and their importance

Viruses infect:

- **Humans**

Smallpox [1]

- **Other vertebrates**

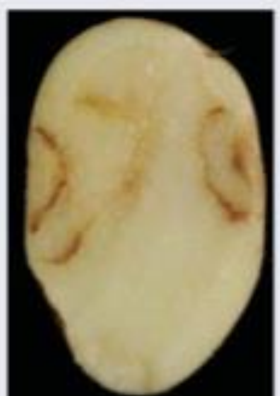
Foot and mouth disease [2]

- **Invertebrates**

Leatherjackets infected with *Tipula* iridescent virus

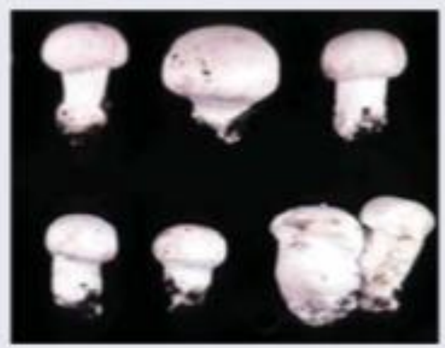
- **Plants**

Delayed emergence of potato caused by tobacco rattle virus infection [3]



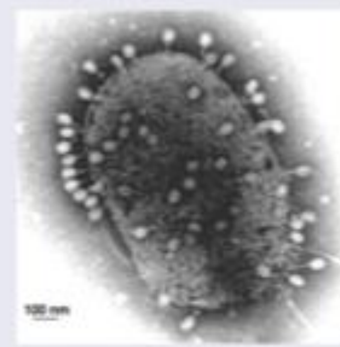
Damaged potato (spraing) caused by tobacco rattle virus infection [3]

- **Fungi**



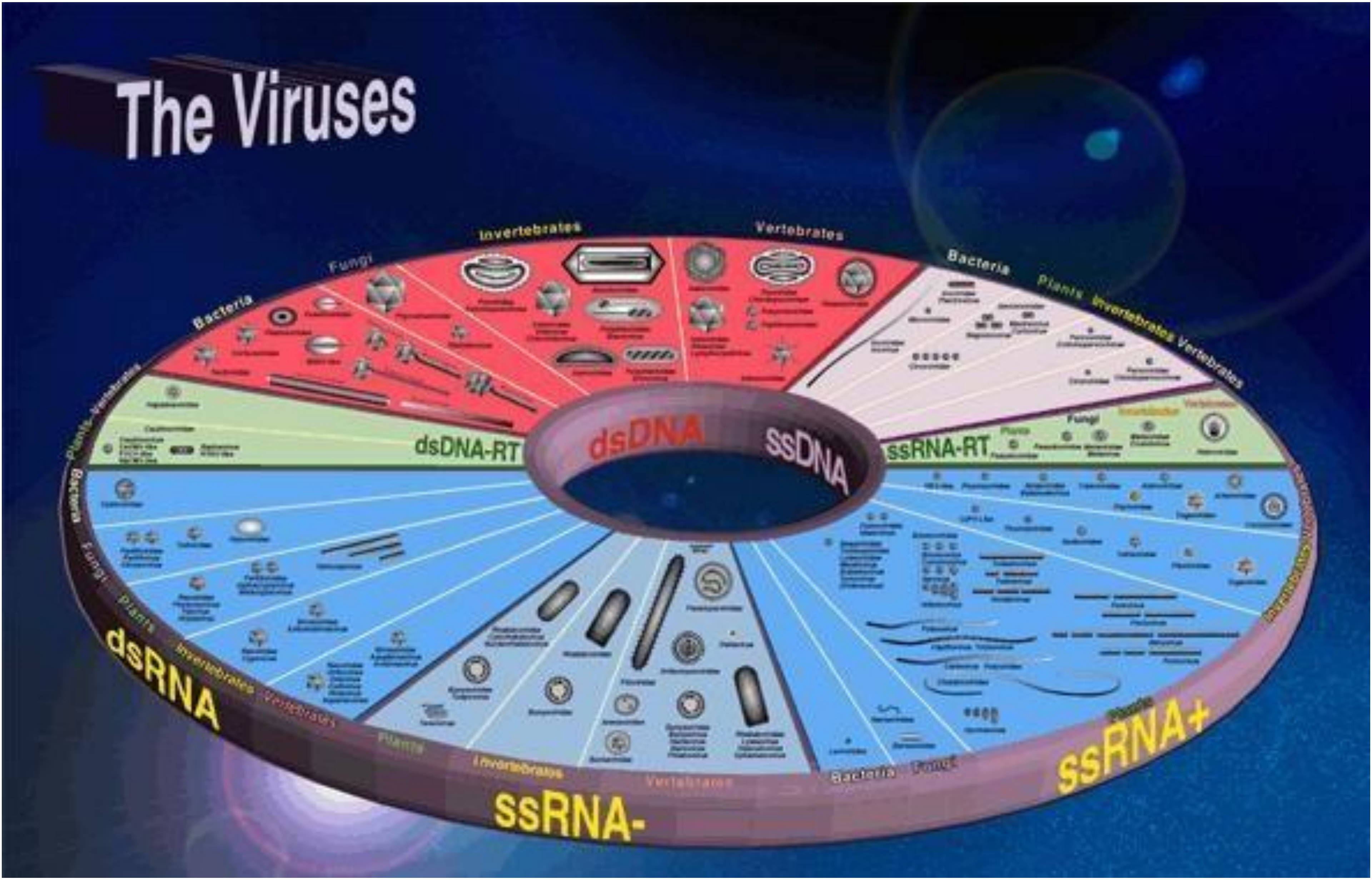
Mushroom virus X [4]

- **Bacteria**



Escherichia coli cell with phage T4 attached [5]

Virosphere!


The Viruses
dsDNA
ssDNA
dsDNA-RT
ssRNA-RT
dsRNA
ssRNA-
ssRNA+
Bacteria
Fungi
Invertebrates
Vertebrates
Plants

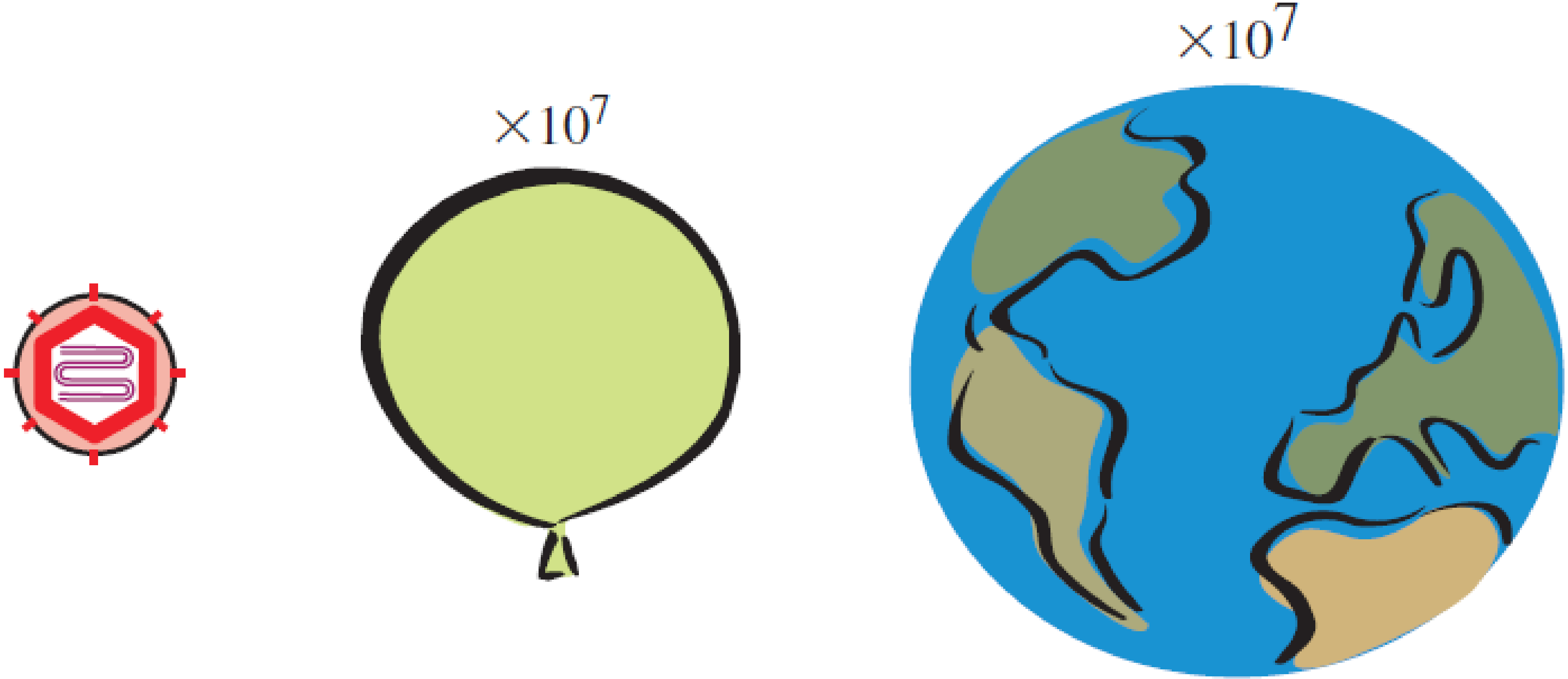
Useful viruses

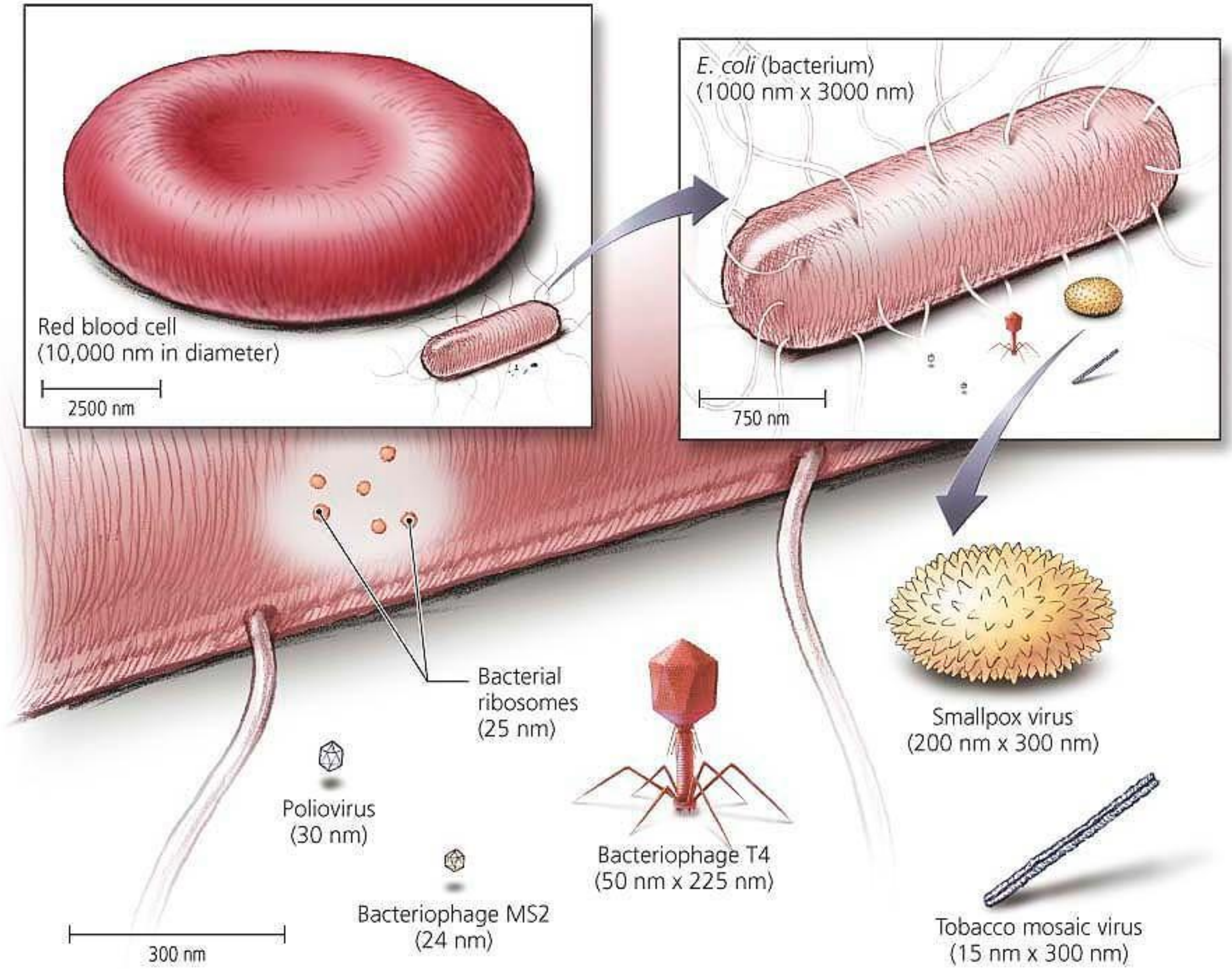
- Phage typing of bacteria
- Sources of enzymes (polymerases, T4 ligase, reverse transcriptase)
- Pesticides (baculoviruses – lepidoptera, hymenoptera, myxoma virus - rabits) SPECIFICITY!
- Anti-bacterial agents (S. aureus phage phi812)
- Anti-cancer agents (adeno-associated viruses)
- Gene vectors (capsids used as vehicles for gene delivery)
- Mass protein production

Fundamental discoveries in biology

- Phage T2 and *E. coli* were used to provide evidence that genes are composed of DNA.
- The first enhancers to be characterized were in genes of simian virus 40 (SV40).
- The first transcription factor to be characterized was the transplantation (T) antigen of SV40.
- The first nuclear localization signal of a protein was identified in the T antigen of SV40.
- Introns were discovered during studies of adenovirus transcription.
- The role of the cap structure at the 5’ end of eukaryotic messenger RNA was discovered during studies with vaccinia virus and a reovirus.
- The first internal ribosomal entry site to be discov- ered was found in the RNA of poliovirus.
- The first RNA pseudoknot to be discovered was that in the genome of turnip yellow mosaic virus.

Most viruses are 25-400nm in size



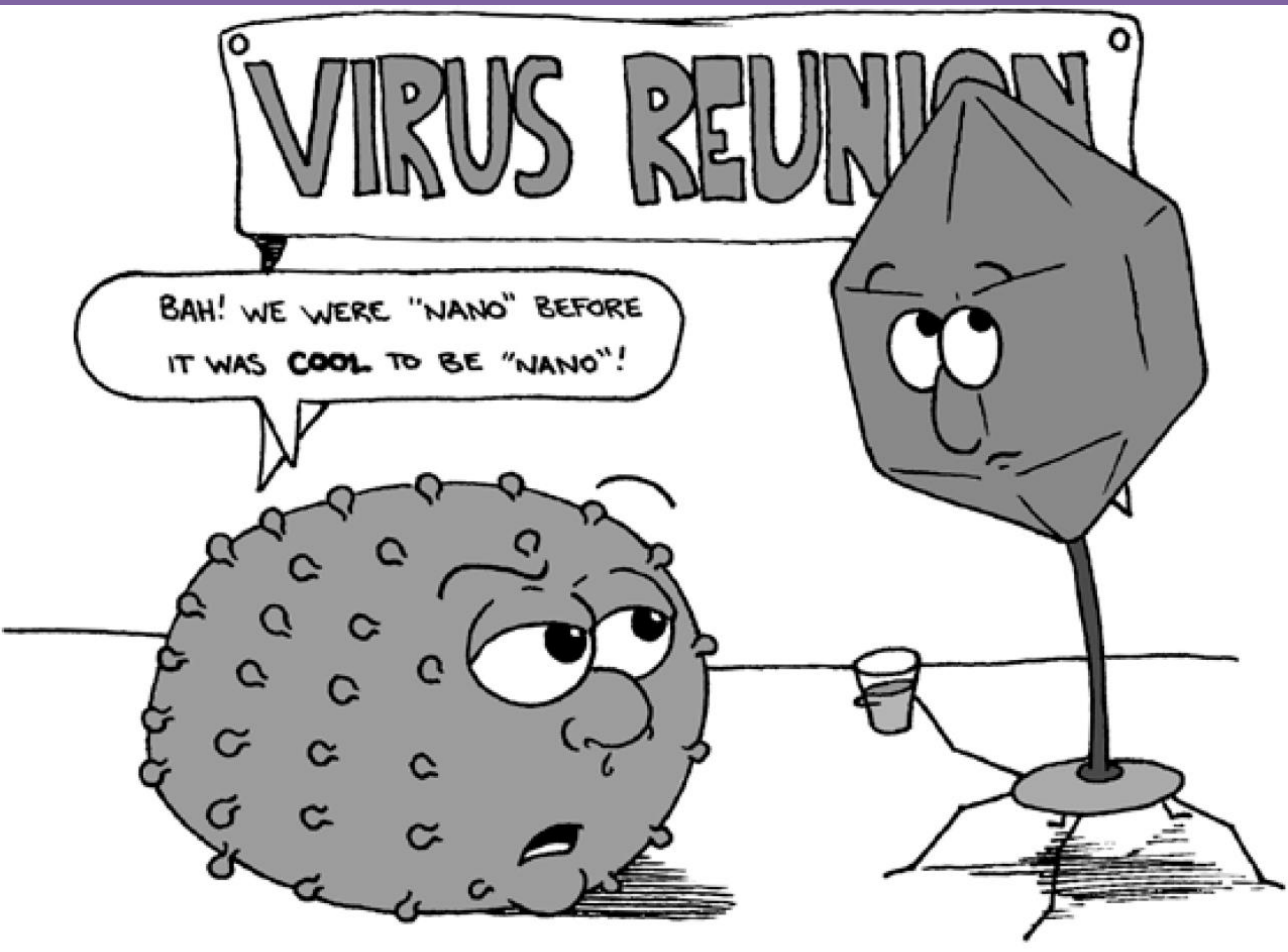


Red blood cell
(10,000 nm in diameter)
2500 nm
E. coli (bacterium)
(1000 nm x 3000 nm)
750 nm
Bacterial
ribosomes
(25 nm)
Smallpox virus
(200 nm x 300 nm)
Poliovirus
(30 nm)
Bacteriophage T4
(50 nm x 225 nm)
Bacteriophage MS2
(24 nm)
Tobacco mosaic virus
(15 nm x 300 nm)
300 nm

Units of length

Meter	1				
Centimeter	100	1			
Milimeter	1,000	10	1		
Micron	1,000,000	10,000	1,000	1	
Nanometer	1,000,000,000	10,000,000	1,000,000	1,000	1
Angstrom	10,000,000,000	100,000,000	10,000,000	10,000	10

Angstrom	1				
Nanometers	.1	1			
Microns	.0001	.001	1		
Milimeters	.0000001	.000001	.001	1	
Centimeters	.00000001	.0000001	.0001	.1	1
Meters	.0000000001	.000000001	.000001	.001	.01


VIRUS REUNI
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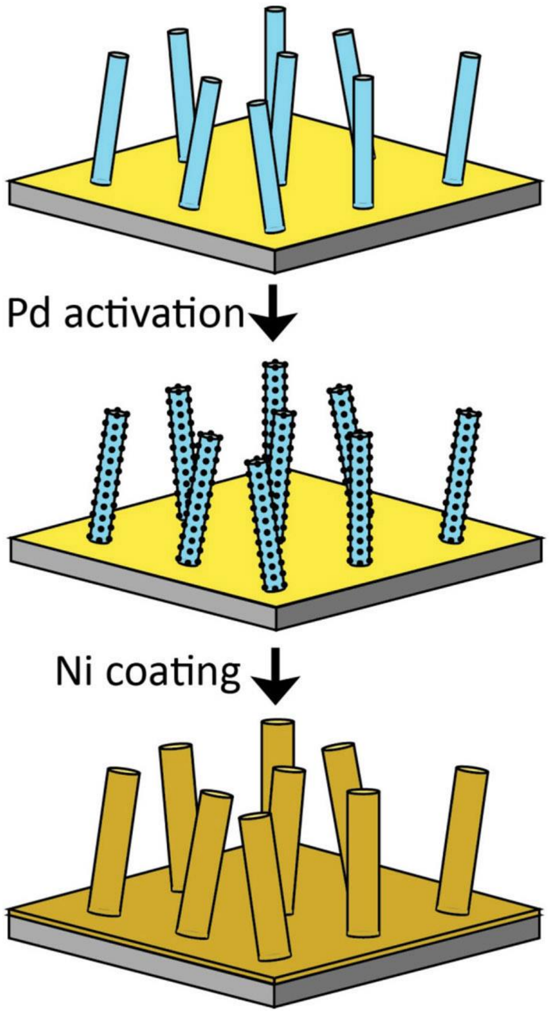
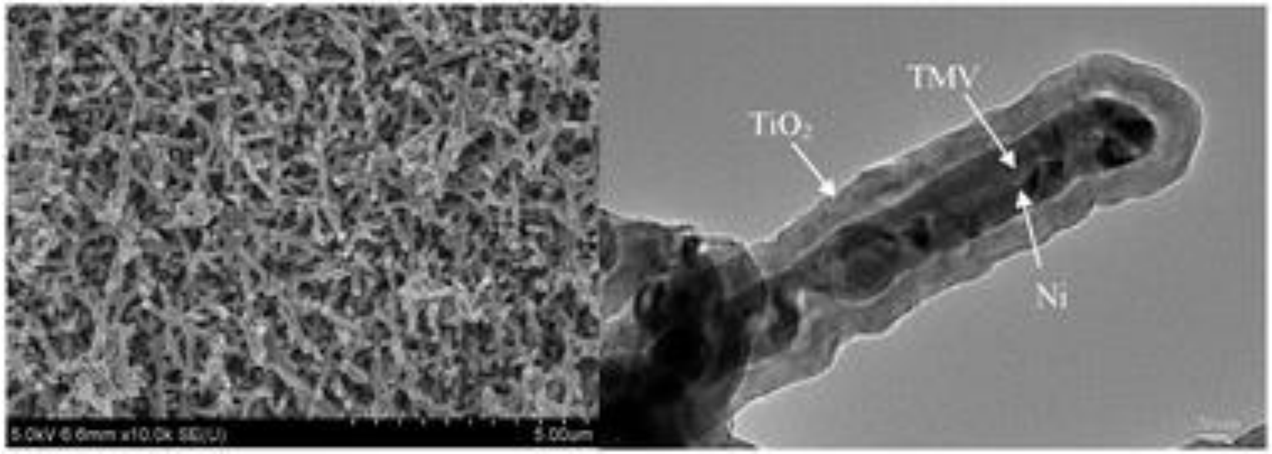
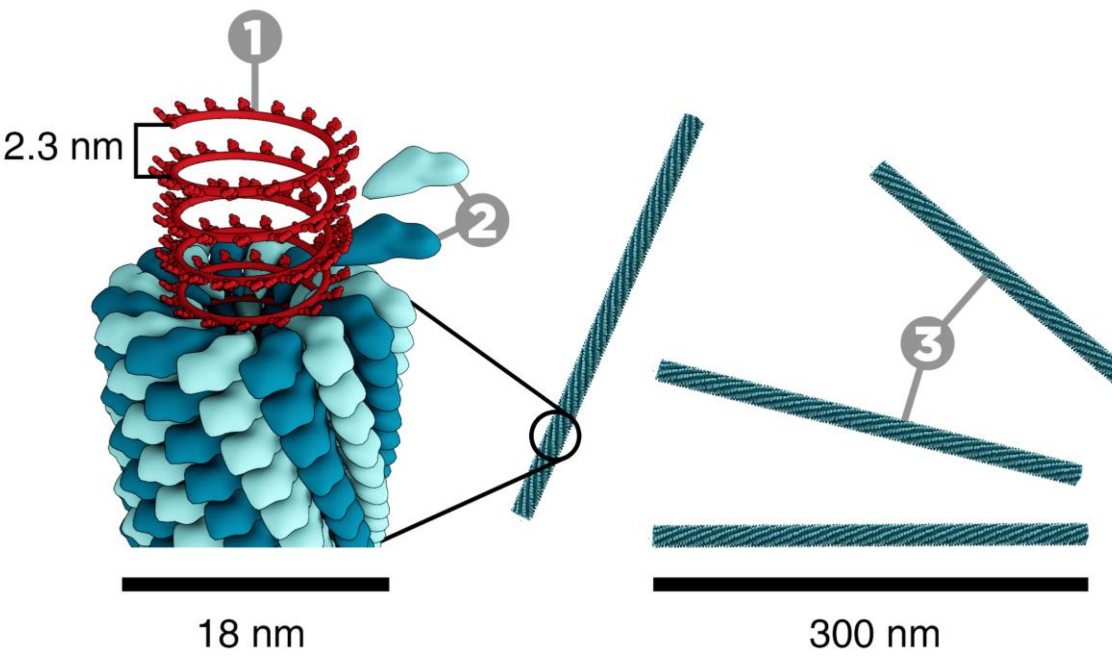
Using TMV to increase surface of electrodes







Methods to study virus structures

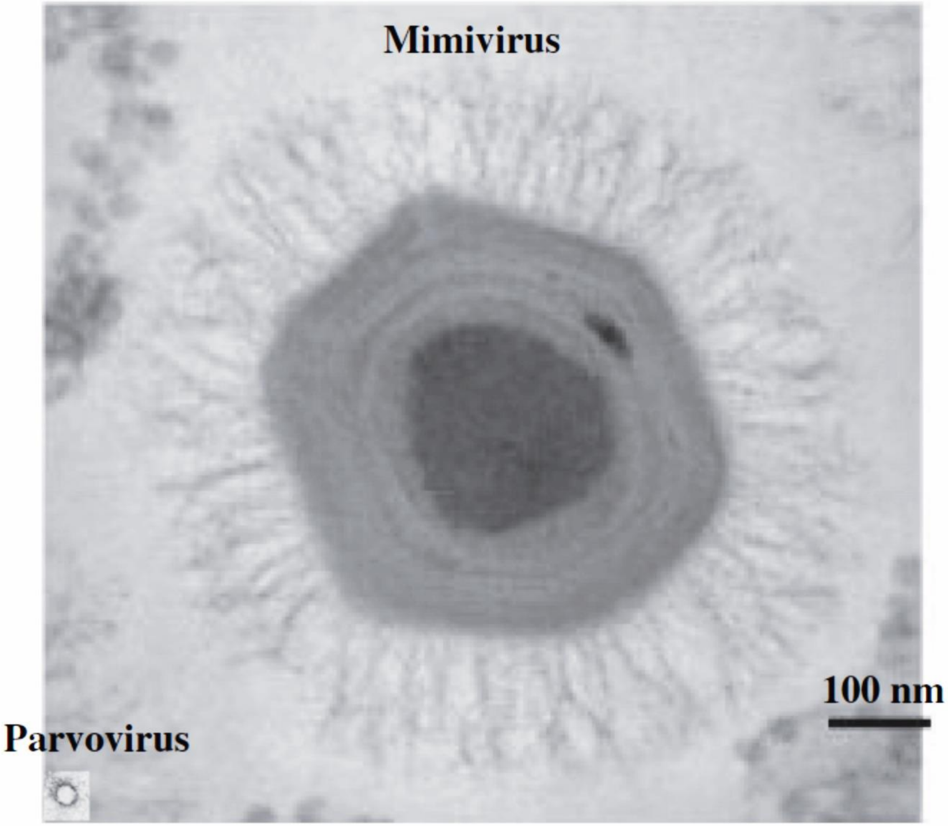
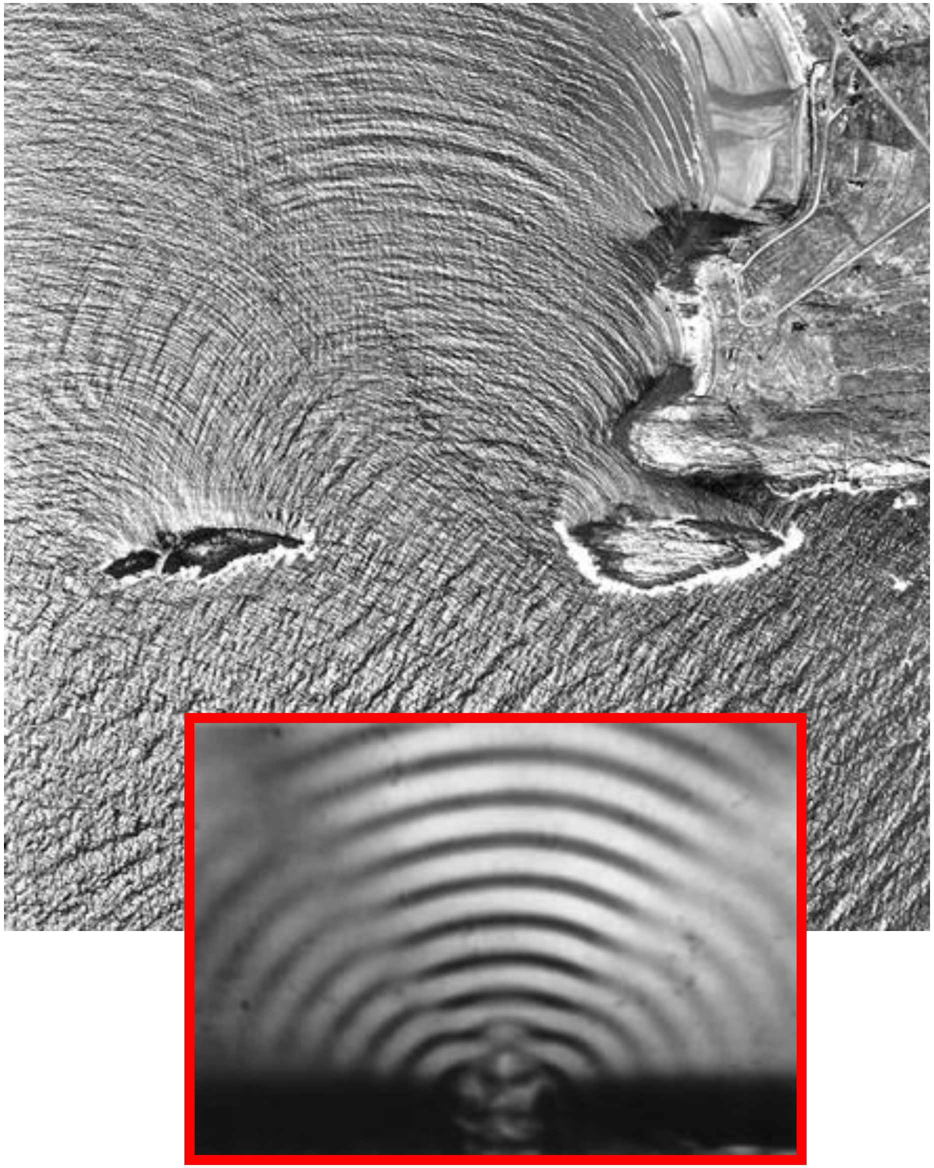
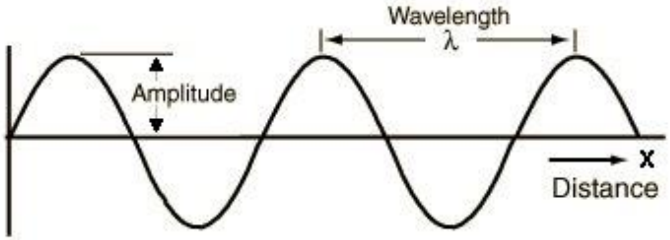


