MEGA LECTURE

IB DP BIOLOGY

Theme A: Unity and Diversity

A2.3 Viruses

Revision Notes · Higher Level only

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A2.3 Viruses

> **Higher Level only:** The whole of A2.3 is examined at **Higher Level only**. Standard Level students are not assessed on viruses. Everything in these notes is therefore HL material.

What the syllabus requires

By the end of A2.3 you should be able to work confidently with each of the following. Use this list as a final checklist before the exam.

Understanding	You should be able to...
Structural features common to viruses	State that all viruses have a nucleic acid genome enclosed in a protein capsid, are very small and are non-living outside a host cell.
Diversity of viruses	Describe the range of genome types (DNA or RNA, single- or double-stranded), capsid shapes and host ranges, using named examples.
The lytic cycle	Outline the sequence of events by which a bacteriophage replicates and destroys its host cell.
The lysogenic cycle	Explain how a temperate phage integrates its genome as a prophage and can later switch to the lytic cycle.
Retroviruses	Explain how a retrovirus such as HIV uses reverse transcriptase to convert its RNA genome into DNA that integrates into the host genome.
Rapid evolution	Explain why viruses, especially RNA viruses, evolve quickly, and relate this to vaccines, antigenic shift and drift, and pandemics.
Origin of viruses	Discuss the leading hypotheses for how viruses may have originated.

1. What a virus is

A virus