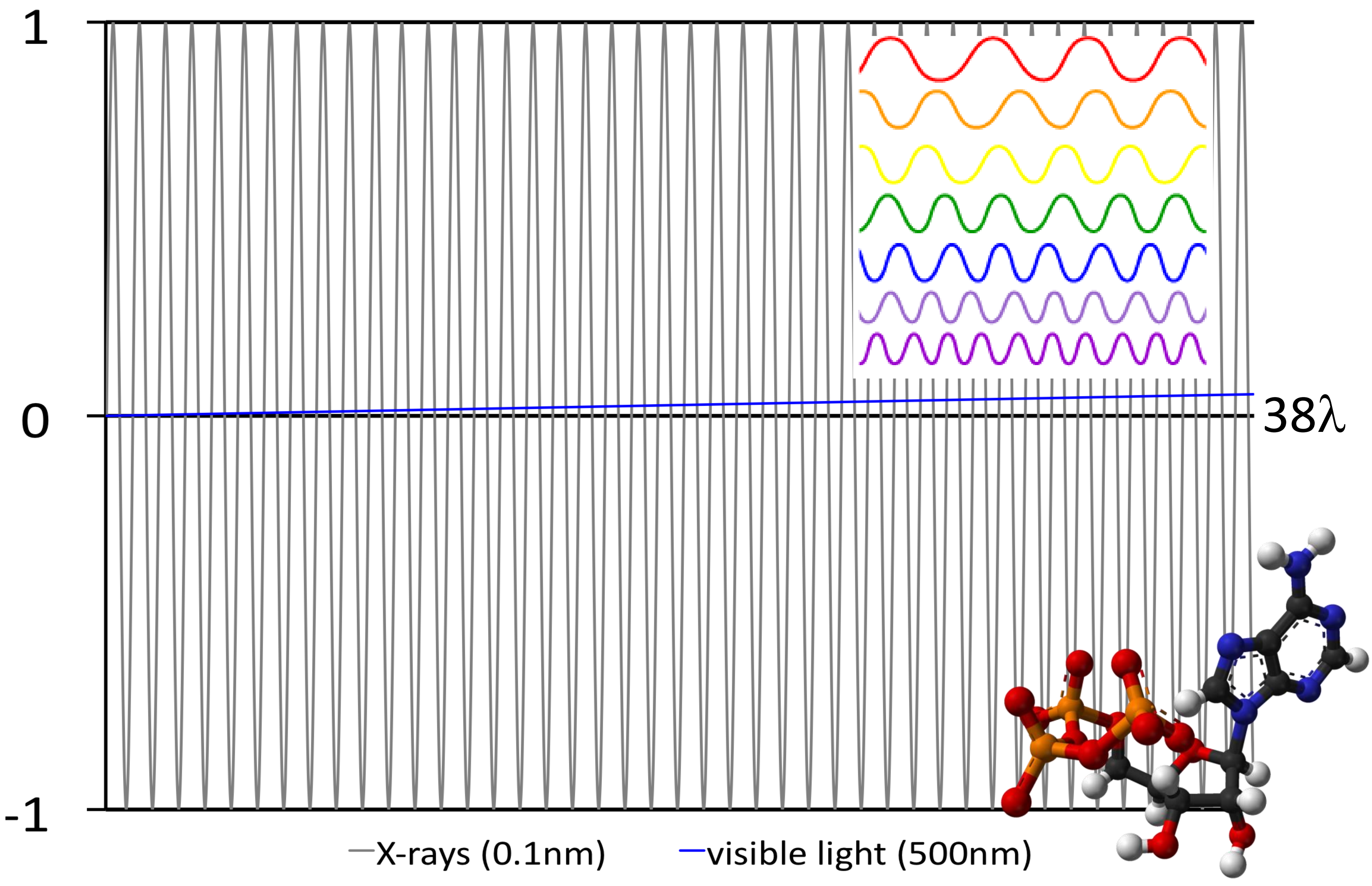
Figure 1.3 Virions of mimivirus, one of the largest viruses, and a parvovirus, one of the smallest viruses.

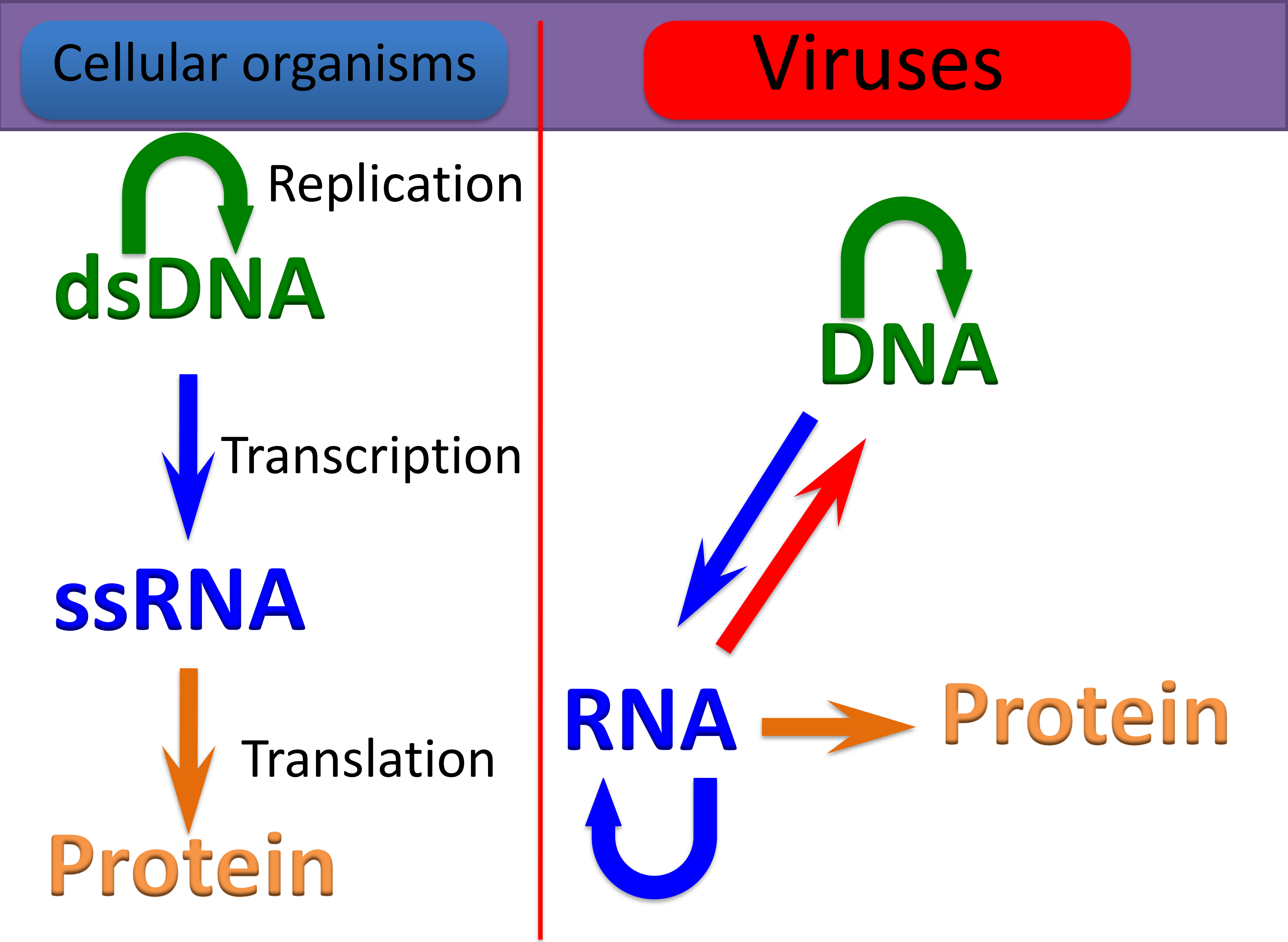
Wavelength and diffraction





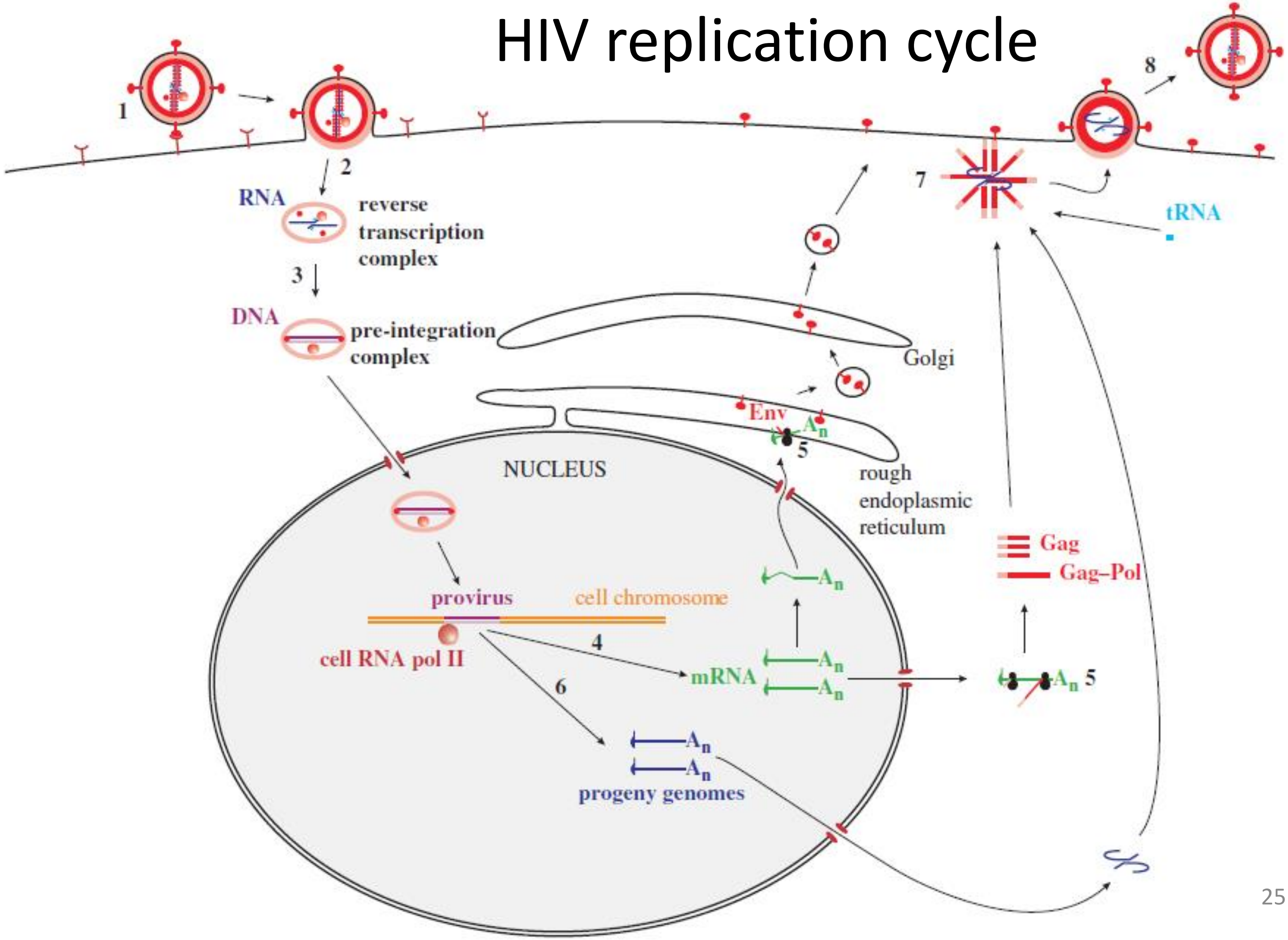
Wavelength comparison of X-rays and visible light




Cellular organisms
Viruses
Replication
dsDNA
Transcription
ssRNA
Translation
Protein
DNA
RNA
Protein

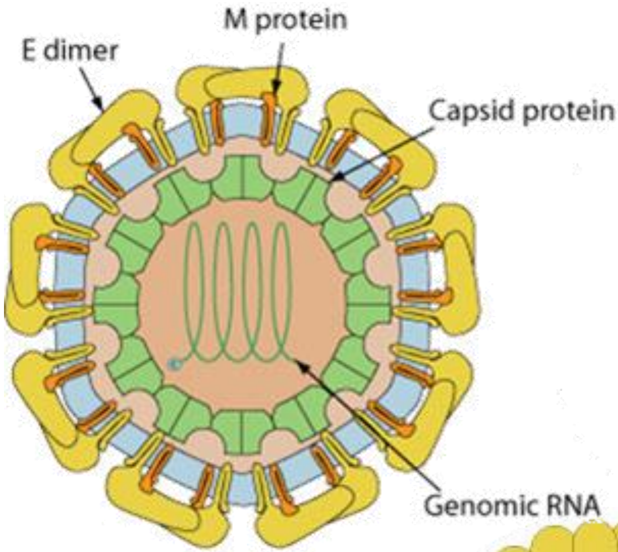
Viruses are intracellular parasites

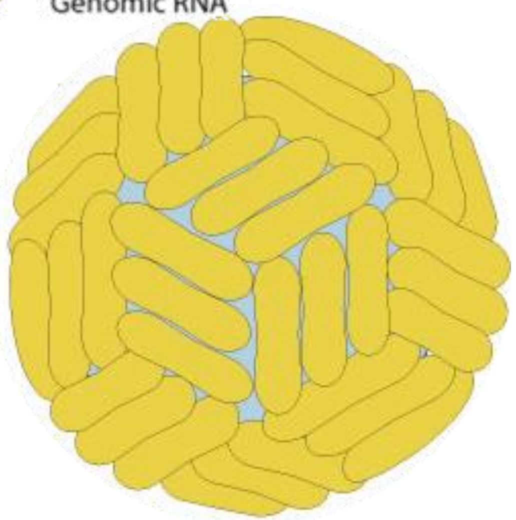
HIV replication cycle



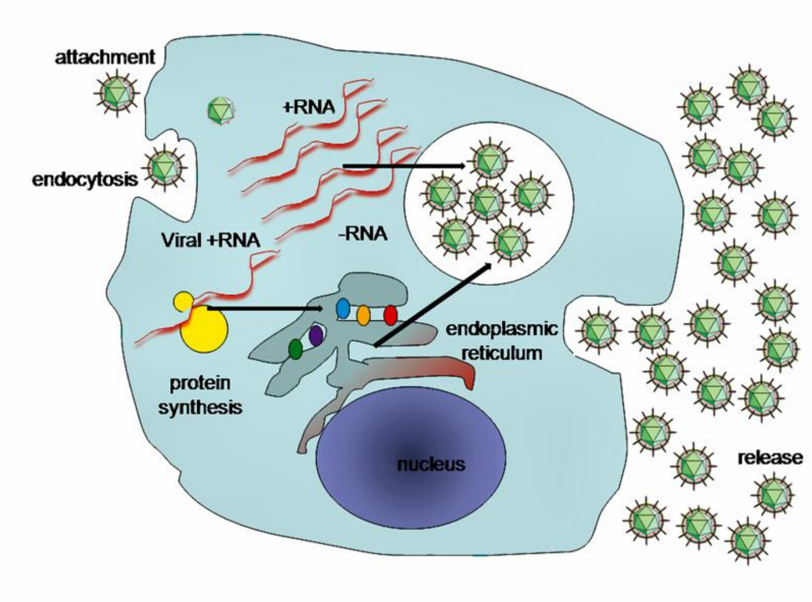
Two forms of virus existence

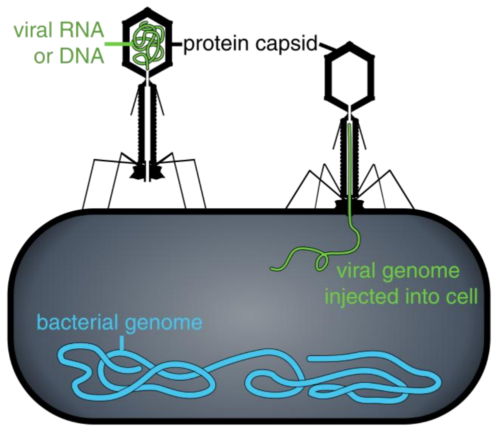
"Virion" – virus particle





Cell infection





Are viruses alive?

Pro-life	Anti-life
Have genes	Do not have cellular structure
They evolve	No metabolism
Subject to natural selection	Require host cell for pro-creation
Procreate	New viruses assemble from parts

Virus definition

A virus is a very small, non-cellular parasite of cells. Its genome, which is composed of either DNA or RNA, is enclosed in a protein coat.

Learning outcomes

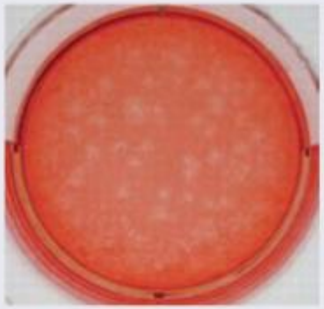
- discuss reasons for studying viruses
- explain how viruses differ from other

organisms

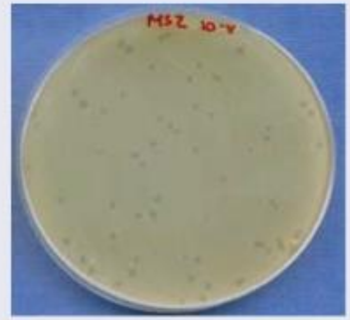
- define the term ‘virus’

Methods used in virology

Virus Isolation and Culture



Animal virus plaques in a cell culture [1]

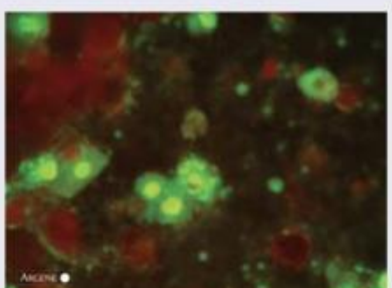


Phage plaques in a lawn of bacterial cells [2]

Density Gradient Centrifugation

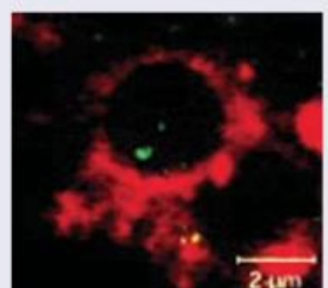
Separation of virus particles in a density gradient [3]

Fluorescence Microscopy



Virus-infected cells detected using a virus-specific antibody labelled with a fluorescent dye [4]

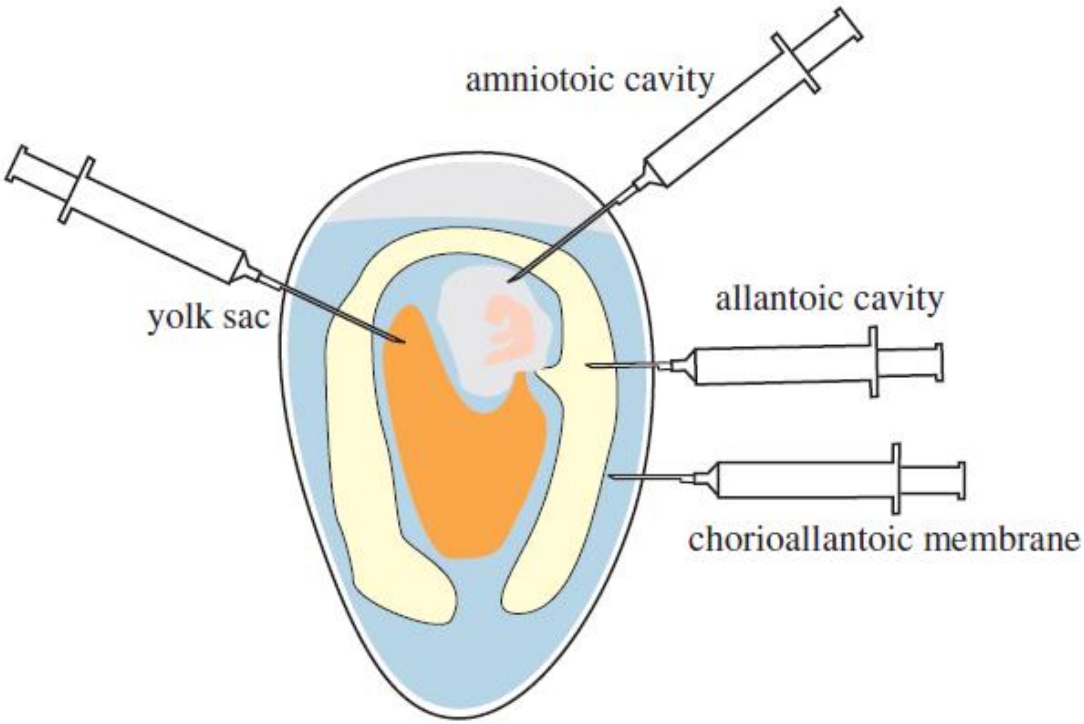
Confocal Microscopy



An endosome (labelled red) containing virus protein (labelled green) in an infected cell [5]

Virus production in eggs

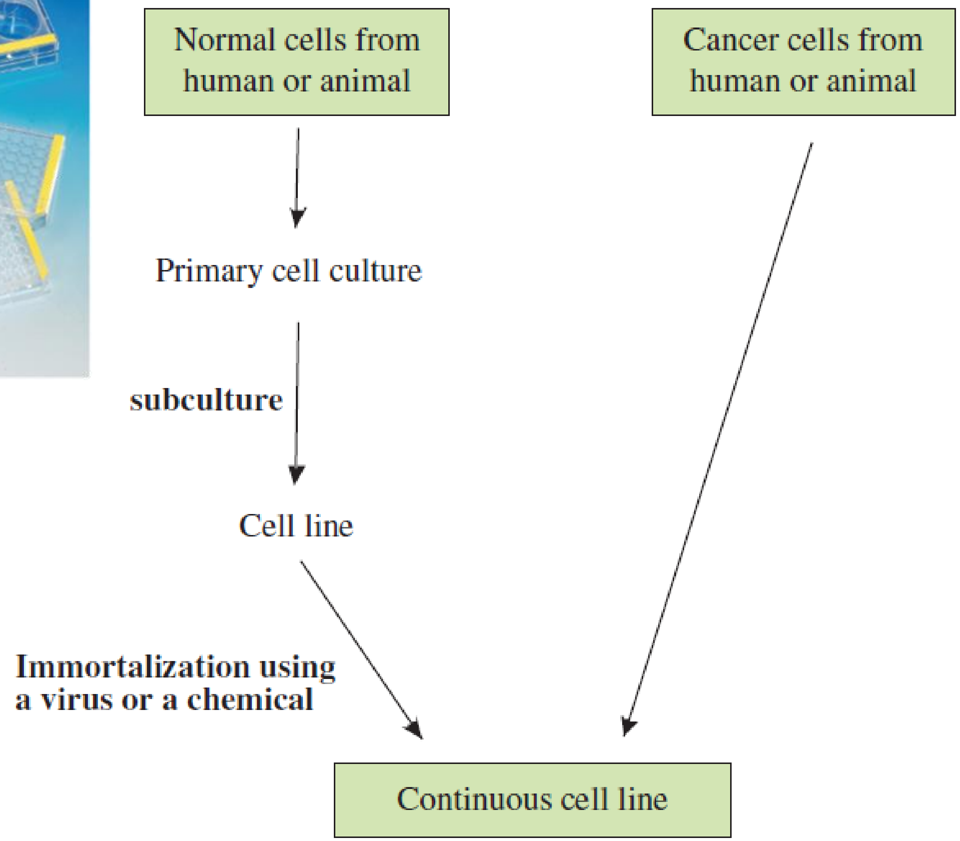
Sites into which viruses can be inoculated



Inoculation of an egg

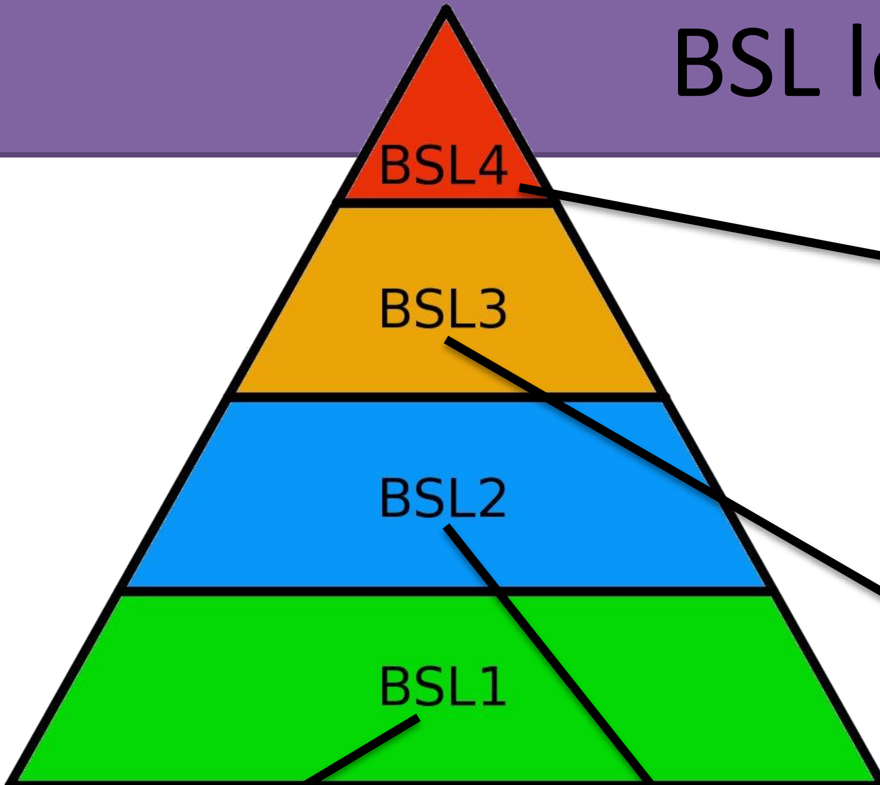
Virus production honeybee pupae

Virus production in vitro in tissue culture

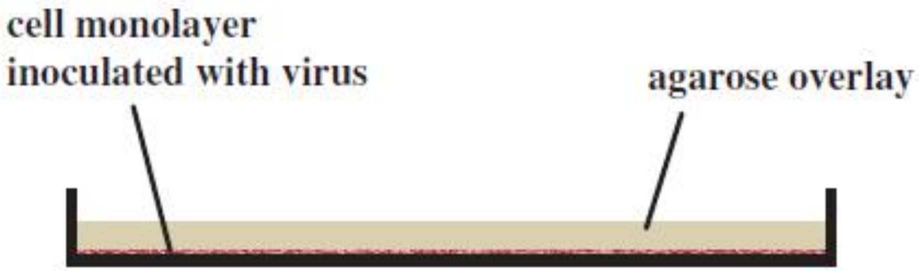


Sterile work with tissue cultures

BSL levels

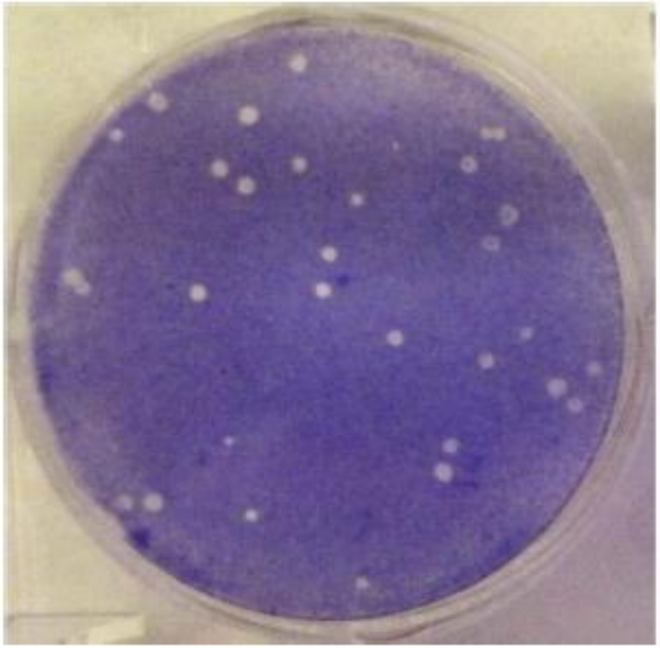


Plaque assay for animal viruses



A cell monolayer is inoculated with virus and overlaid with agarose.

Plaques formed by influenza virus in a cell monolayer



HeLa 300 tis bb./ml, 10.2.14
Fixed after 72h
BEST OF CMC

HRV16 from stock 28.11.13,
PFU 5.10^3

Phage plaque assay

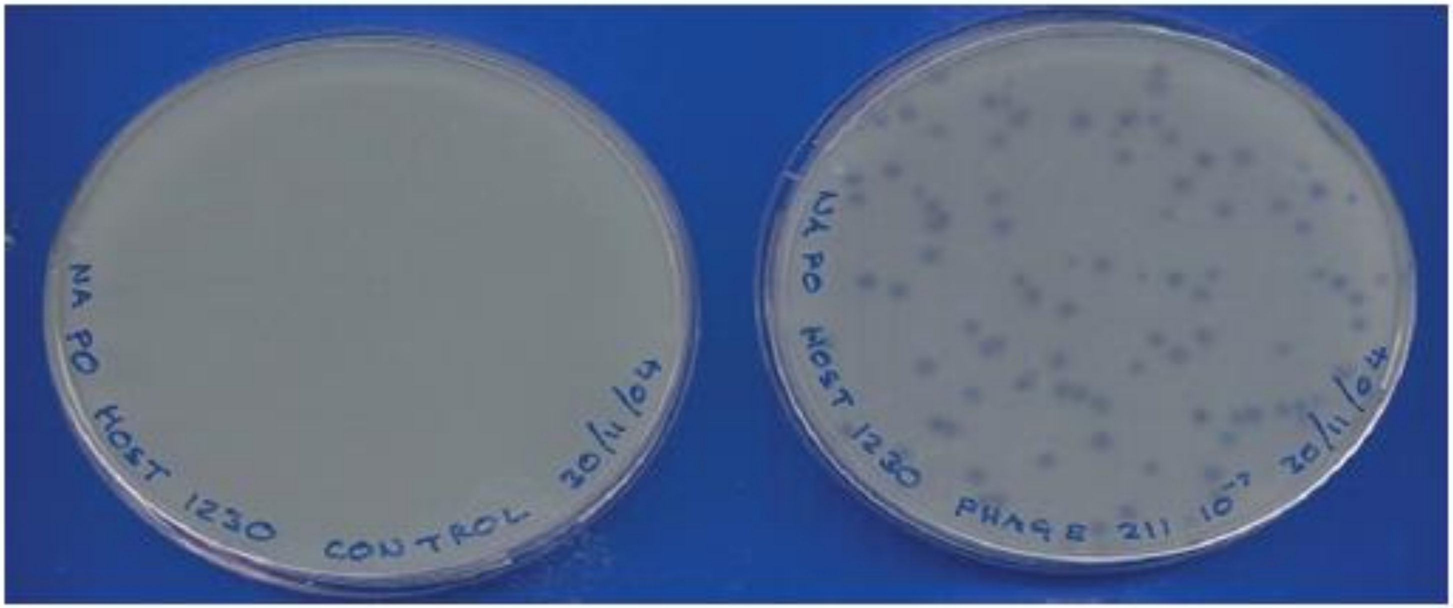
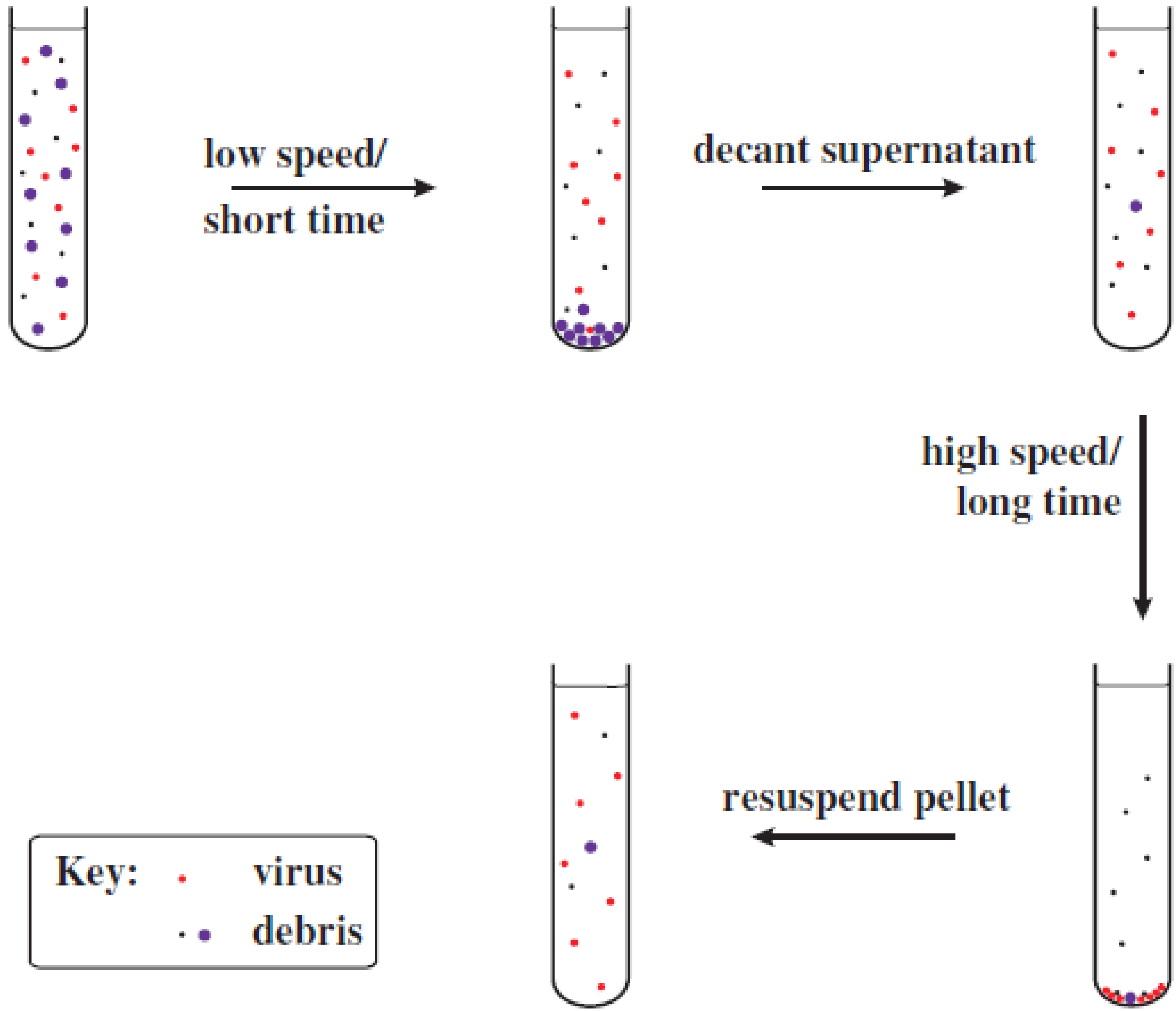
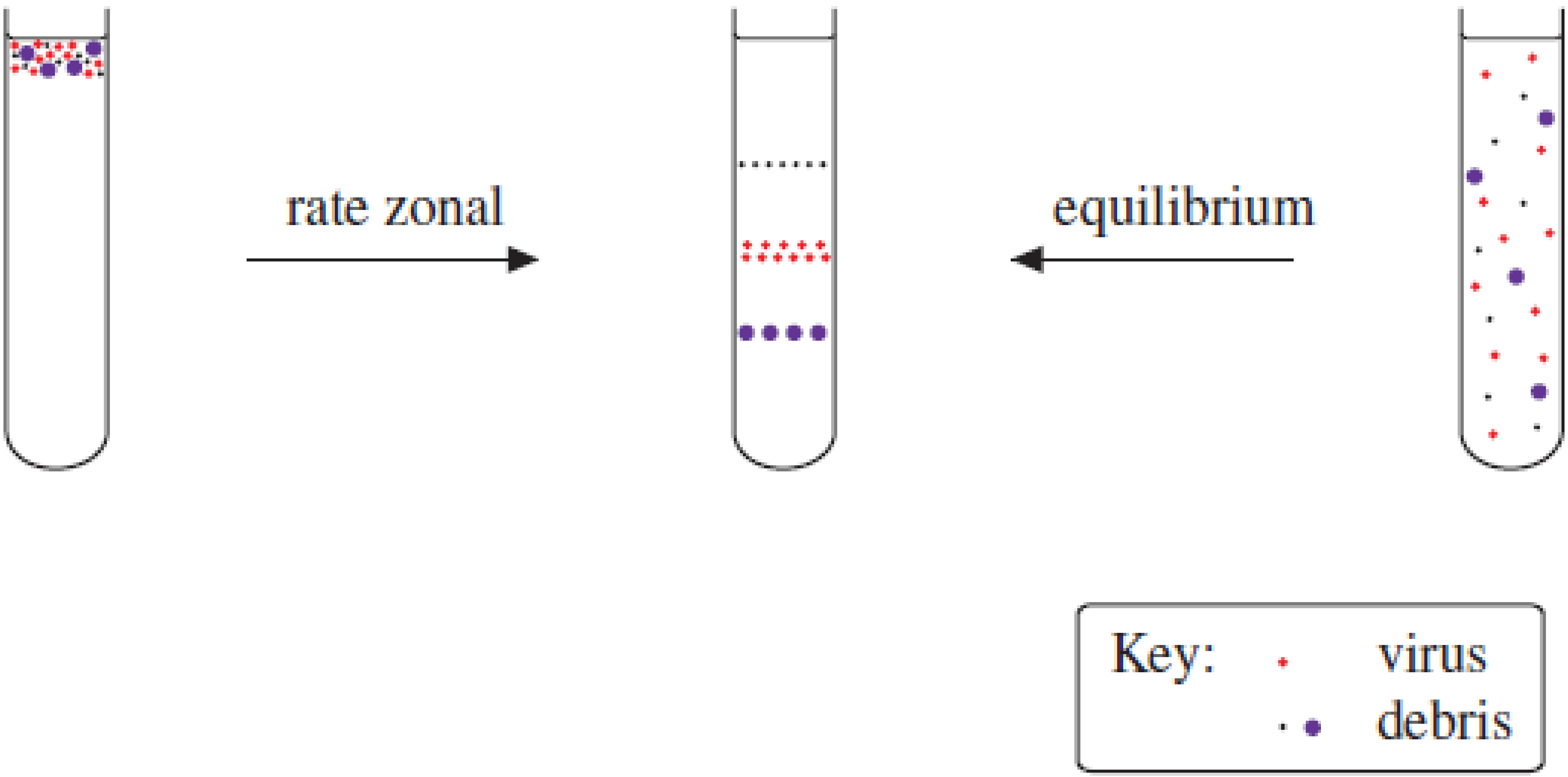


Figure 2.6 Plaques formed by a phage in a bacterial lawn. The control plate on the left was inoculated with only the bacterial host. The plate on the right was inoculated with phage and bacterial host.

Differential centrifugation



Density gradient centrifugation



SDS-PAGE

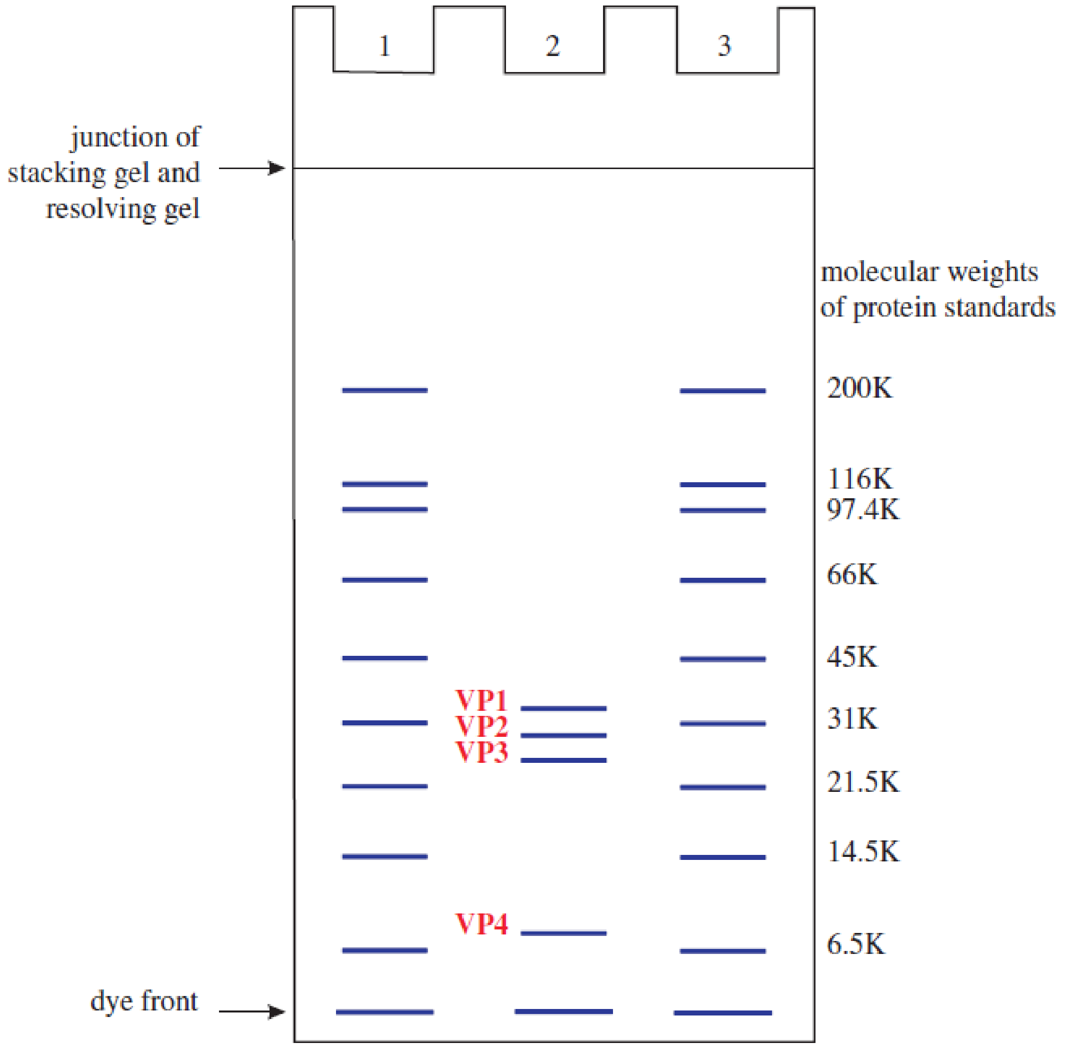
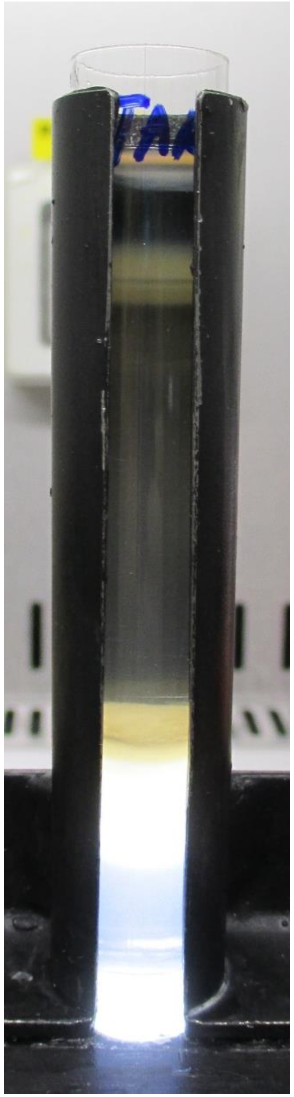
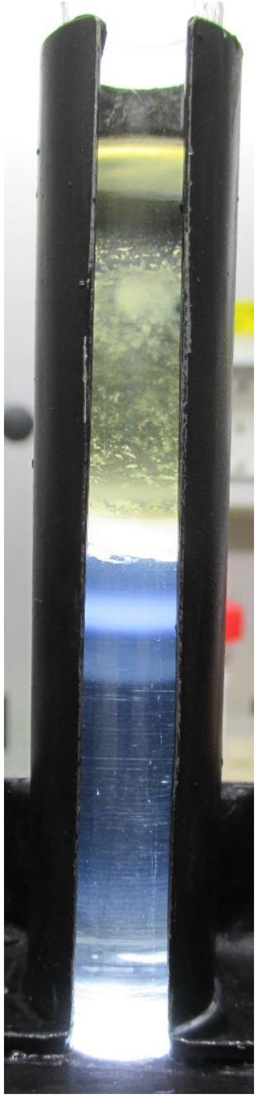


Figure 2.9 Diagram illustrating separation of proteins and estimation of their molecular weights using SDS-PAGE. Lanes 1 and 3 contain standard proteins of known molecular weight. Lane 2 contains the four capsid proteins of a picornavirus.

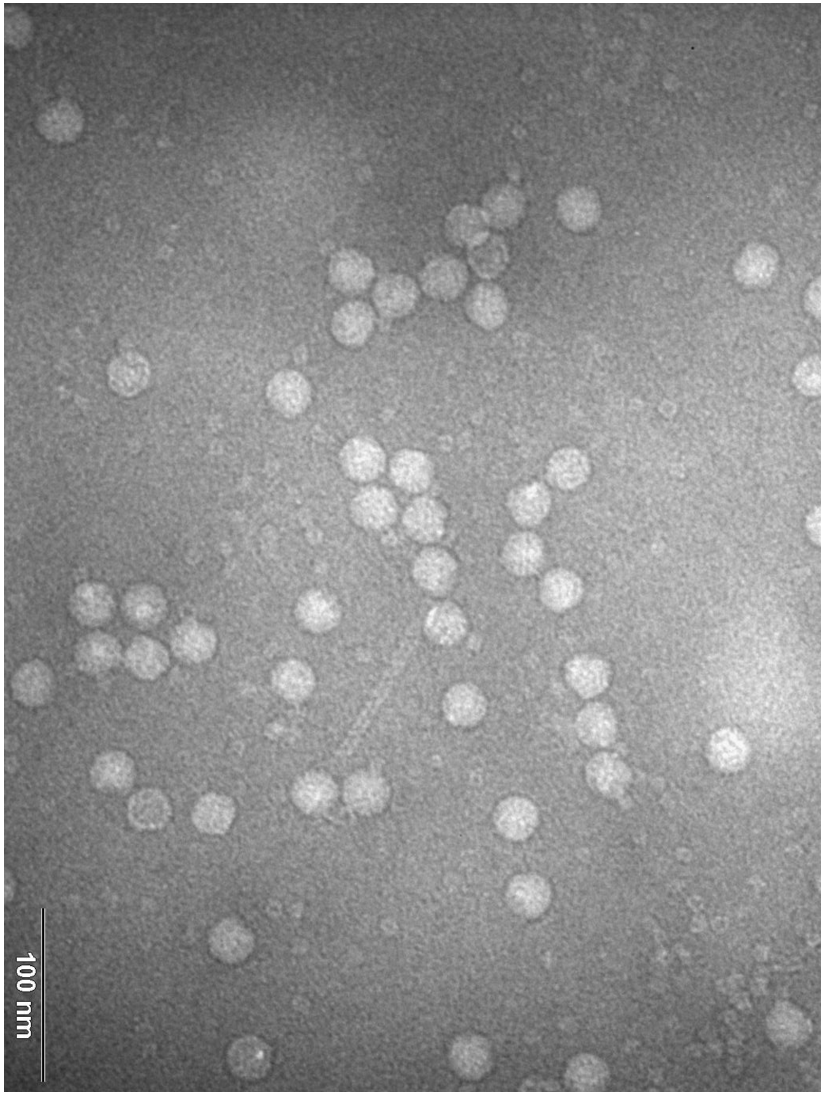
Israeli acute bee paralysis virus



tartrate gradient

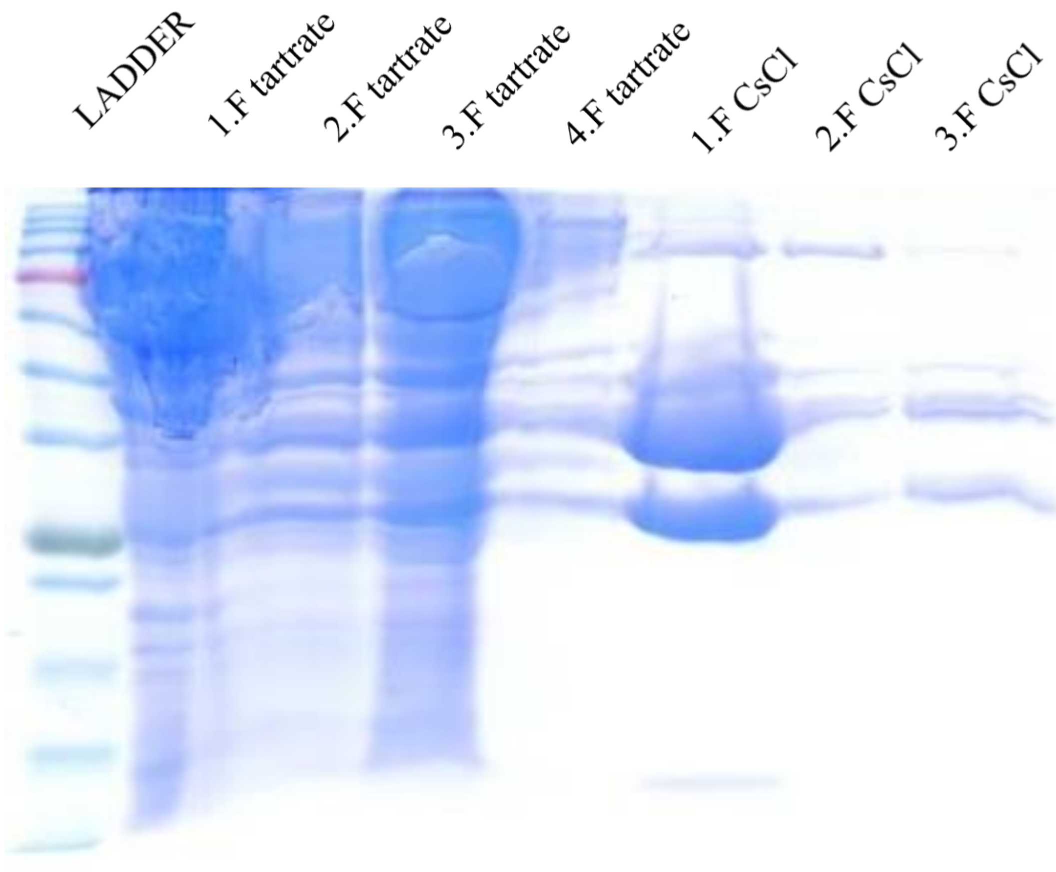


CsCl gradient



CsCl gradient – middle fraction

SDS-PAGE of IAPV

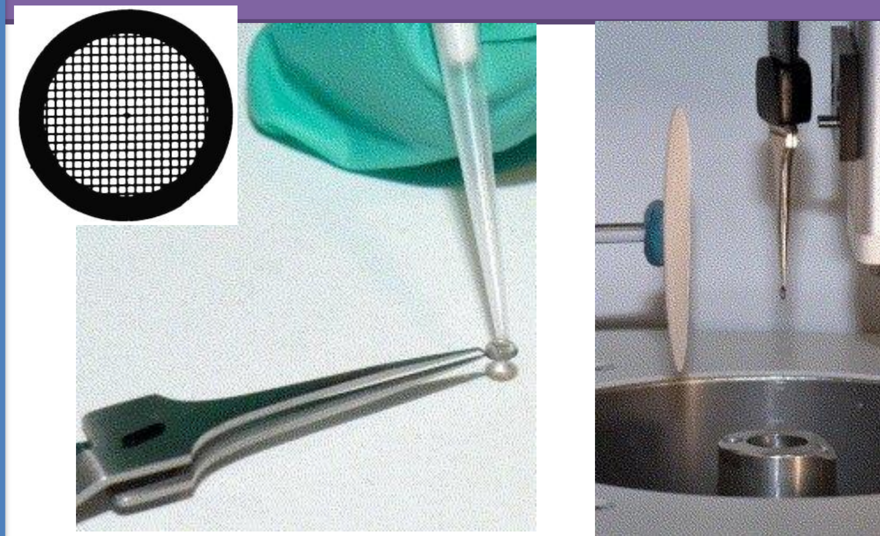


1.F tartrate A_{260}=133.083, A_{280} = 160.379
2.F tartrate A_{260}=36.575, A_{280} = 28.762
3.F tartrate A_{260}=86.795, A_{280} = 70.081
4.F tartrate A_{260}=10.029, A_{280} = 6.267

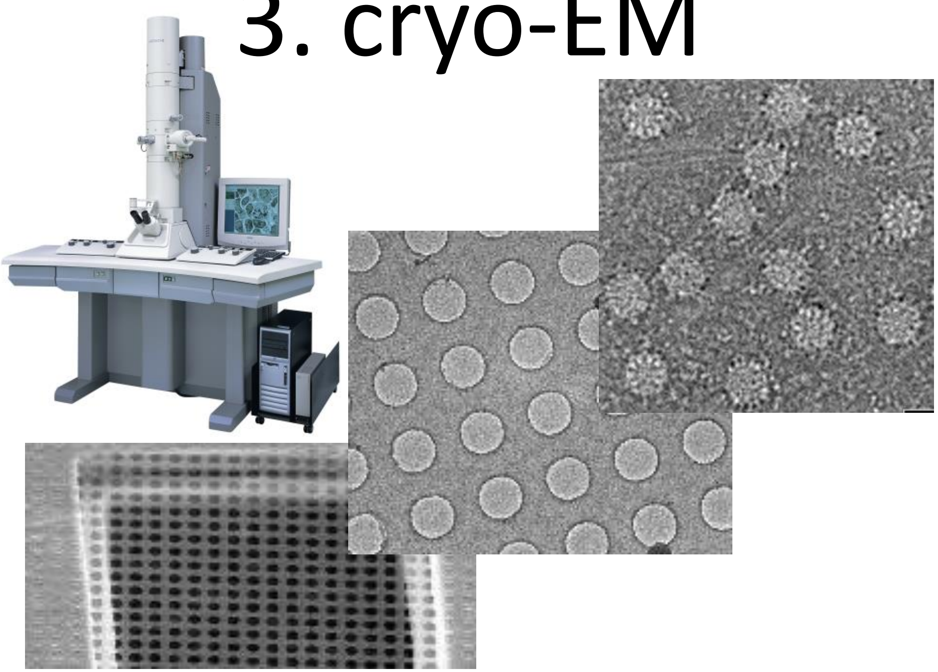
1.F CsCl A_{260}=111.613, A_{280} = 63.564
1.F CsCl A_{260}=2.555, A_{280} = 1.556
1.F CsCl A_{260}=6.836, A_{280} = 3.918

1. Virus purification

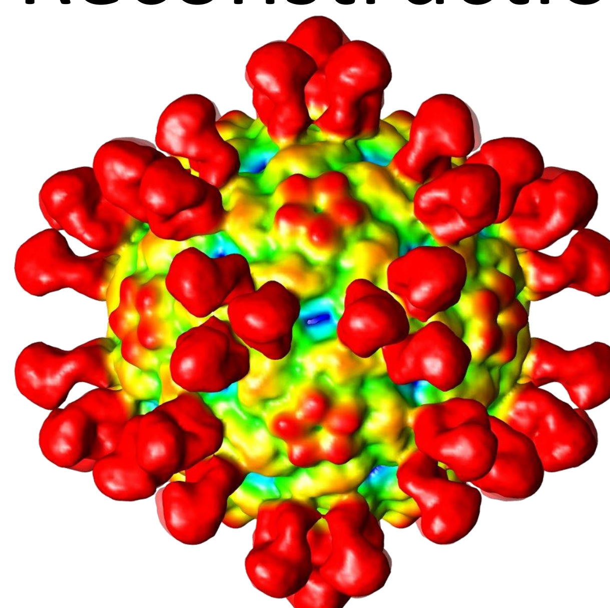
2. Grid preparation



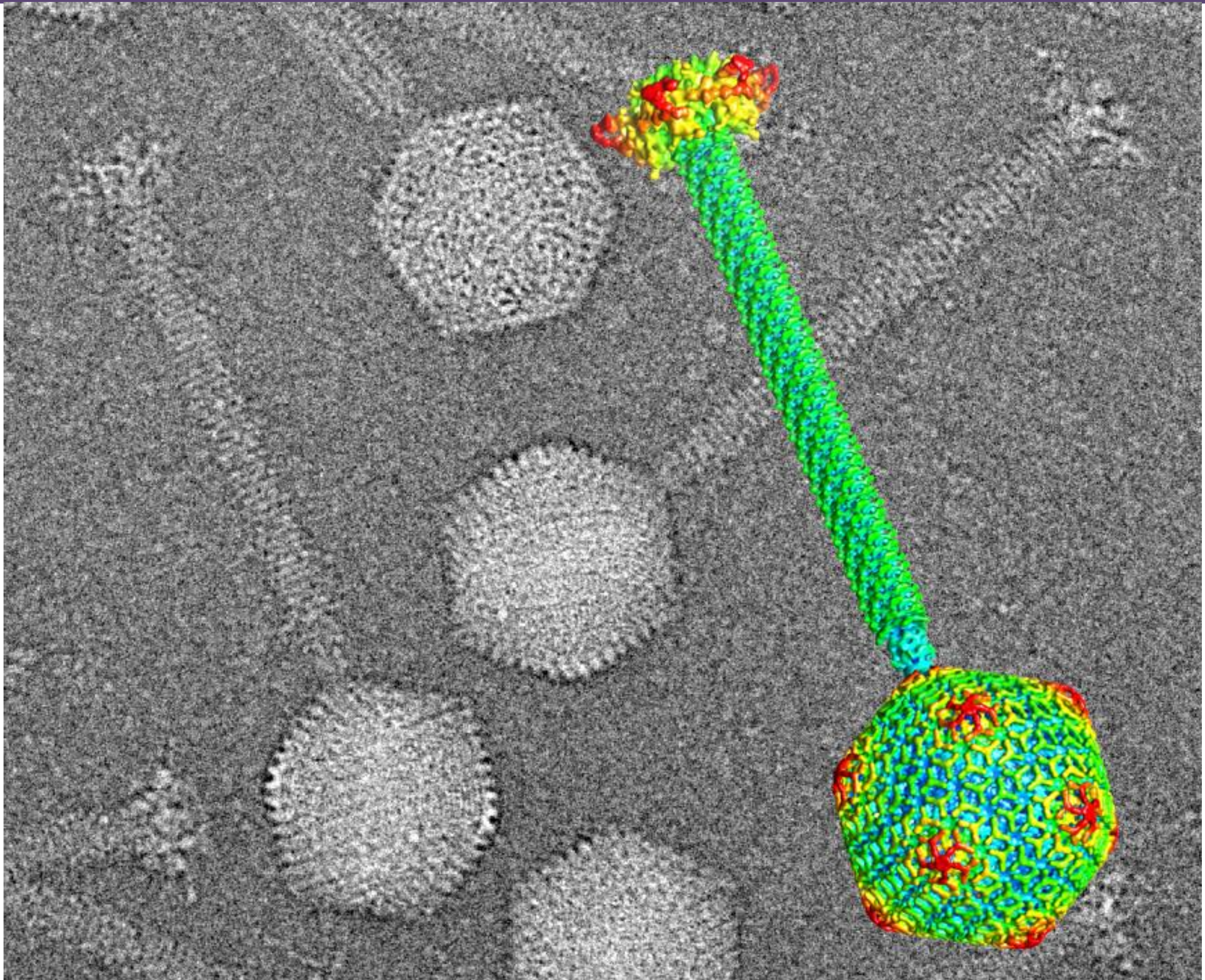
3. cryo-EM



4. Reconstruction

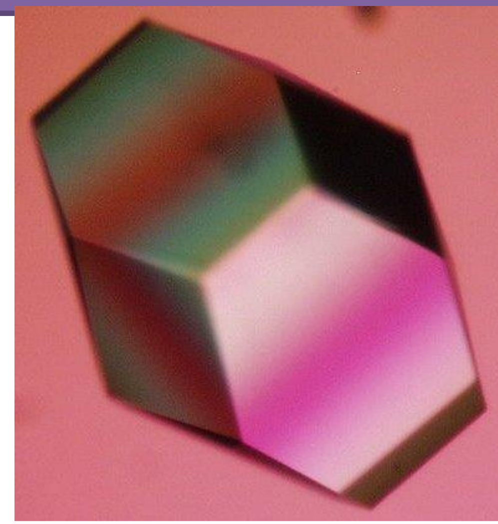


Cryo-EM of phage phi812

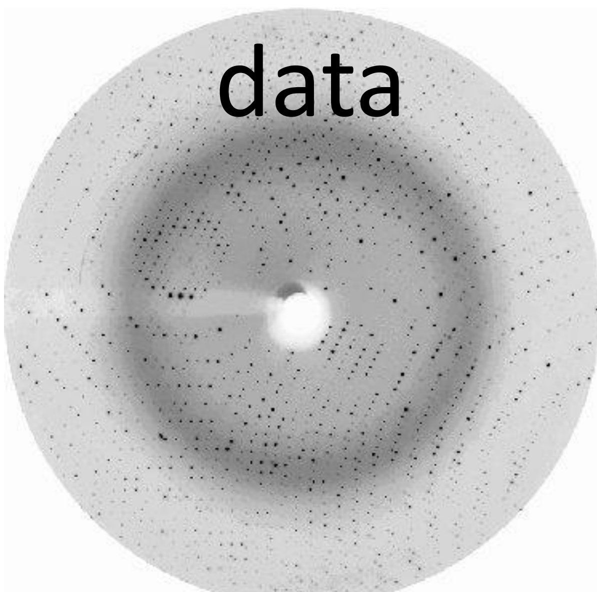


1. Virus purification

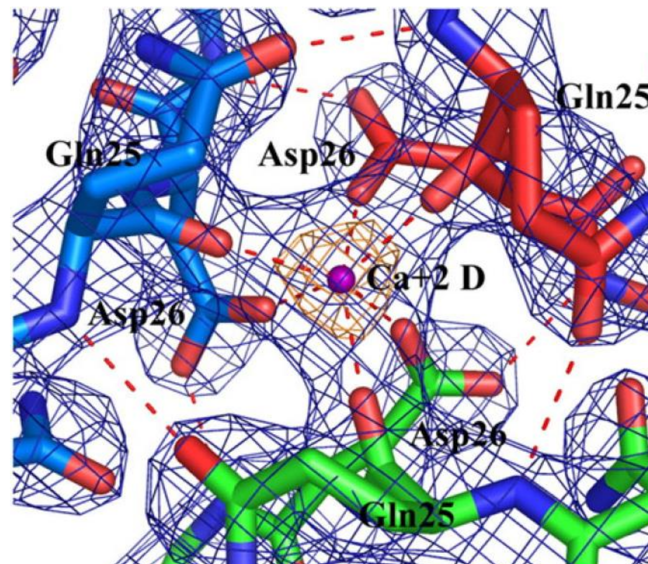
2. Crystallization



3. Diffraction data

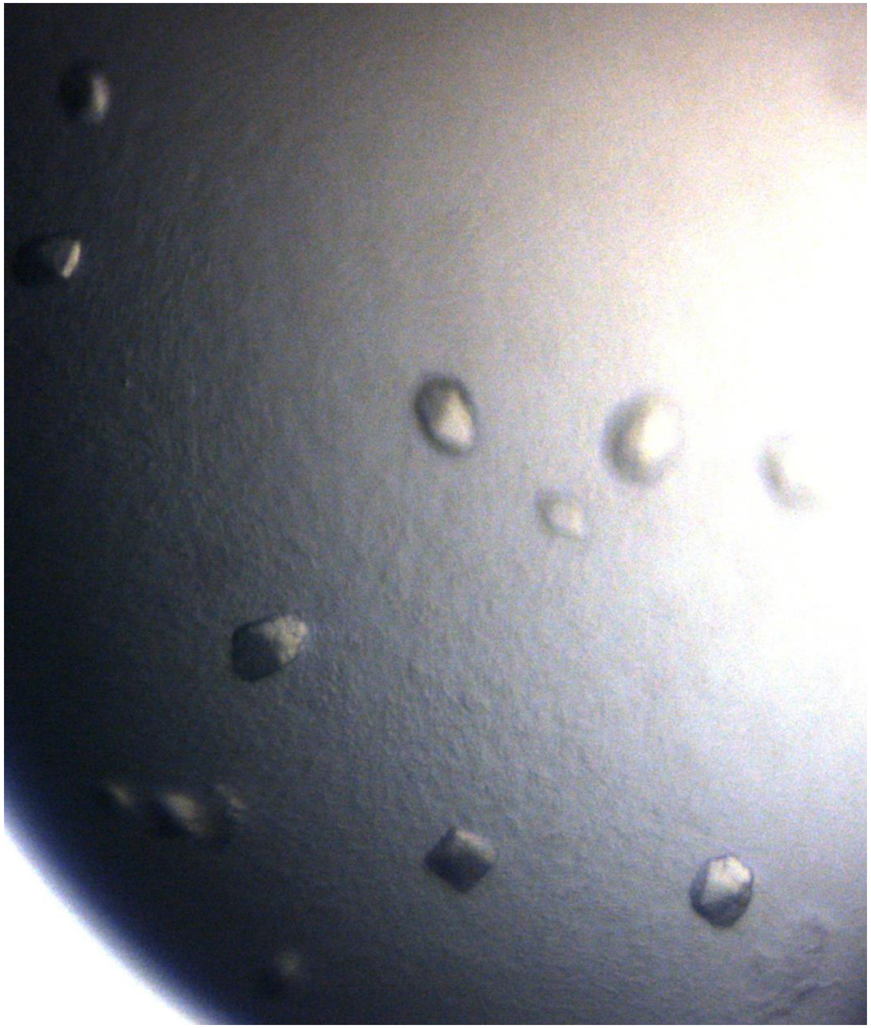


4. Solve structure

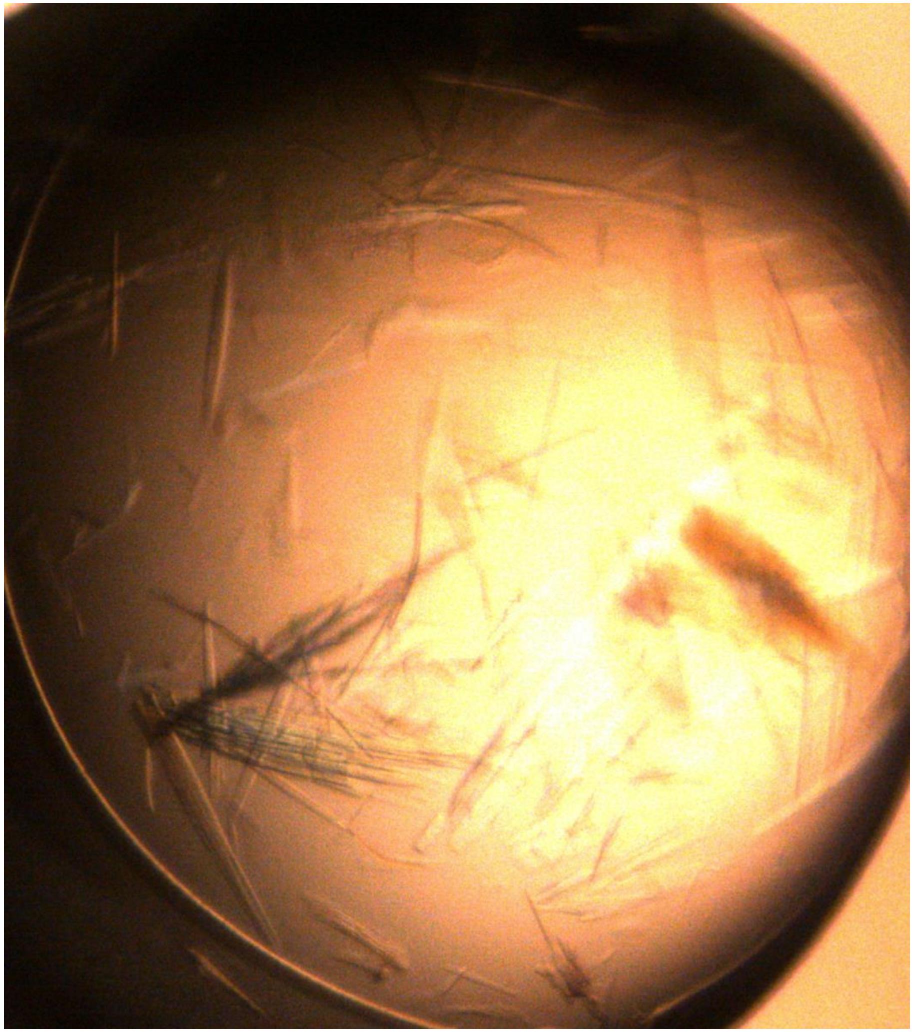


Crystals of IAPV

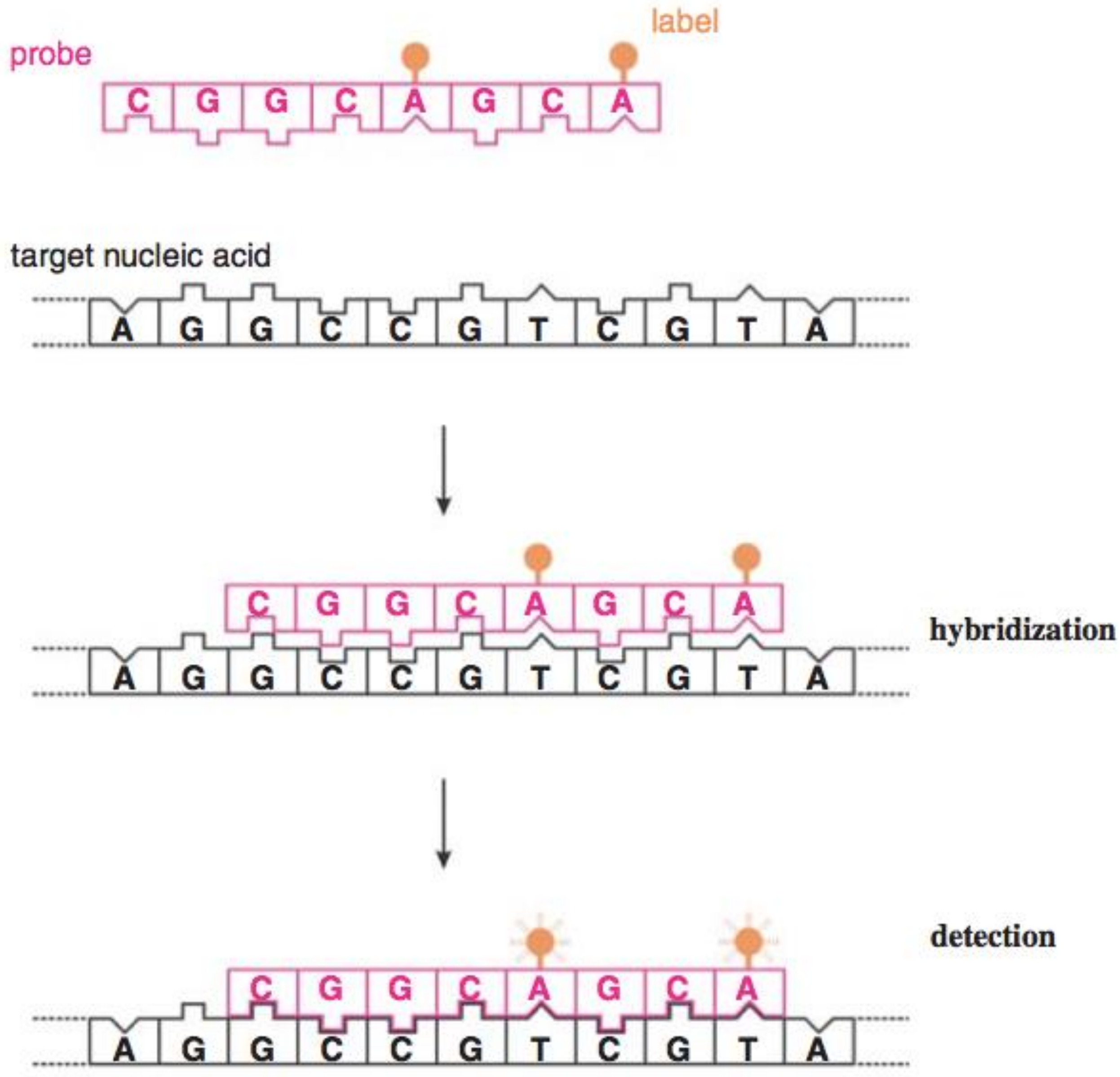
0.1 M Cadmium Chloride
0.1 M Na acetate pH 4.5
15 % PEG 400



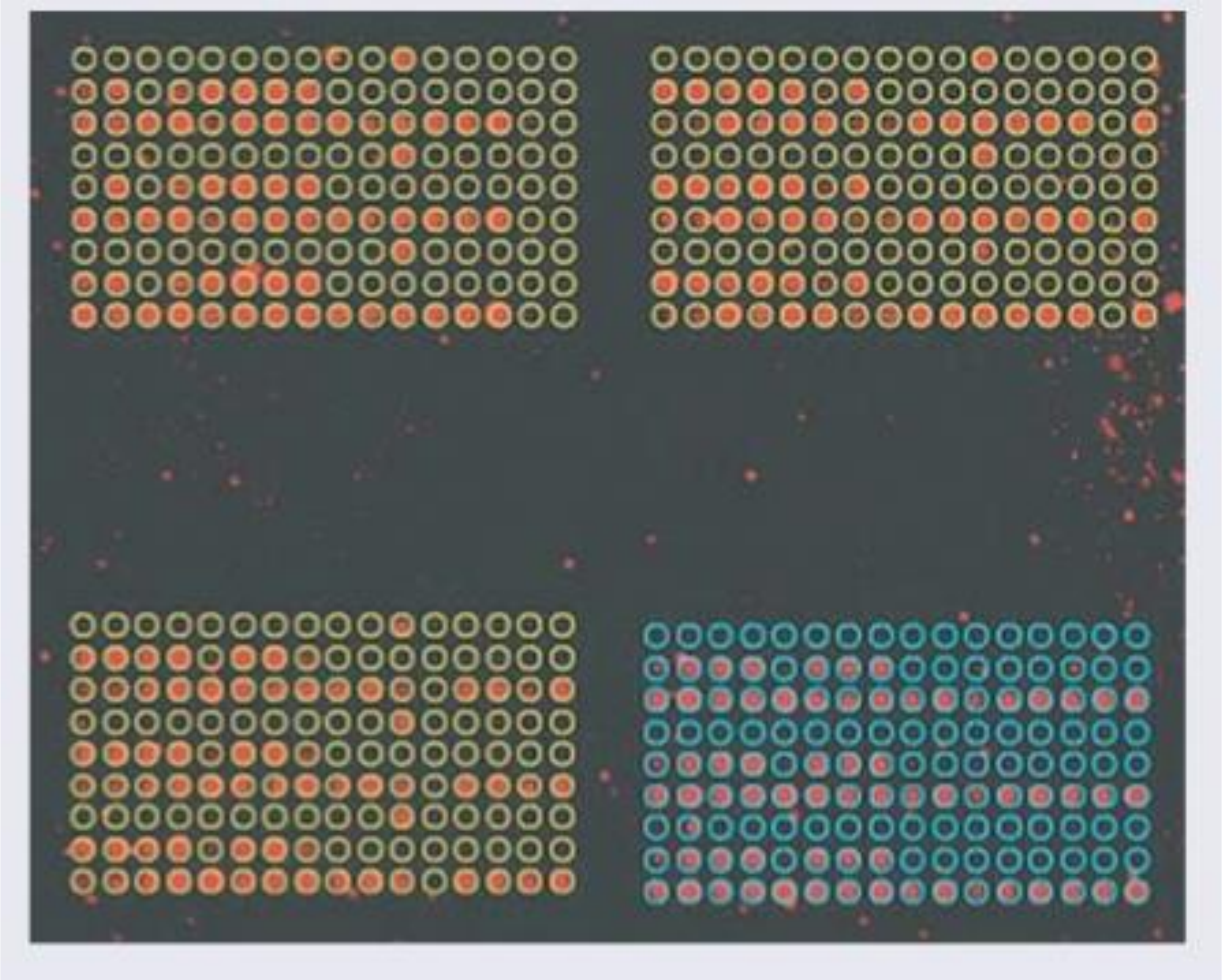
0.2 M Na/K Phosphate
0.1 M BisTris Propane pH 7.5
20 % PEG (w/v)3350



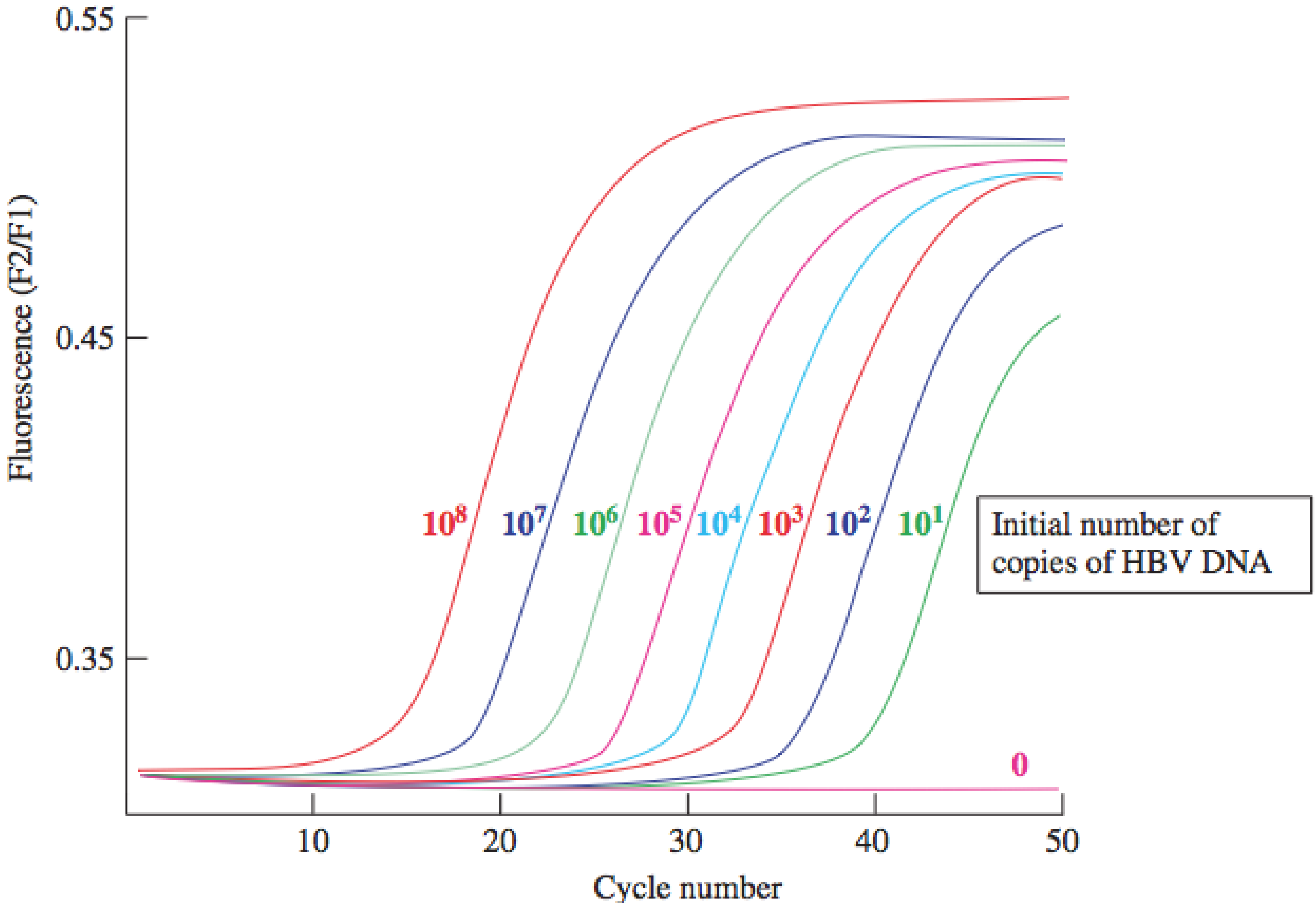
Hybridization detection of nucleic acids



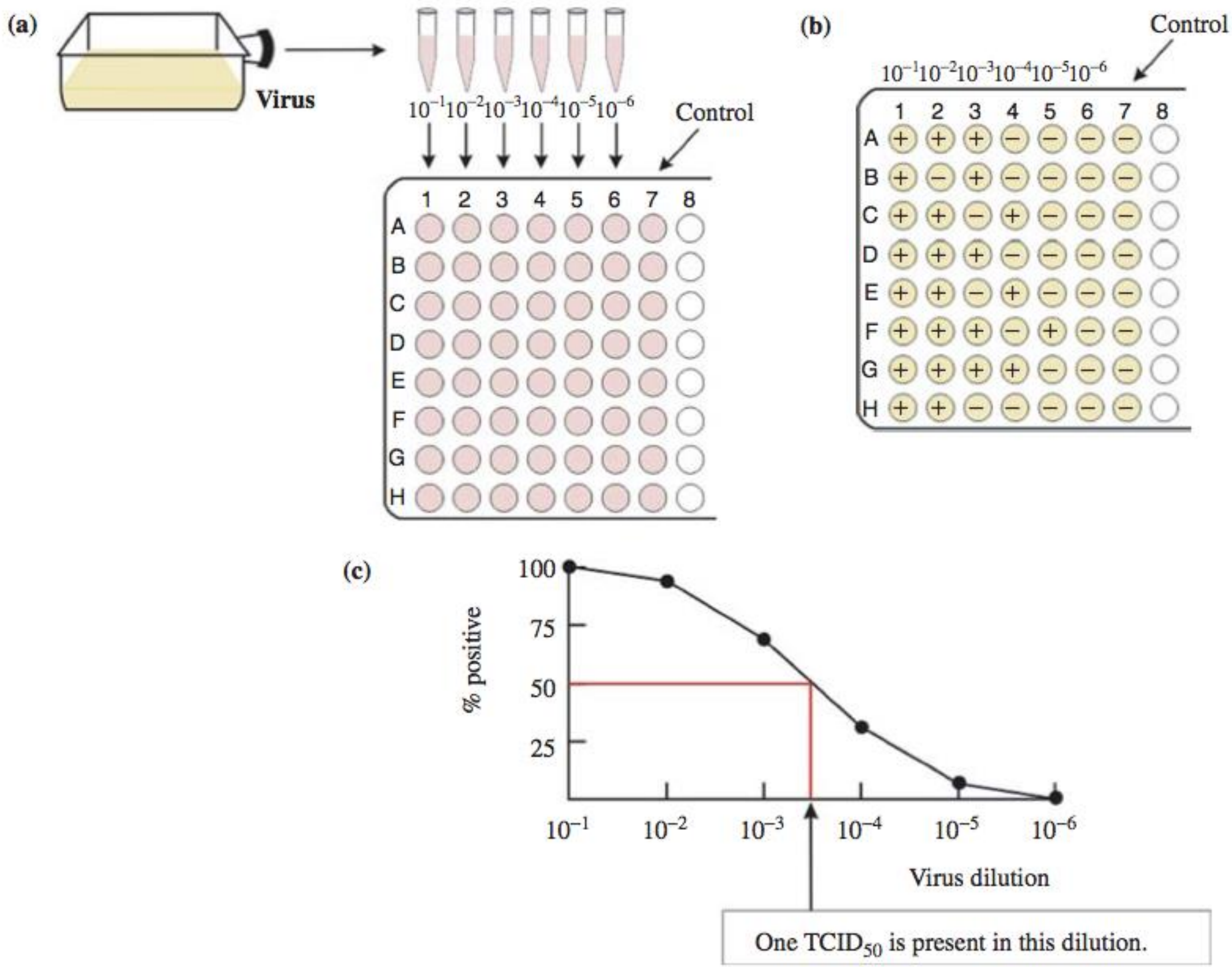
Microarrays



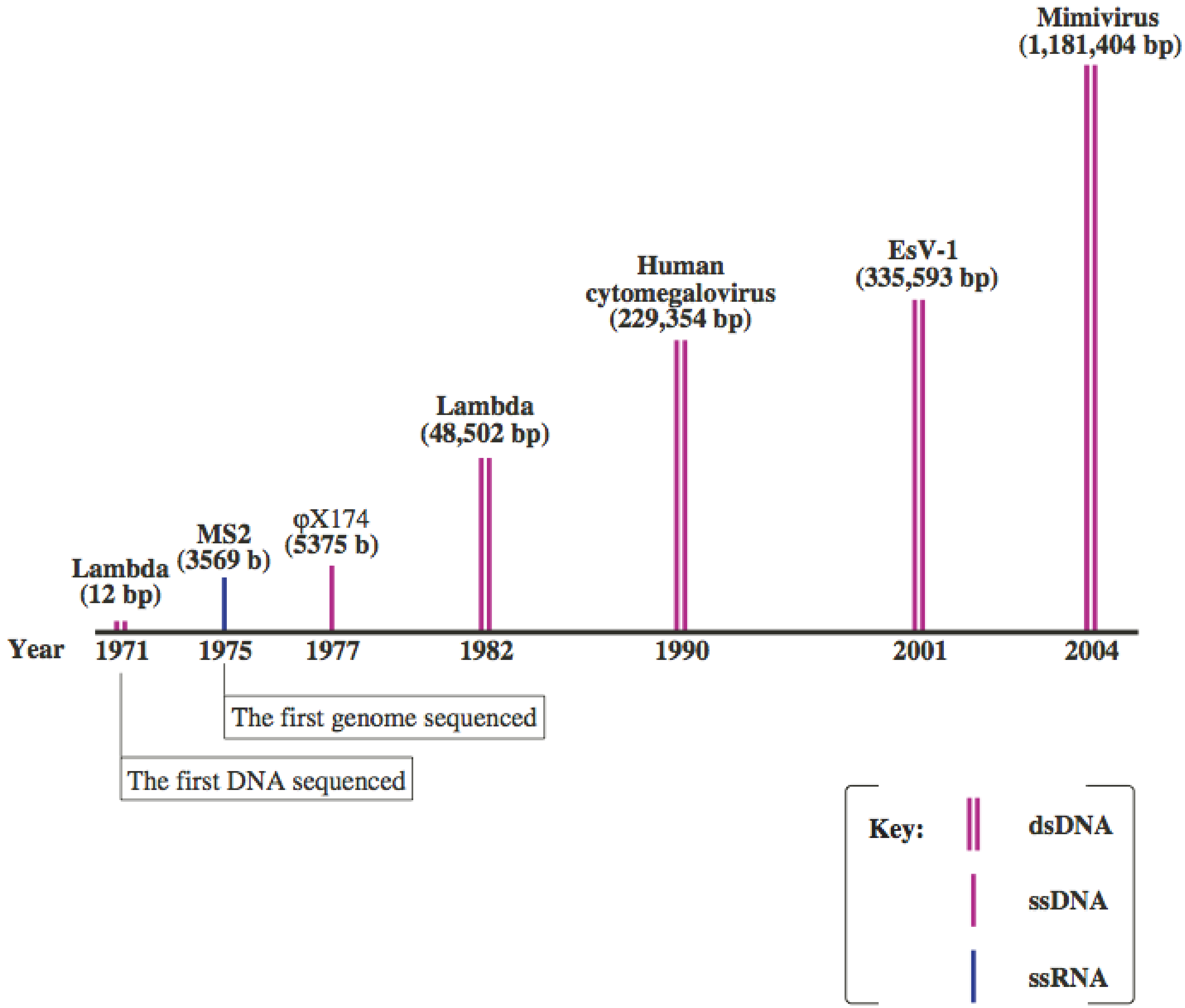
rtPCR assay


0.55
0.45
0.35
Fluorescence (F2/F1)
10
20
30
40
50
Cycle number
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0
Initial number of copies of HBV DNA

TCID$_{50}$ assay



Sequencing of virus genomes

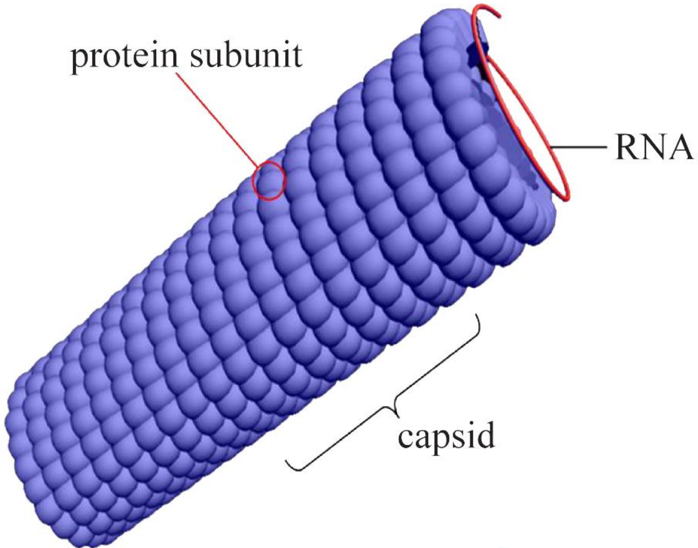


Learning outcomes

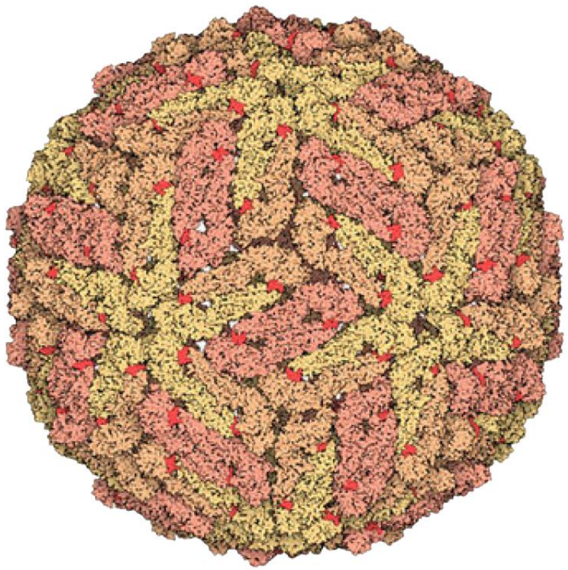
- outline methods for
  - cultivation of viruses;
  - purification of viruses;
  - detection of viruses and their components;
  - assay of virus infectivity;
  - investigation of virus gene function;
- assess the value of virus genome sequencing.

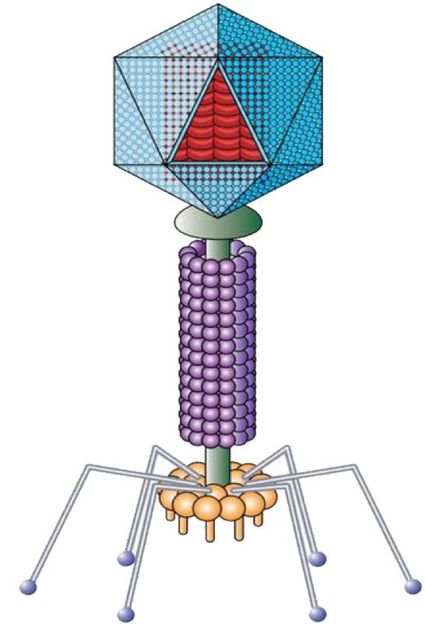
Virus structures

Helical

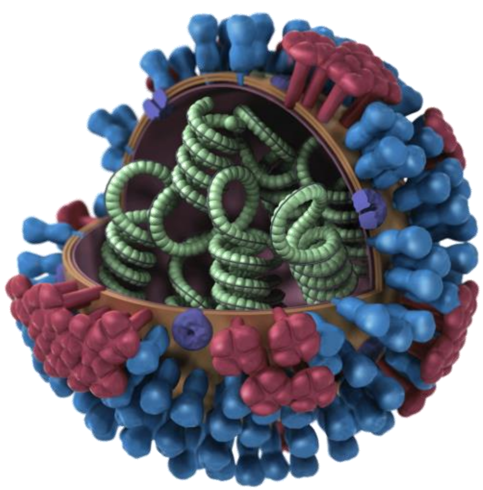


Icosahedral

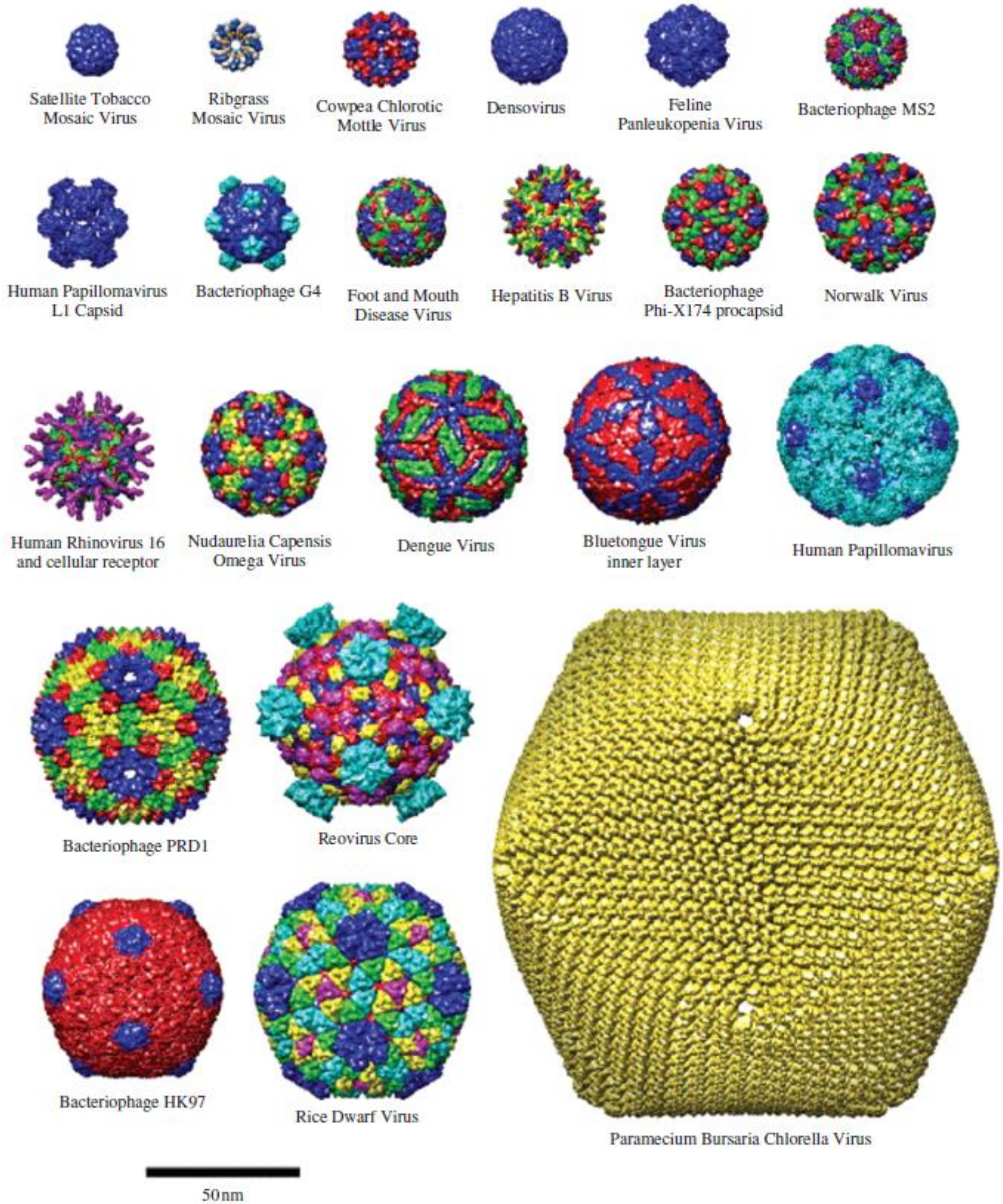




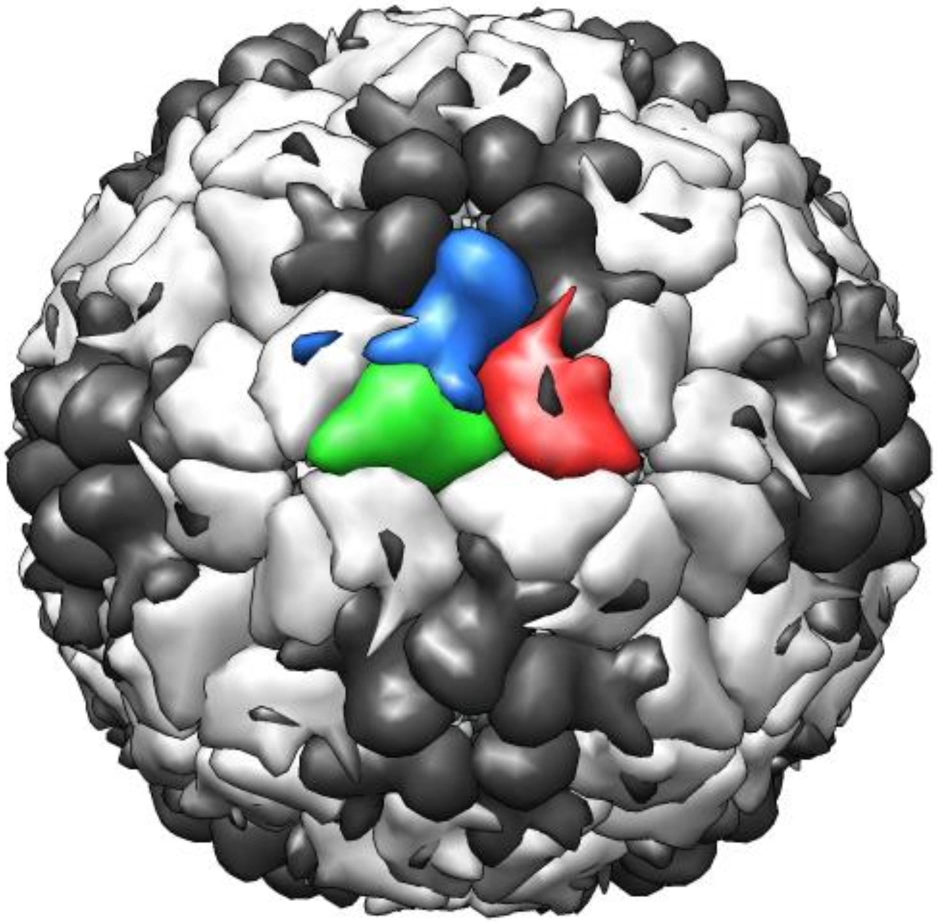
Complex



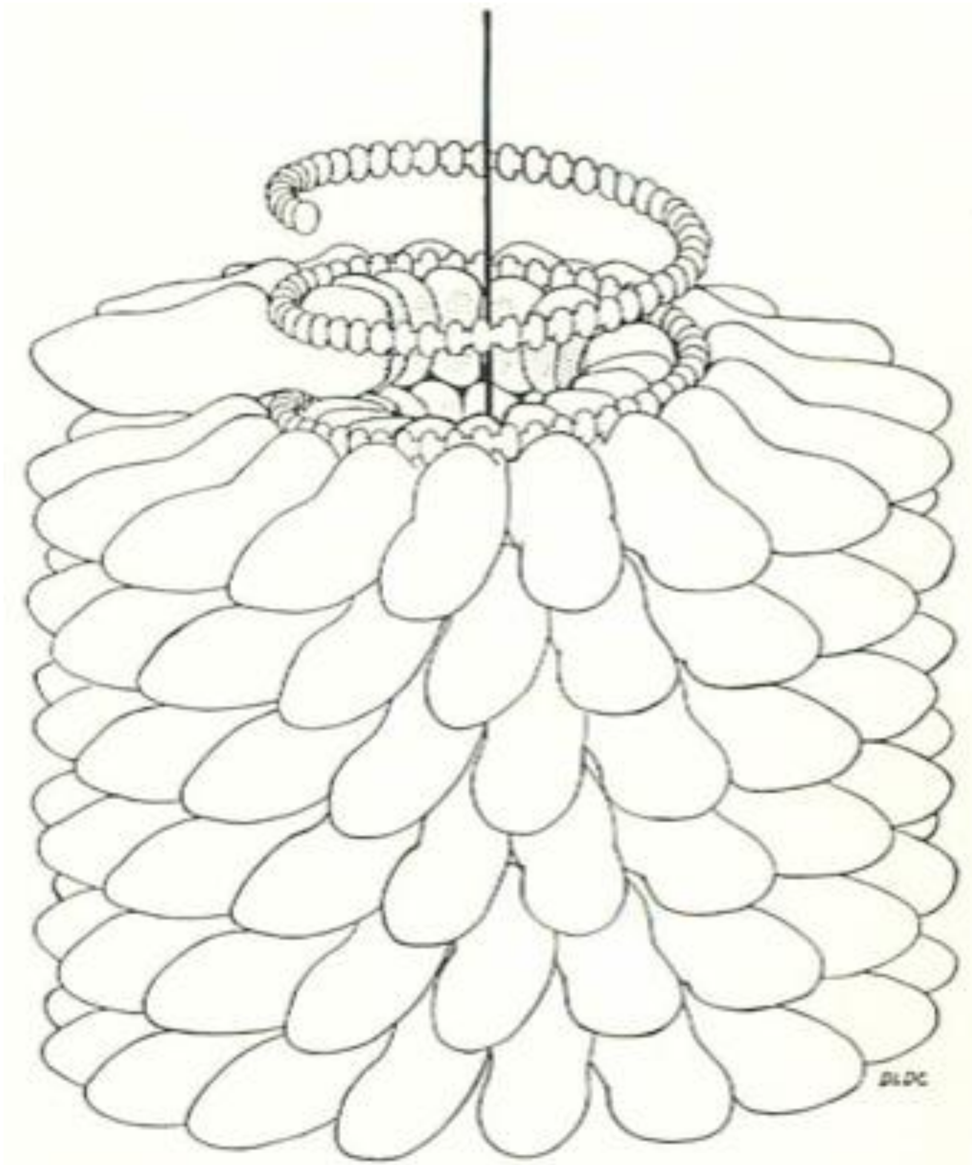
Irregular

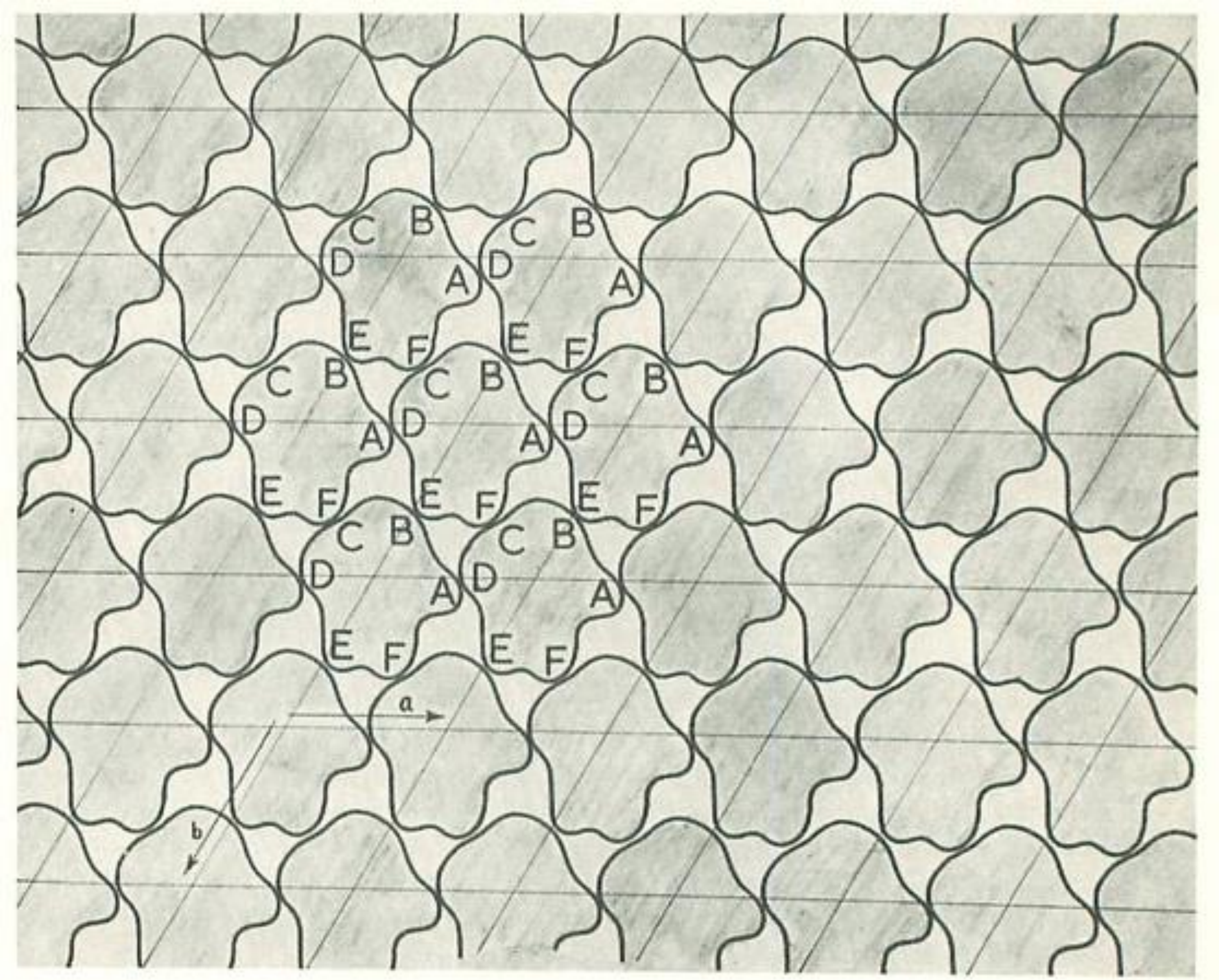

Satellite Tobacco Mosaic Virus
Ribgrass Mosaic Virus
Cowpea Chlorotic Mottle Virus
Densovirus
Feline Panleukopenia Virus
Bacteriophage MS2
Human Papillomavirus L1 Capsid
Bacteriophage G4
Foot and Mouth Disease Virus
Hepatitis B Virus
Bacteriophage Phi-X174 procapsid
Norwalk Virus
Human Rhinovirus 16 and cellular receptor
Nudaurelia Capensis Omega Virus
Dengue Virus
Bluetongue Virus inner layer
Human Papillomavirus
Bacteriophage PRD1
Reovirus Core
Paramecium Bursaria Chlorella Virus
Bacteriophage HK97
Rice Dwarf Virus
50nm

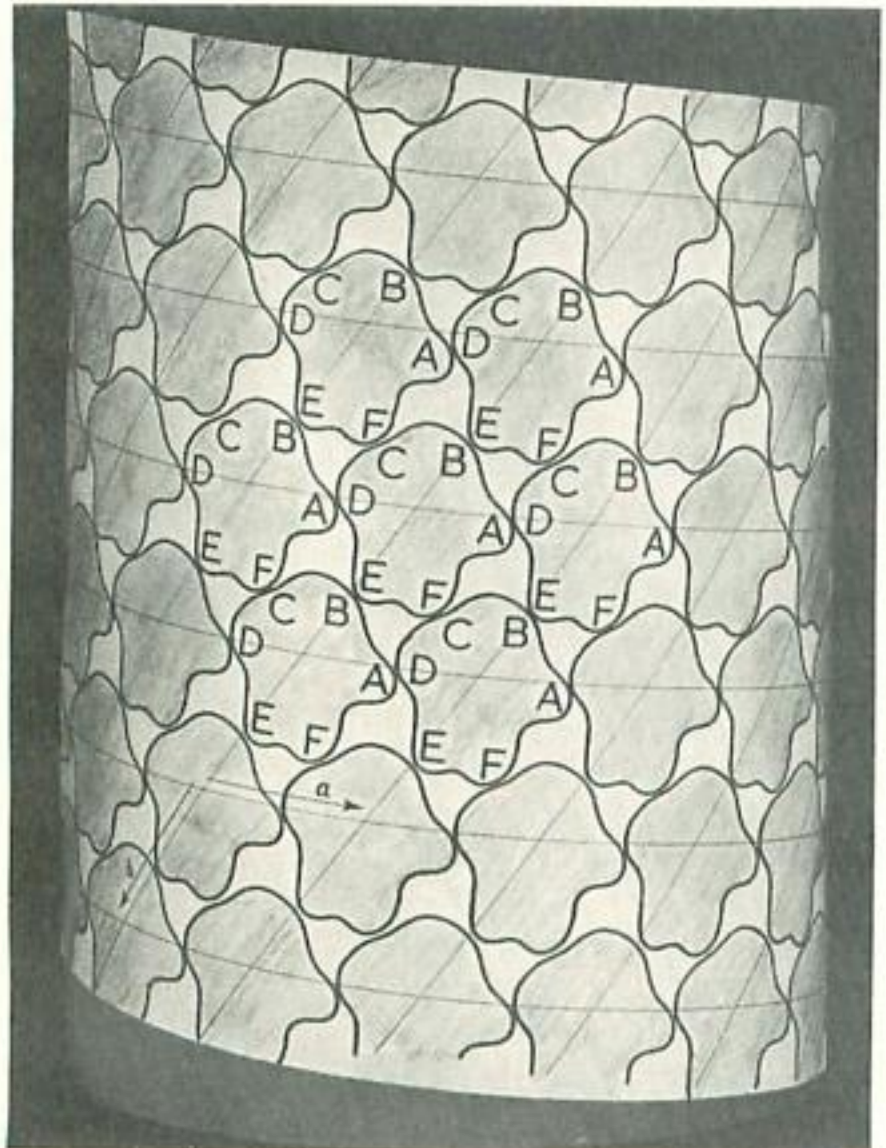
Picornavirus virion

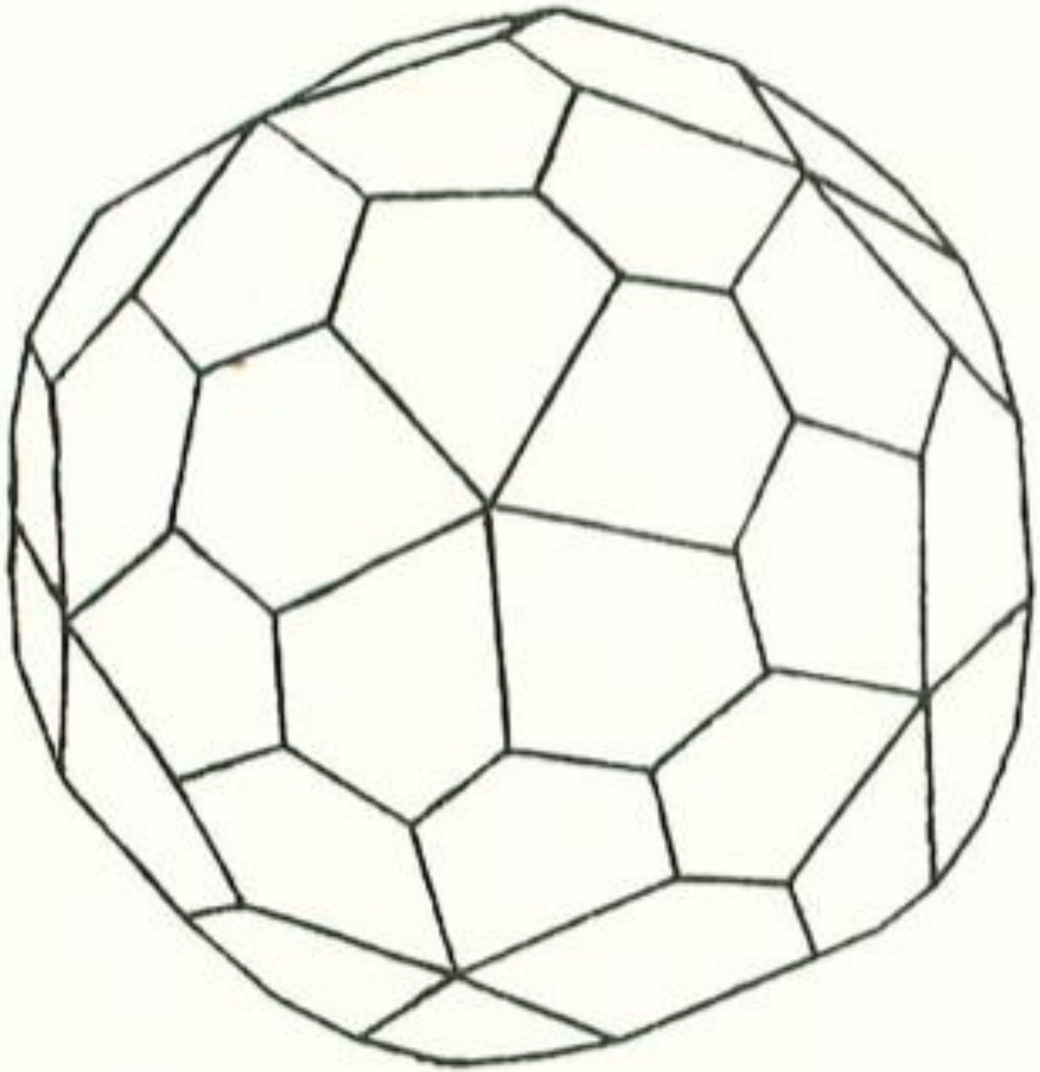


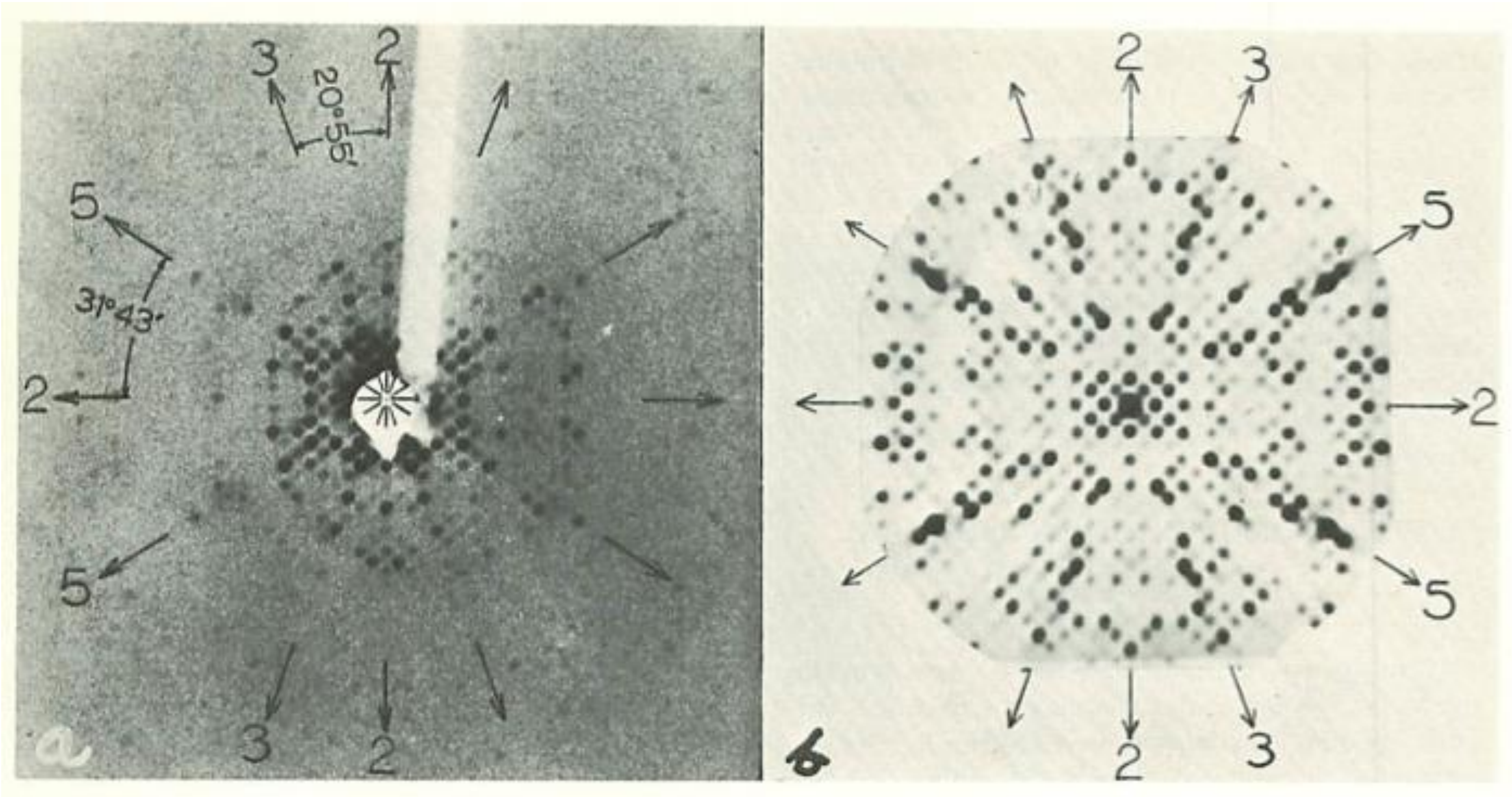
Icosahedron




C B
D A
E F
C B
D A
E F
C B
D A
E F
C B
D A
E F
C B
D A
E F
C B
D A
E F
C B
D A
E F
a
b

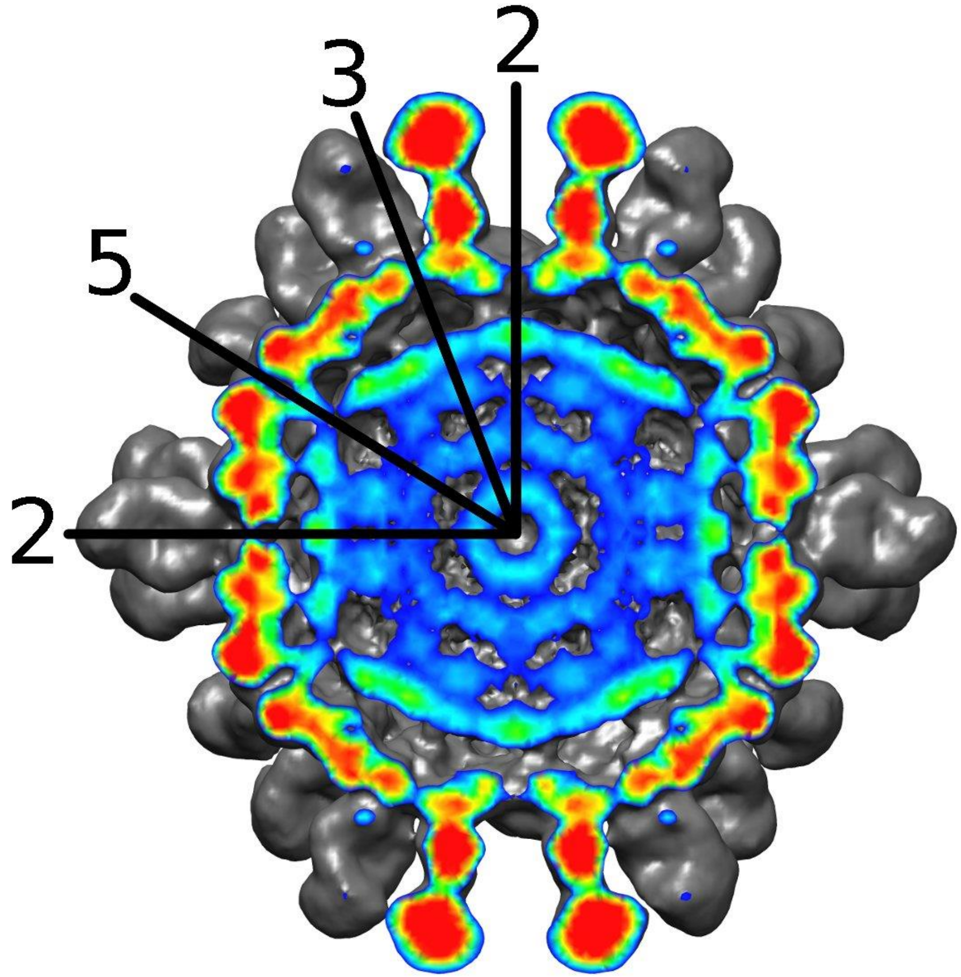

C B D A E F
C B D A E F
C B D A E F
C B D A E F
C B D A E F
C B D A E F
C B D A E F
a

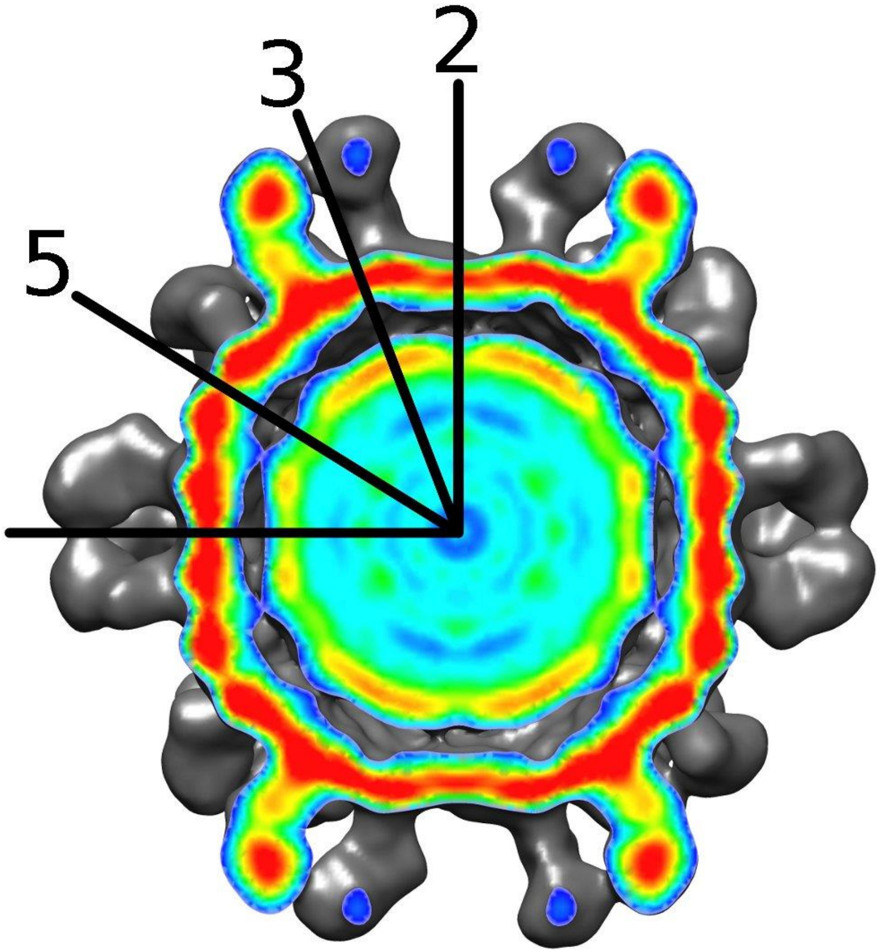


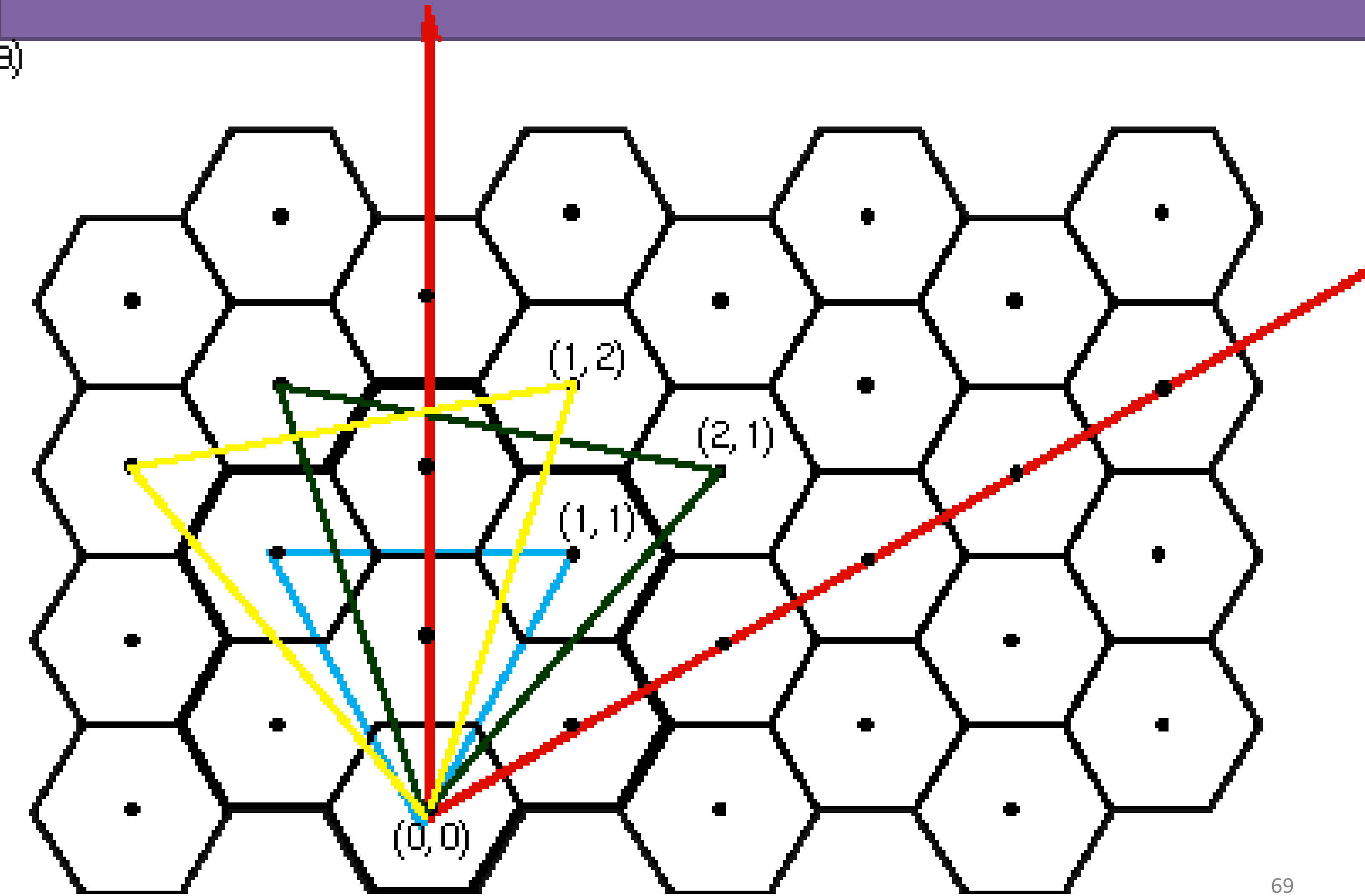

3
2
20°55′
5
31°43′
2
5
3
2
a
2
3
5
2
5
3
2
b

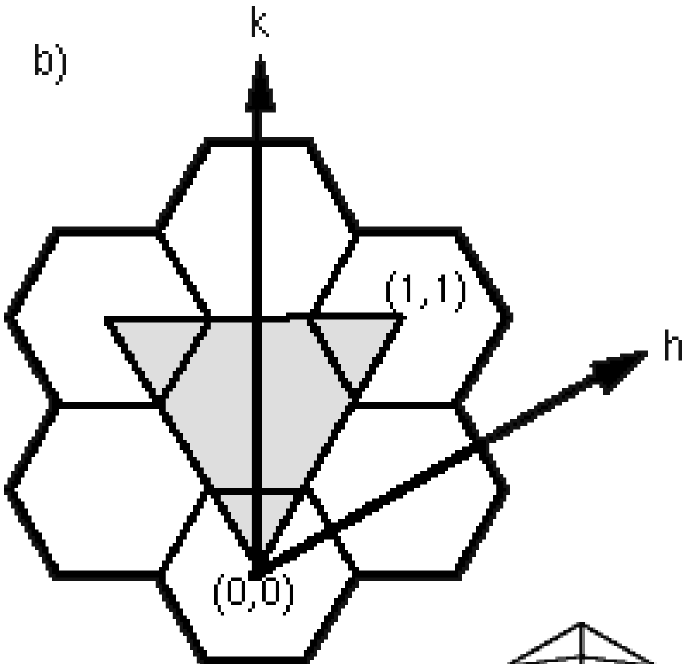
E18 Fab

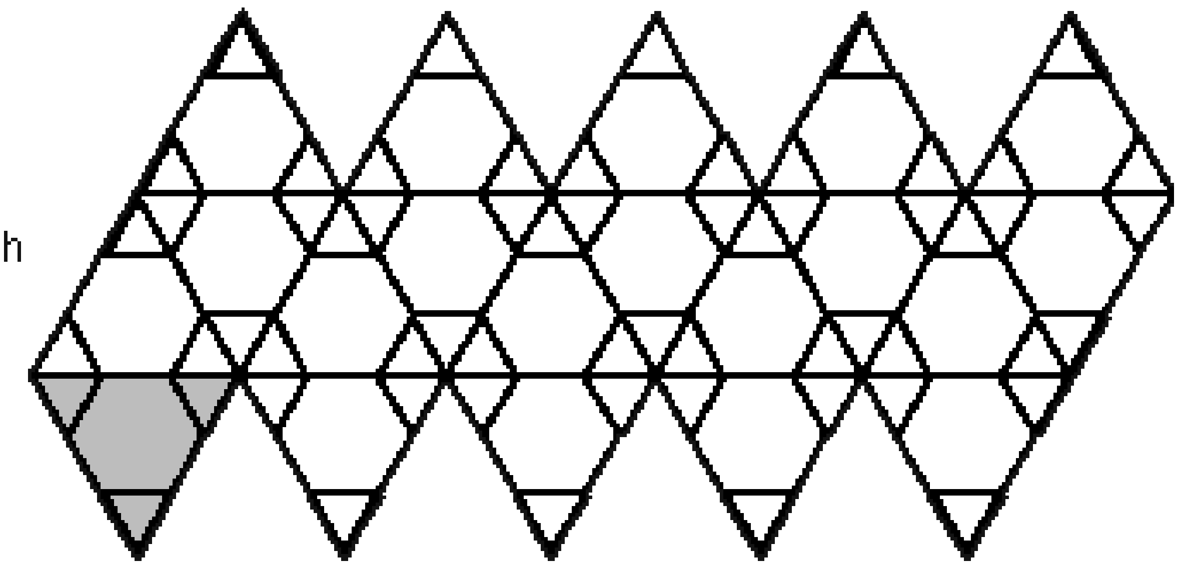
E19 Fab

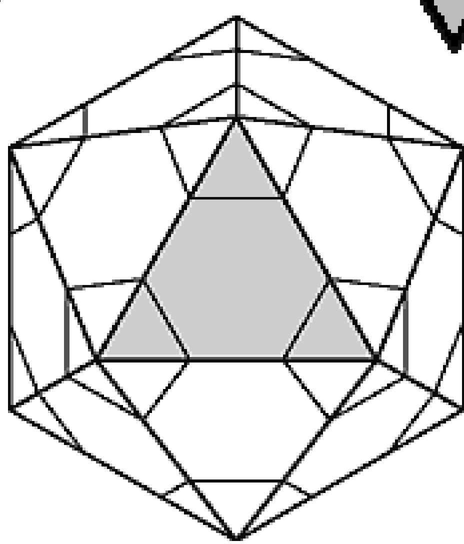


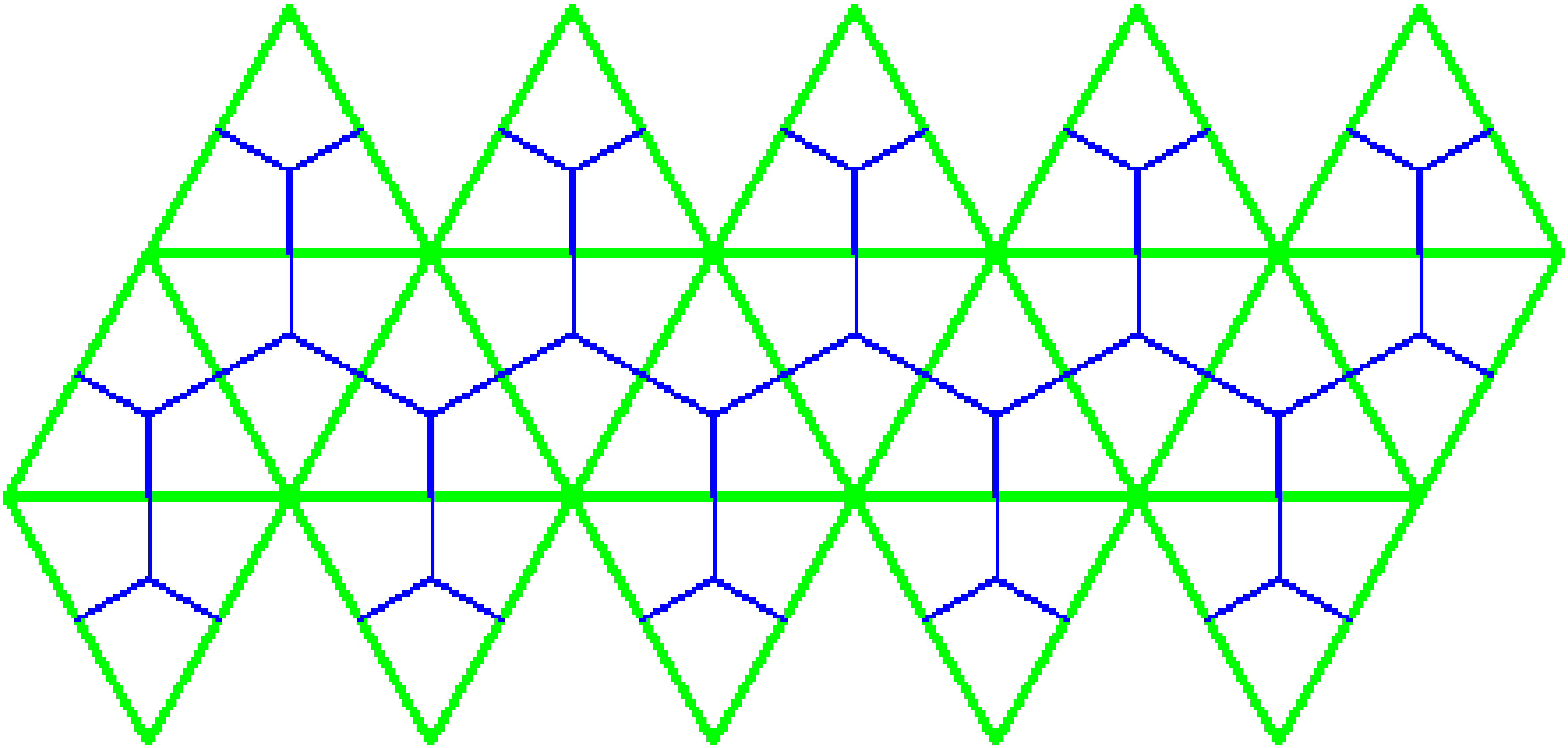


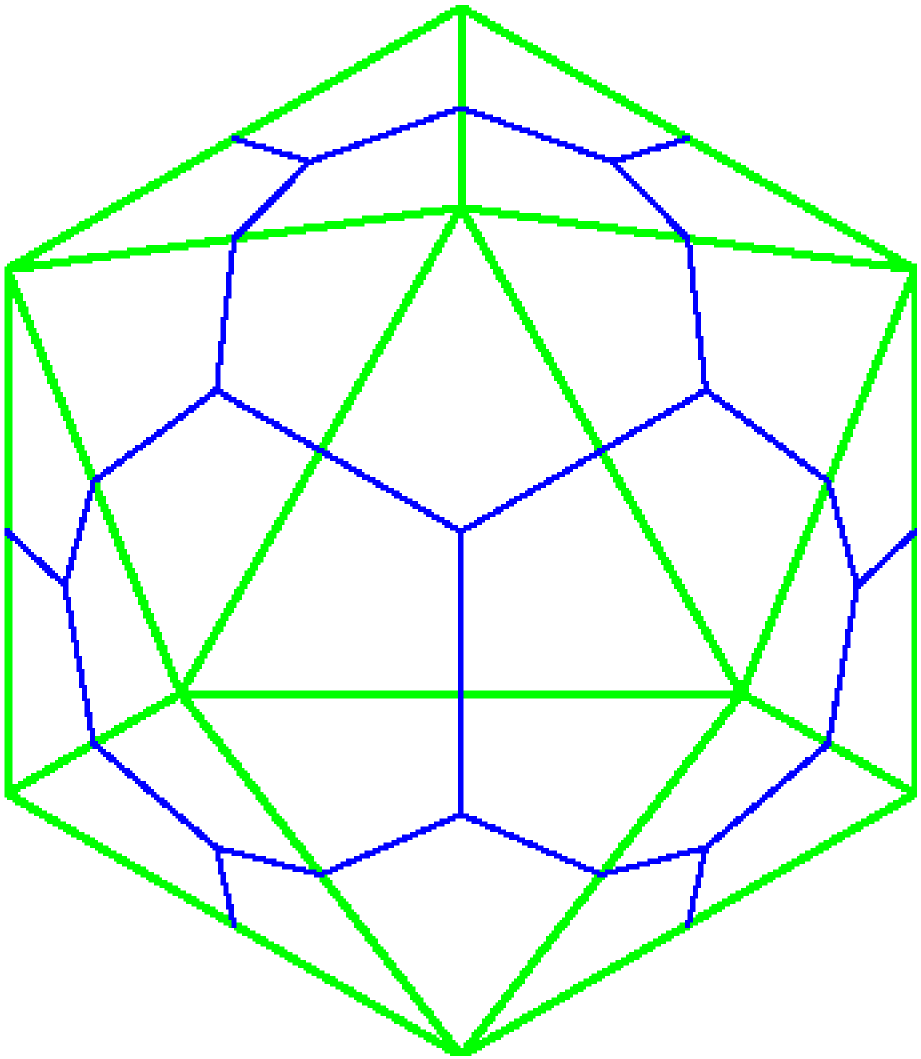

3)
(1, 2)
(2, 1)
(1, 1)
(0, 0)

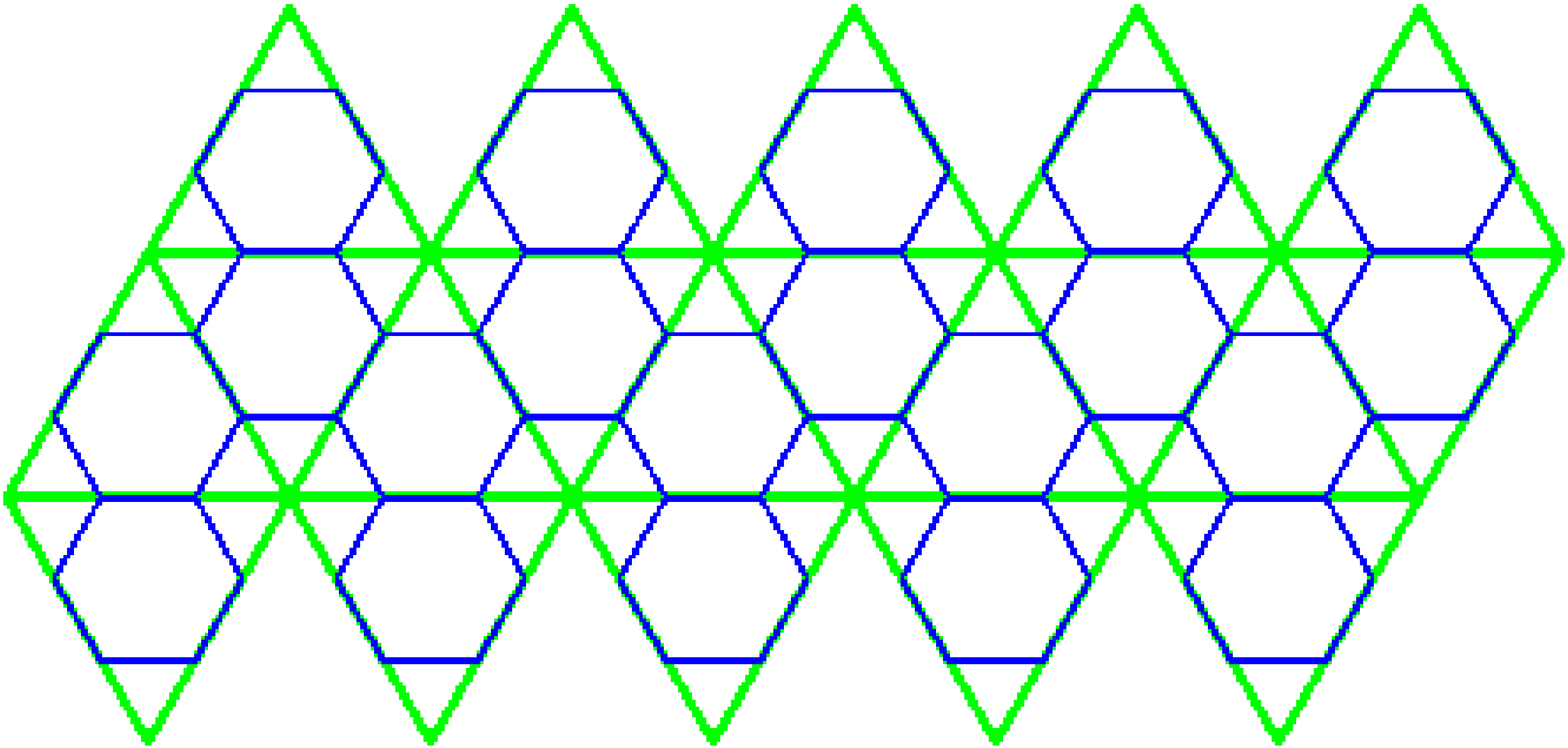

b)
k
(1,1)
h
(0,0)

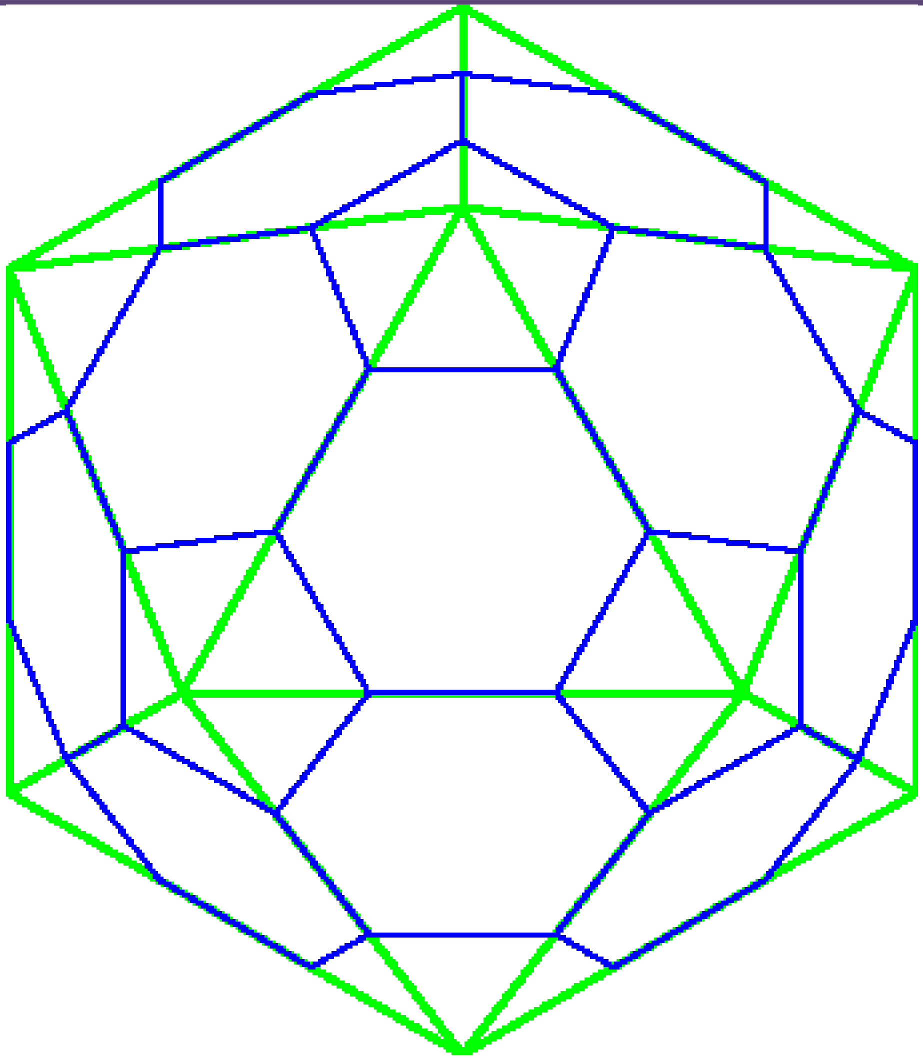


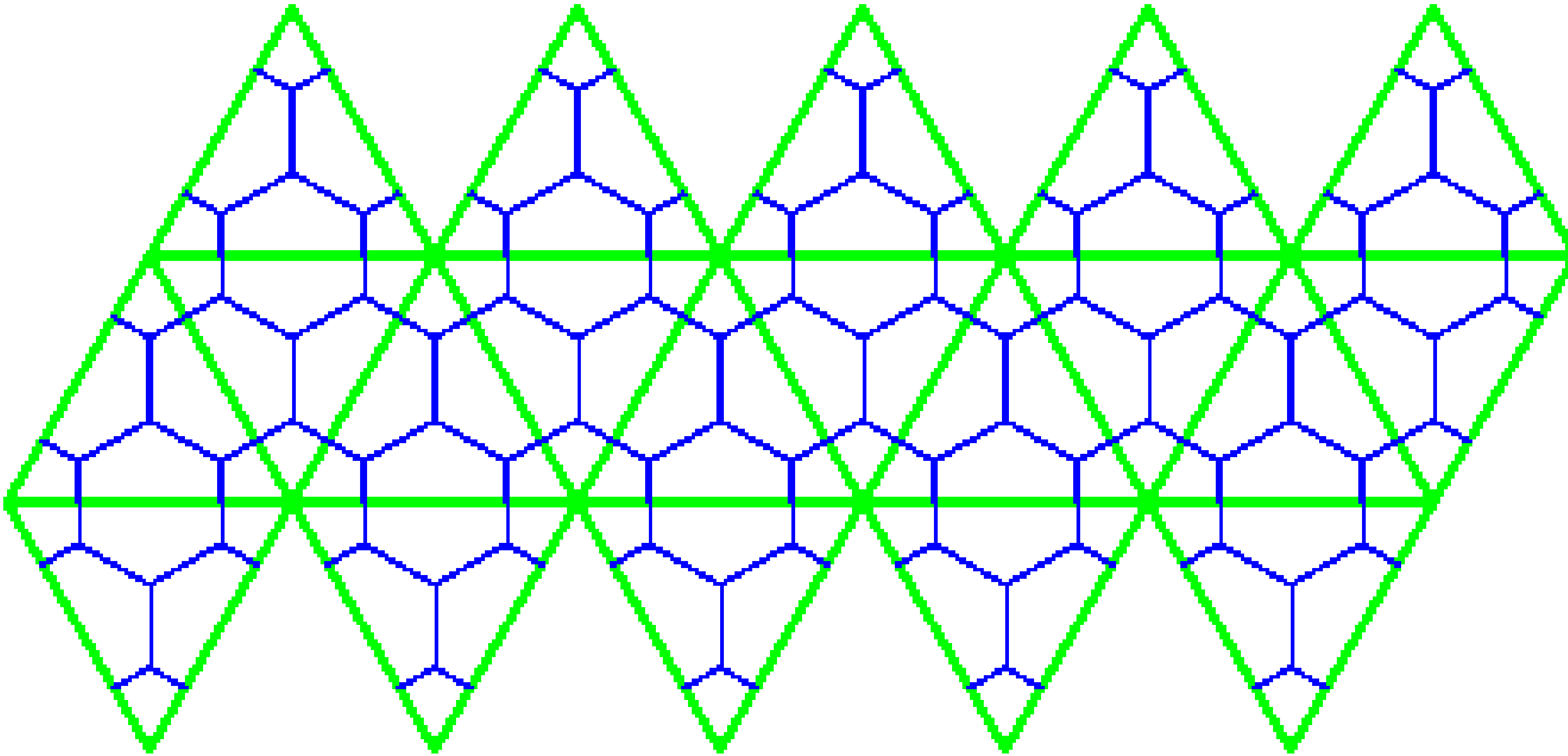


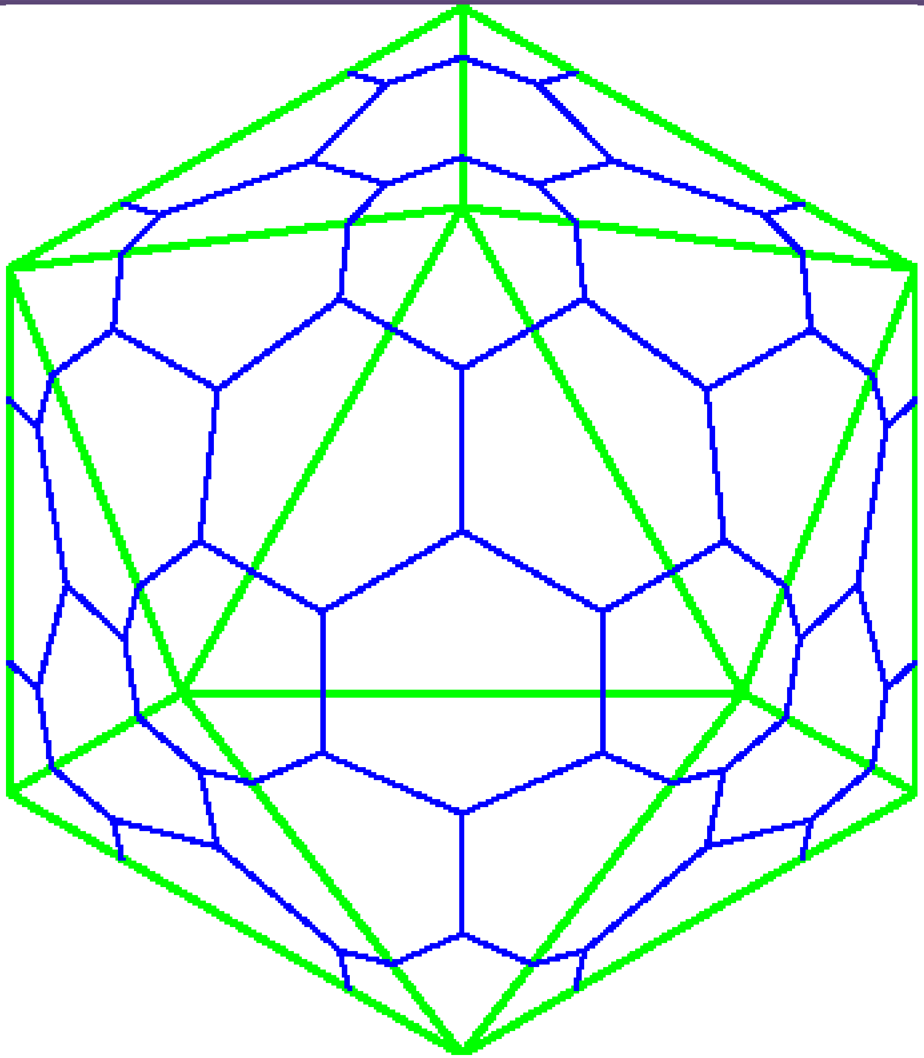


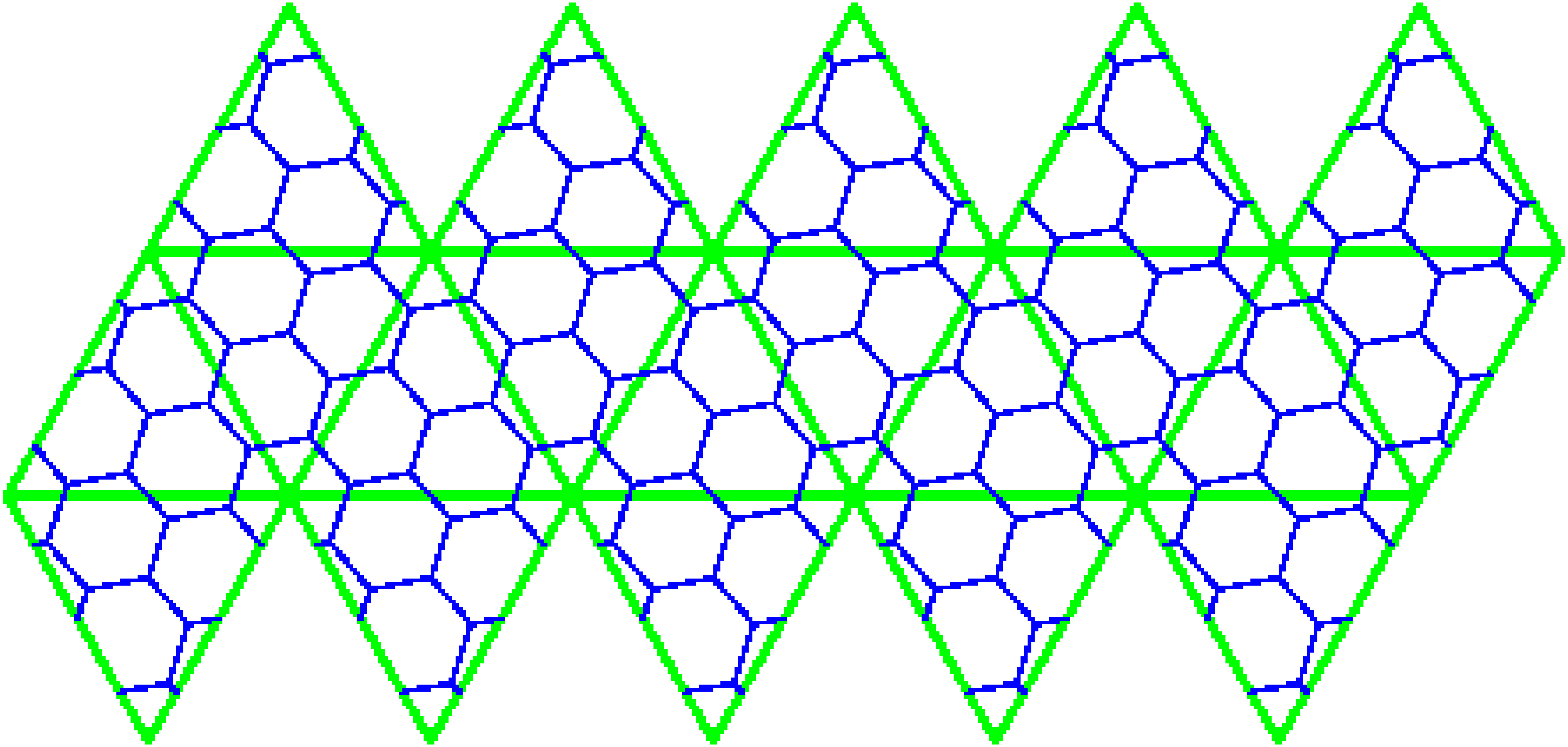


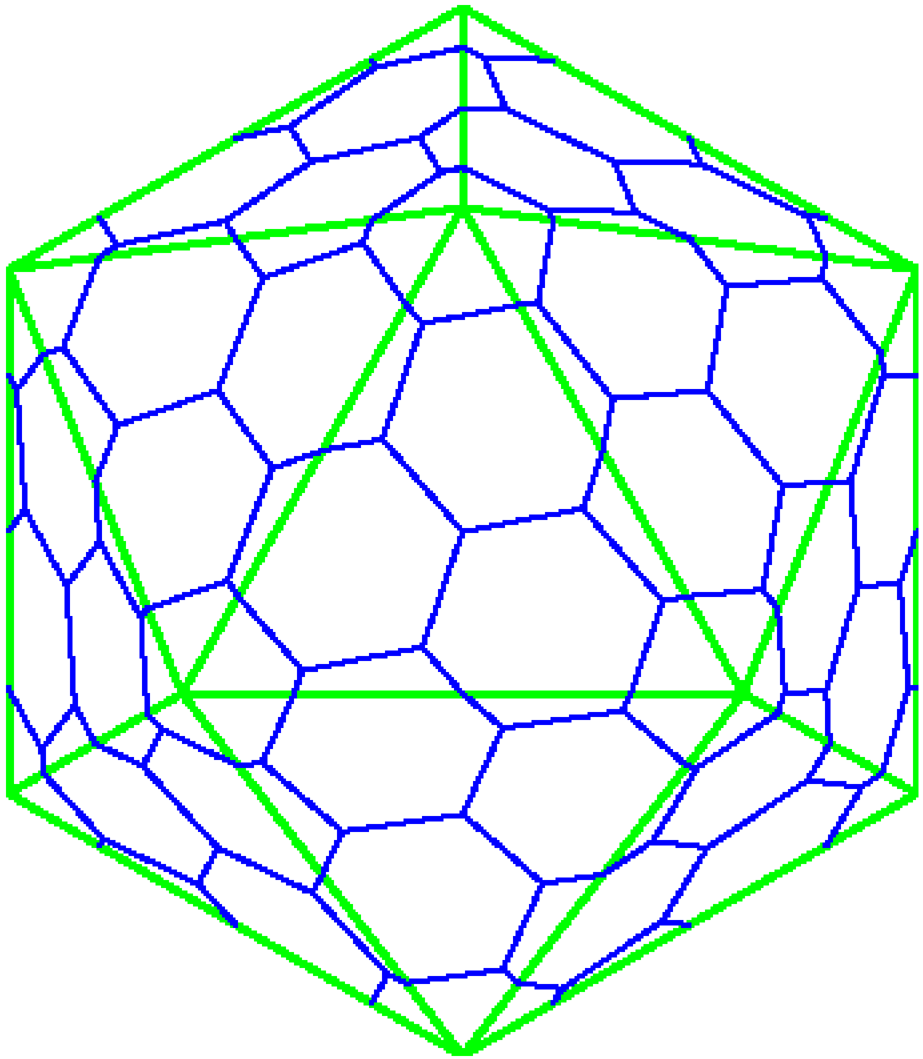












DNA genomes	Examples
ss, linear	Parvoviruses
ds, linear	Poxviruses
ss, circular	Phage φX174
ds, circular	Baculoviruses

RNA genomes	
ss, linear	Tobacco mosaic virus
ds, linear	Reoviruses
ss, circular	Hepatitis delta virus

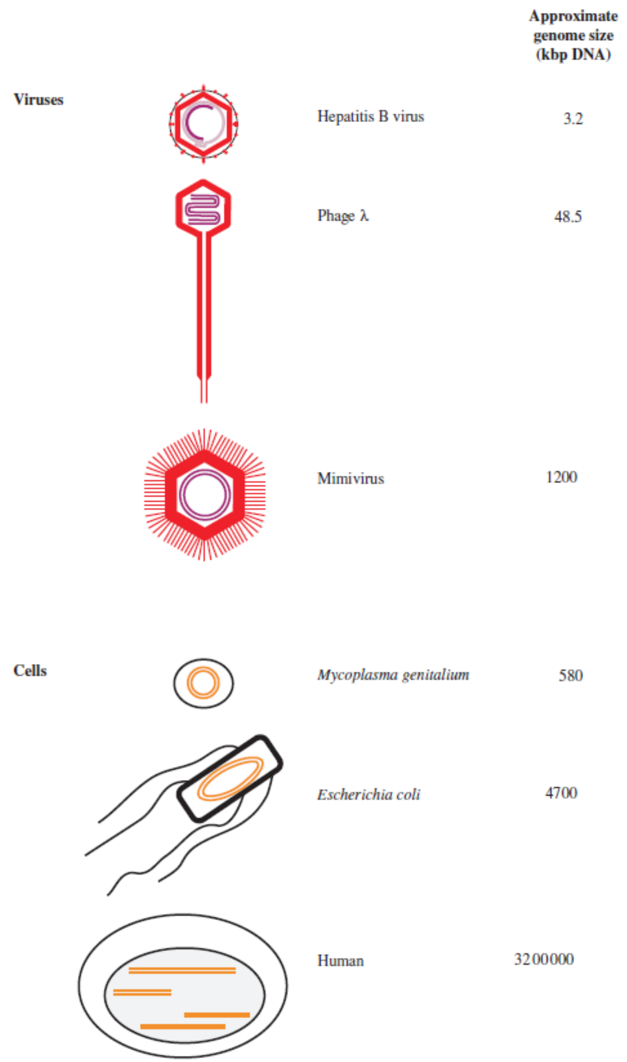


Figure 3.2 **Genome sizes of some DNA viruses and cells.** Not to scale.

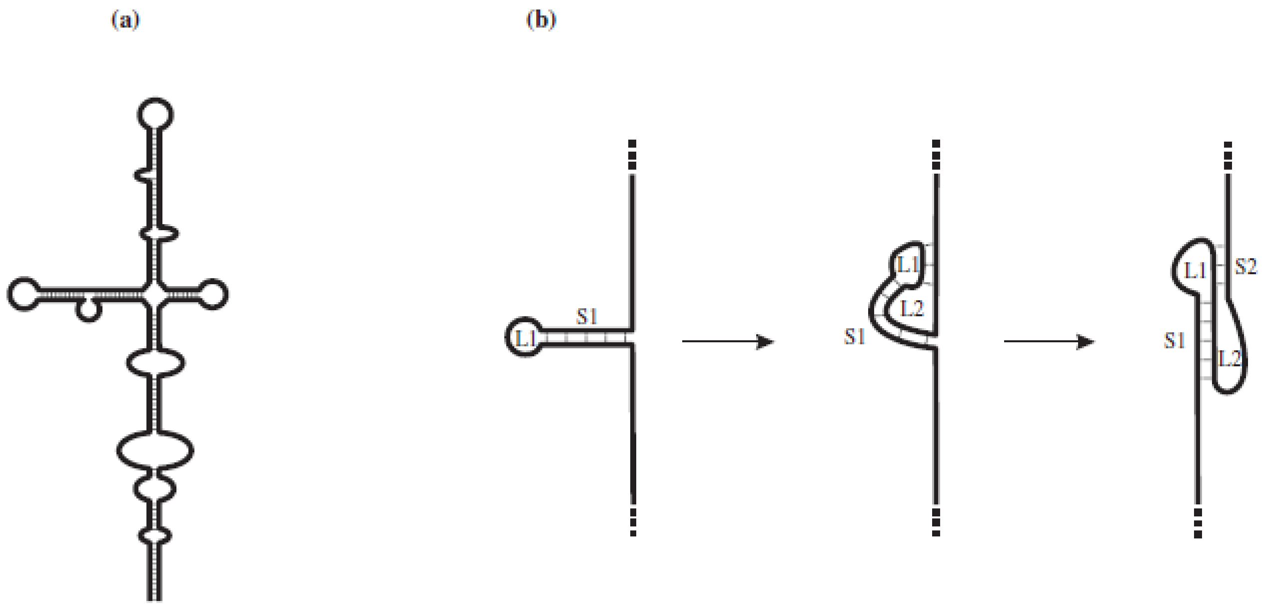


Figure 3.3 **Secondary structures resulting from intramolecular base-pairing in single-stranded nucleic acids.** (a) Stem-loops and bulges in ssRNA and ssDNA. (b) Formation of a pseudoknot in ssRNA. A pseudoknot is formed when a sequence in a loop (L1) at the end of a stem (S1) base-pairs with a complementary sequence outside the loop. This forms a second loop (L2) and a second stem (S2).

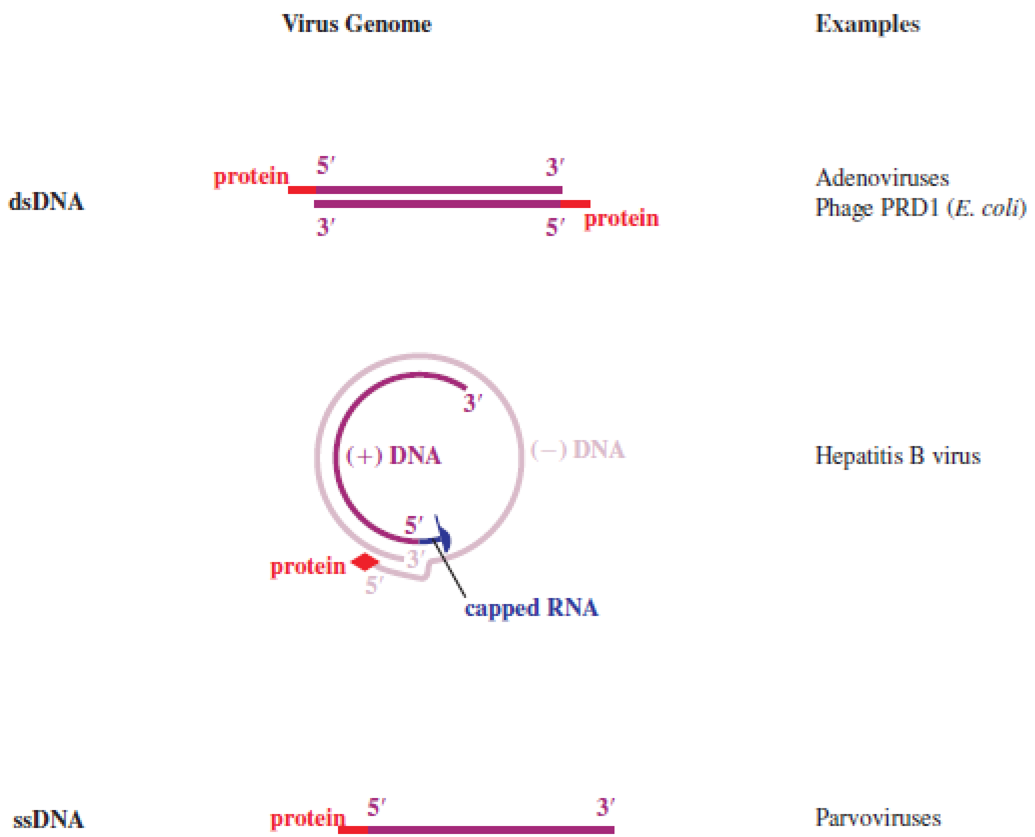


Figure 3.4 **DNA virus genomes with one or both ends modified.** The 5′ end of some DNAs is covalently linked to a protein. One of the hepatitis B virus DNA strands (the (+) strand) is linked to a short sequence of RNA with a methylated nucleotide cap.

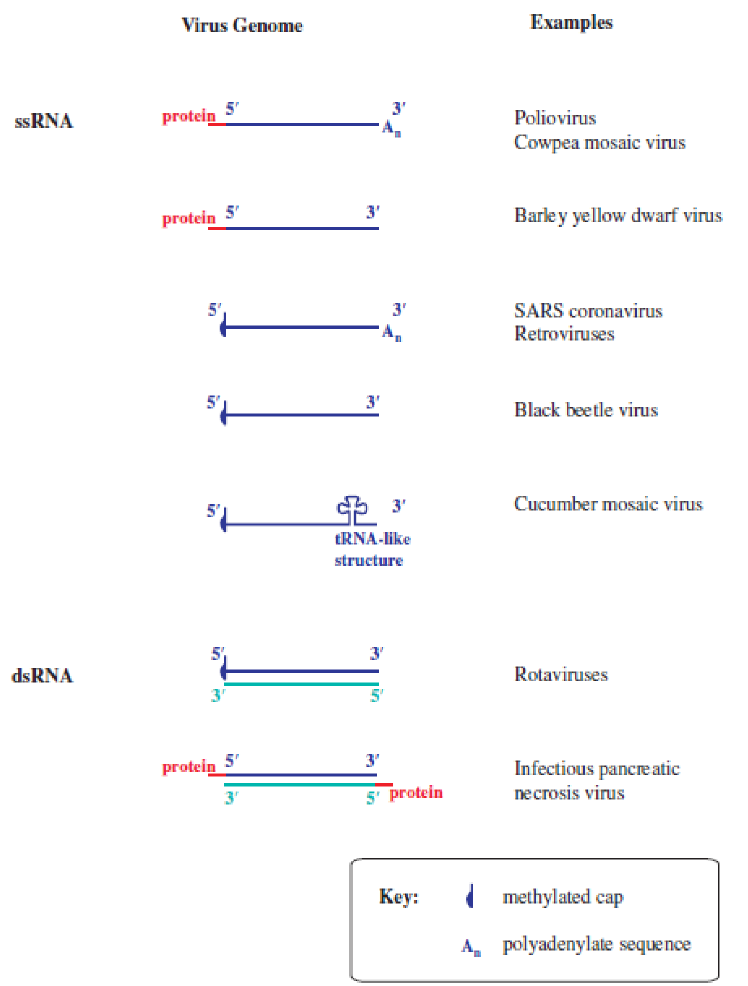


Figure 3.5 **RNA virus genomes with one or both ends modified.** The 5′ end may be linked to a protein or a methylated nucleotide cap. The 3′ end may be polyadenylated or it may be folded like a transfer RNA.

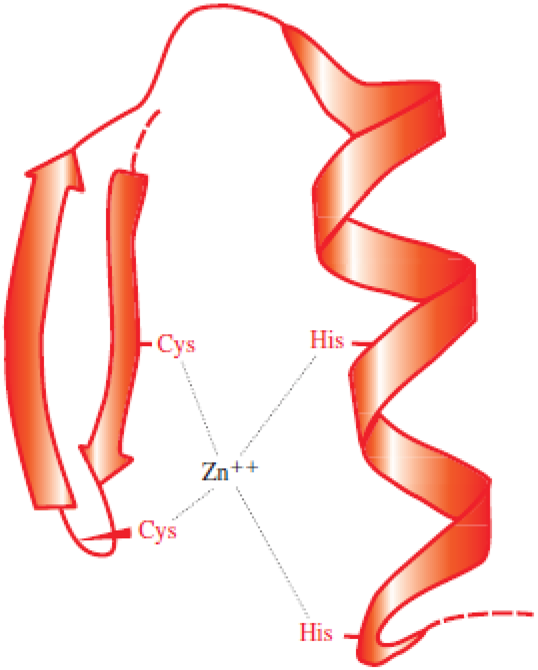


Figure 3.6 A zinc finger in a protein molecule. A zinc finger has recurring cysteine and/or histidine residues at regular intervals. In this example there are two cysteines and two histidines.

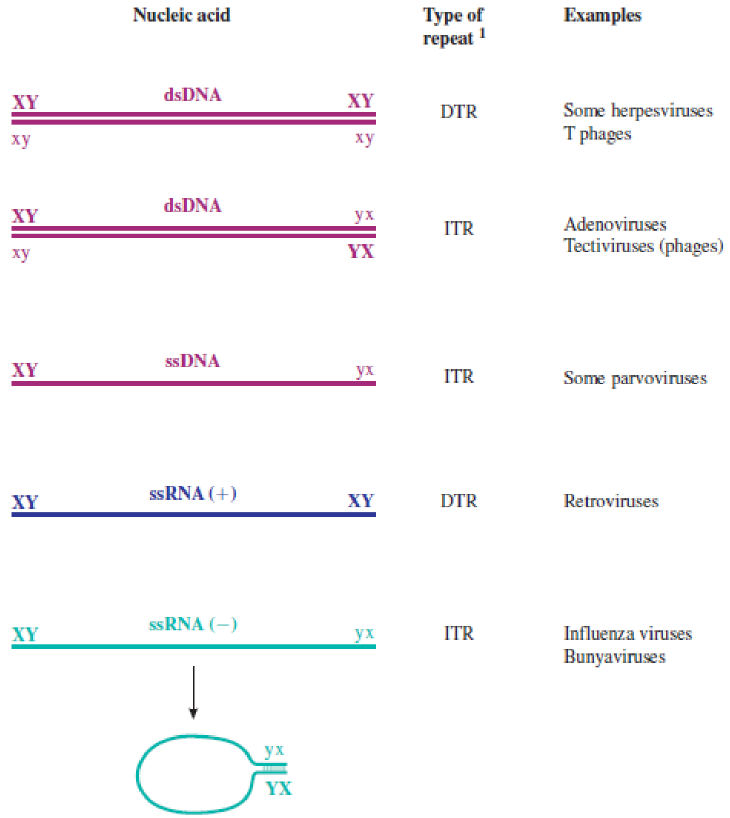


Figure 3.7 **Terminal repeats in virus genomes.**

[1] DTR: direct terminal repeat.
ITR: inverted terminal repeat.

X and x represent complementary sequences.

Y and y represent complementary sequences.

ssRNA (+) has the same sequence as the virus mRNA.

ssRNA (–) has the sequence complementary to the virus mRNA.

The RNAs of ssRNA viruses with ITRs can circularize; a "panhandle" is formed by base pairing between the complementary sequences at the termini.

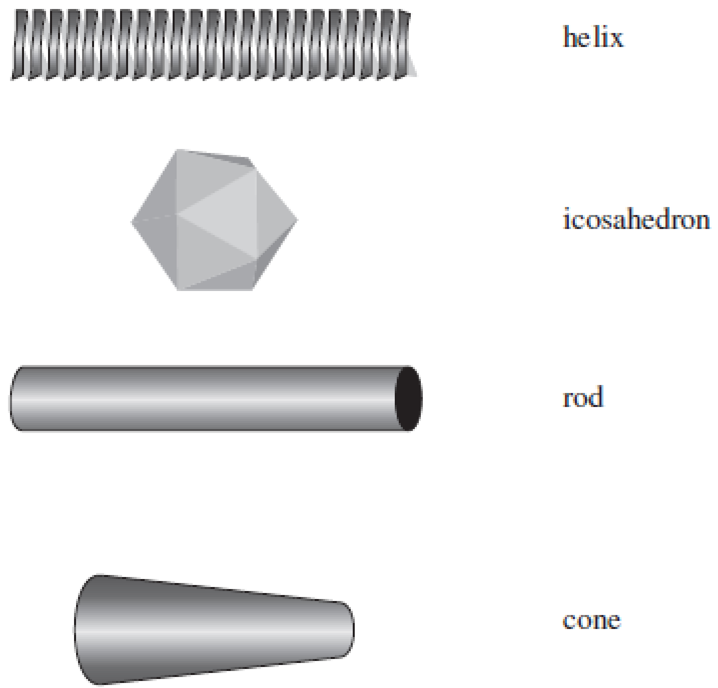


Figure 3.8 Symmetrical structures. All these types of symmetry are seen amongst viruses. The most common are helical and icosahedral symmetries.

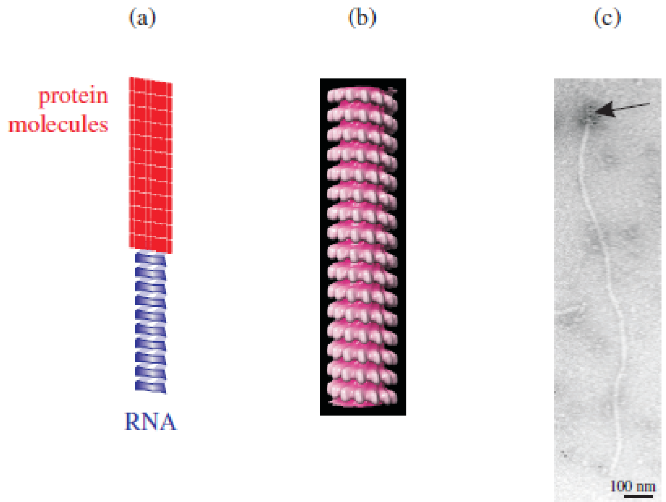


Figure 3.9 **Helical symmetry.** (a) Structure of a capsid with helical symmetry. The ssRNA coil is coated with repeated copies of a protein. (b) Part of measles virus nucleocapsid. The complete nucleocapsid is folded and enclosed within an envelope. (c) Beet yellows virus particle. The virion is a long flexible rod, at one end of which there is a "tail" (arrow) composed of a minor capsid protein, detected here by specific antibodies labeled with gold.

Sources: (b) Reconstructed image from cryo-electron microscopy, courtesy of Dr David Bhella (MRC Virology Unit, Glasgow). Reinterpretation of data in Bhella *et al.* (2004) *Journal of Molecular Biology*, 340, 319 (by permission of Elsevier Limited). (c) Courtesy of Professor Valerian Dolja, originally published in Alzhanova *et al.* (2001) *The EMBO Journal*, 20, 6997. Reproduced by permission of Nature Publishing Group.

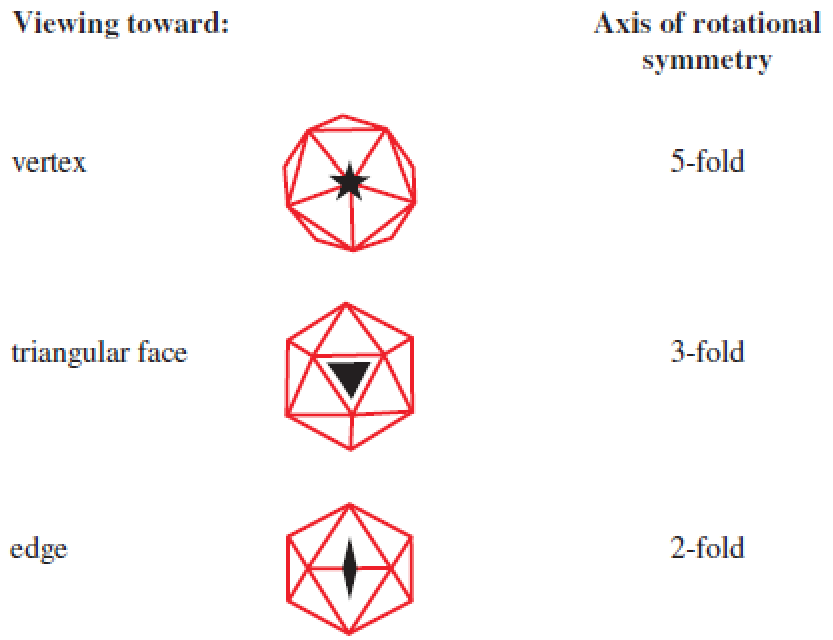


Figure 3.10 The three axes of symmetry of an icosahedron.

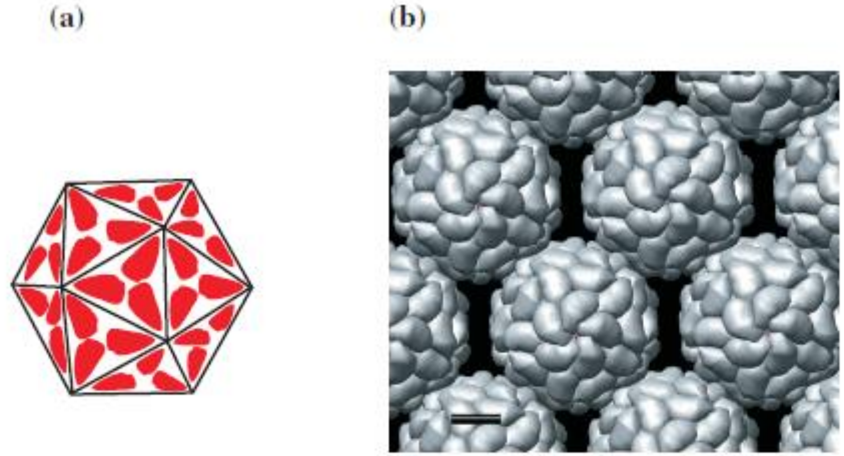


Figure 3.11 Capsid constructed from sixty protein molecules. (a) Arrangement of protein molecules, with three per triangular face. (b) Virions of satellite tobacco mosaic virus. The bar represents 5 nm. Image created with the molecular graphics program UCSF Chimera from the Resource for Biocomputing, Visualization, and Informatics, at the University of California, San Francisco.

Source: Courtesy of Tom Goddard.

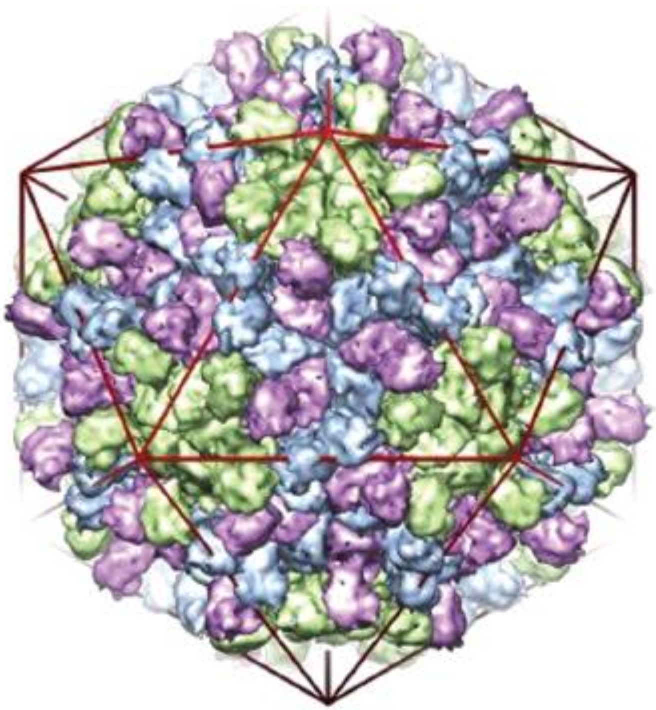


Figure 3.12 Turnip crinkle virus capsid. The capsid is built from 180 copies of the coat protein in three quasi-equivalent conformations; some protein molecules (green) are around the fivefold symmetry axes, while the remainder (pink and blue) are around the threefold symmetry axes. An icosahedron is superimposed.

Source: Bakker *et al.* (2012) *Journal of Molecular Biology*, 417, 65–78. Reproduced by permission of the authors and Elsevier Limited.

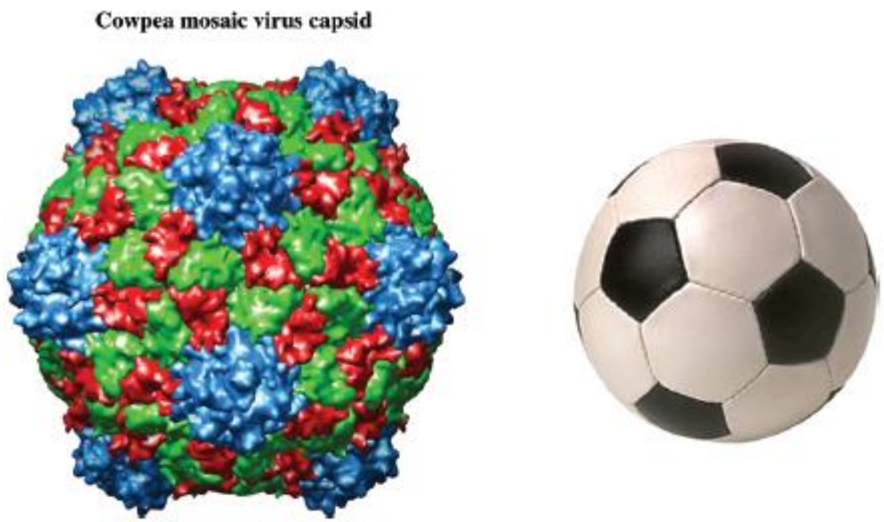


Figure 3.13 Capsid constructed from two protein species. The cowpea mosaic virus capsid is constructed from one protein species (blue) that forms 12 "pentamers," and from a second protein species with two domains (green and red) that forms 20 "hexamers." The football is similarly constructed from 12 "pentamers" and 20 "hexamers." The cowpea mosaic virus image is from the VIPER database (Shepherd *et al.*, 2006).

Source: The image was reconstructed using the data of Lin *et al.* (1999) *Virology*, 265, 20. Reproduced by permission of Elsevier Limited.

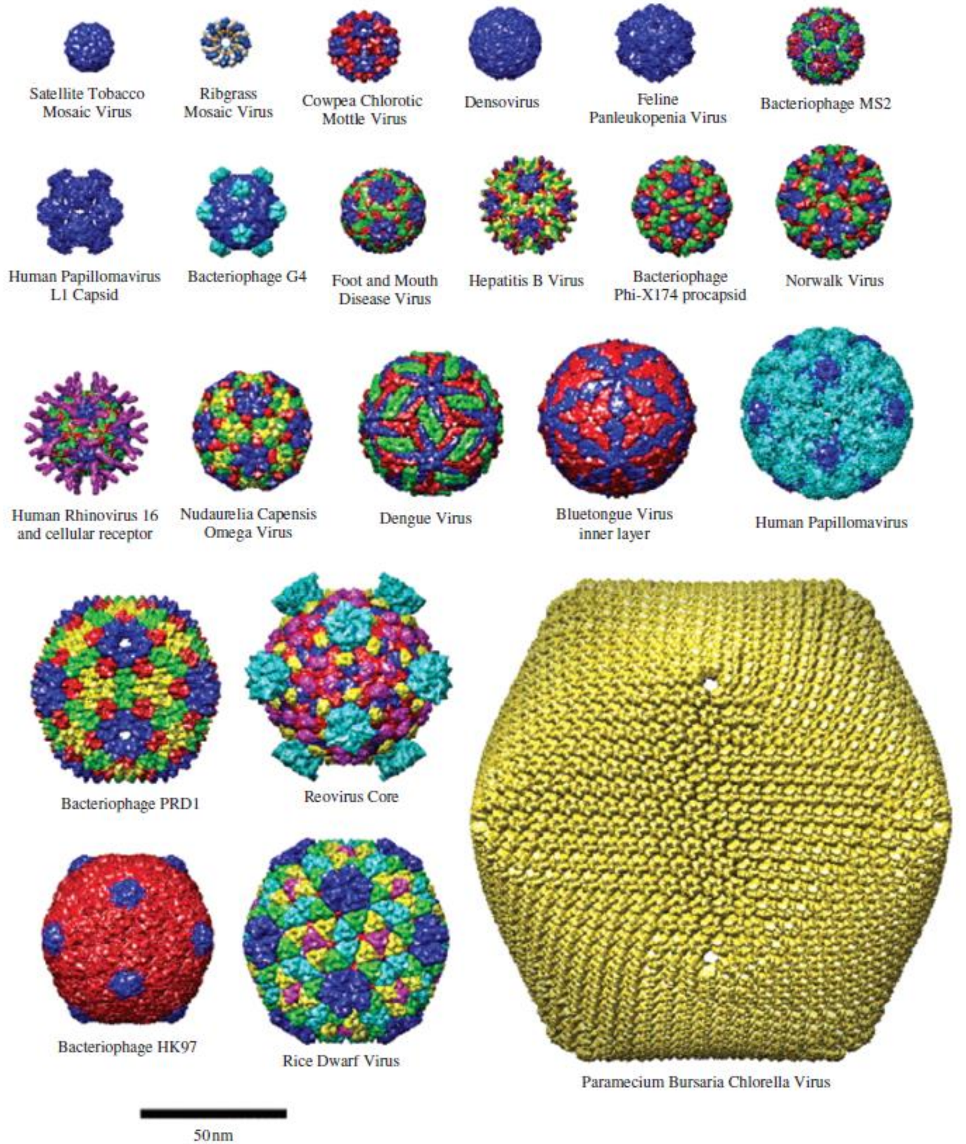


Figure 3.14 **Capsids with icosahedral symmetry.** Some of the wide ranges of capsid architectures and sizes are illustrated. The images were created with the molecular graphics program UCSF Chimera using data from cryo-electron microscopy and X-ray diffraction.

Source: Goddard *et al.* (2005) *Structure*, 13, 473. Reproduced by permission of Elsevier Limited.

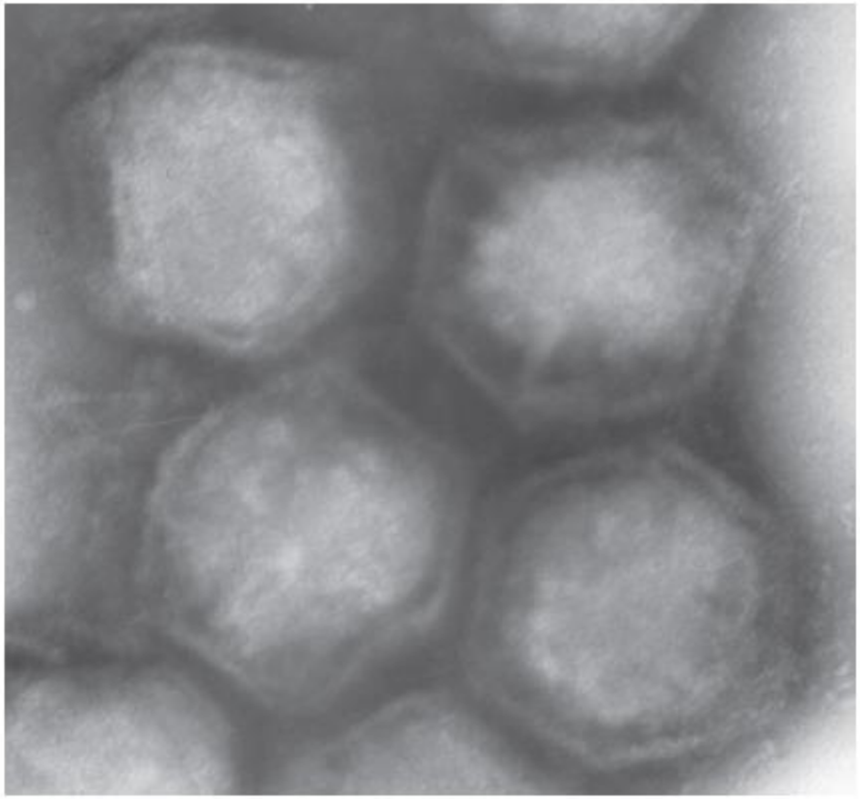


Figure 3.15 Transmission electron micrograph of negatively stained virions of invertebrate iridescent virus 1.

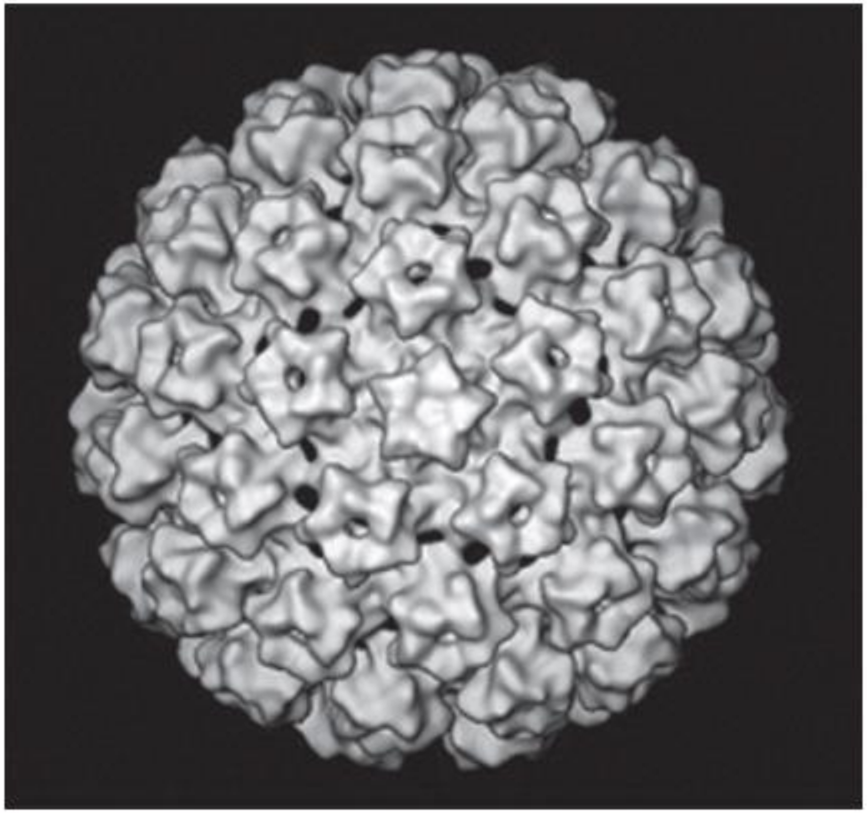


Figure 3.16 **Papillomavirus capsid reconstruction.**

Source: Trus *et al*. (1997) *Nature Structural Biology*, 4, 413, with the permission of the authors and Nature Publishing Group.

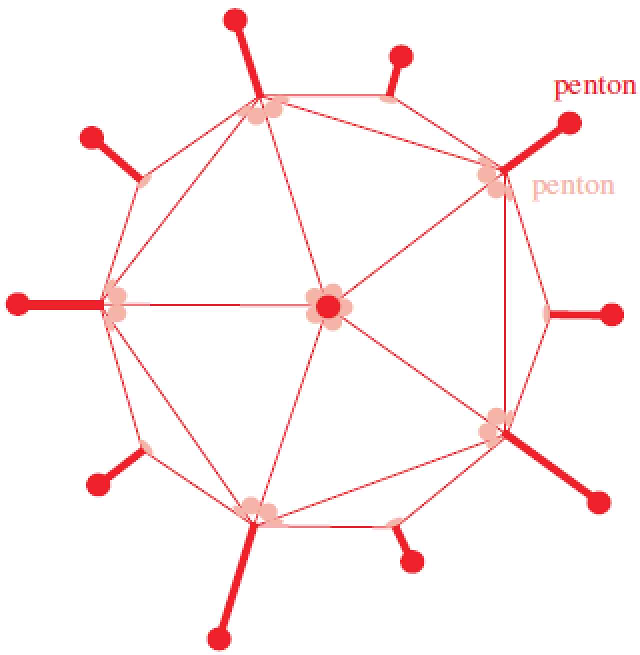


Figure 3.17 Adenovirus virion. At each of the 12 vertices of the virion there is a penton, and attached to each penton there is a protein fiber with a knob at the end. The rest of the capsid is constructed from hexons. See Figure 12.1 for an electron micrograph of an adenovirus.

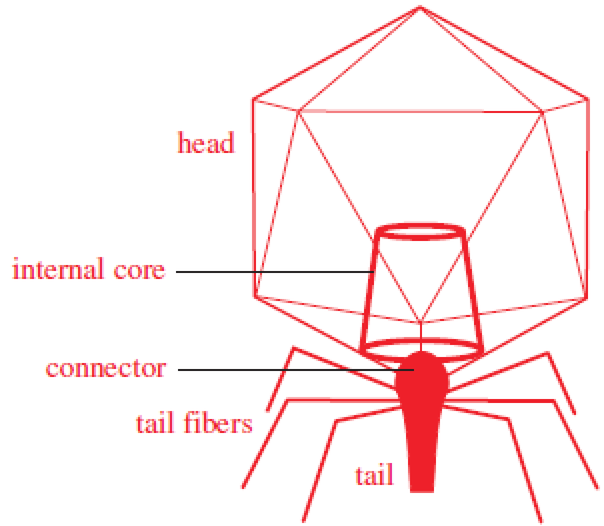


Figure 3.18 **Structure of phage T7.** Each of the components is composed of one or more distinct proteins.

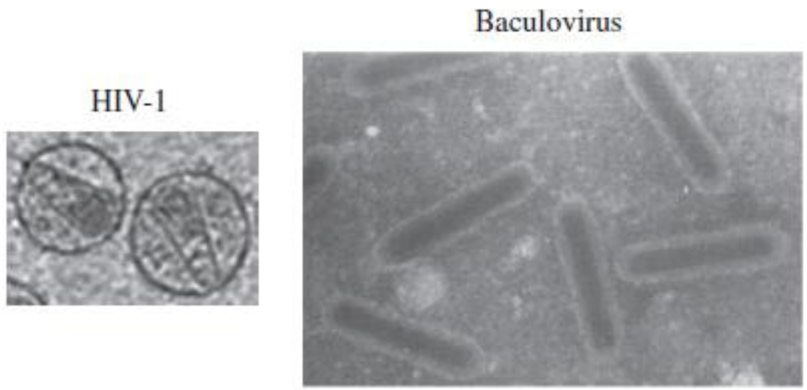


Figure 3.19 **Virions containing conical and rod-shaped capsids.**

Sources: HIV-1 virions from Wei and Yin (2010) *Journal of Structural Biology*, 172, 211. Reproduced by permission of Elsevier and the authors. Baculovirus virions are those of *Aglais urticae* nucleopolyhedrovirus. From Harrap (1972) *Virology*, 50, 124. Reproduced by permission of Elsevier Limited.

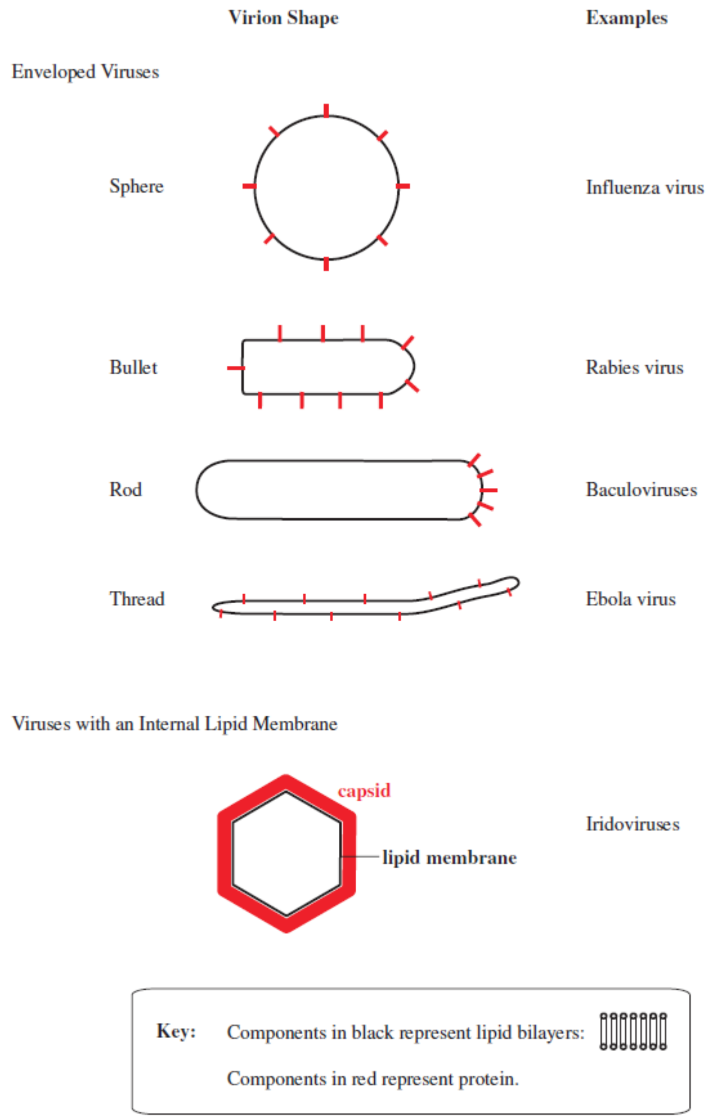


Figure 3.20 **Lipid-containing viruses.**

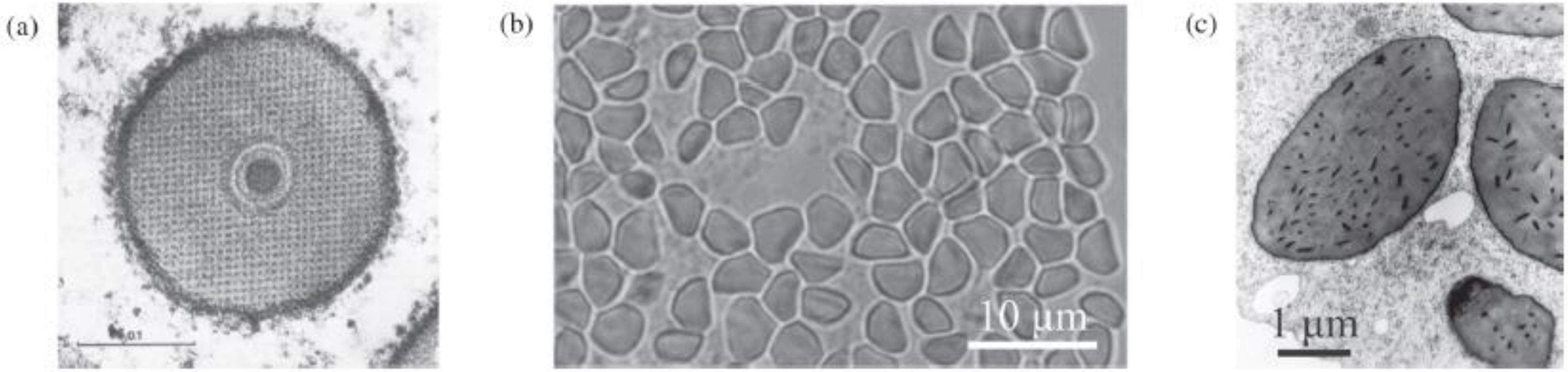


Figure 3.21 Baculovirus occlusion bodies. (a) Transverse section through an occlusion body of a granulovirus of the Indian meal moth (*Plodia interpunctella*). The nucleocapsid surrounded by its membrane can be seen at the center, surrounded by the crystalline protein that forms the occlusion body. The bar represents 0.1 µm. (b), (c) Nucleopolyhedrovirus of the leatherjacket (*Tipula paludosa*). (b) Light micrograph of occlusion bodies. (c) Electron micrograph of a thin section of an occlusion body. The virions are randomly embedded in the crystalline protein.

Sources: (a) Arnott and Smith (1967) *Journal of Ultrastructure Research*, 21, 251. Reproduced by permission of Elsevier Limited. (b), (c) Courtesy of Dr Liz Boslem.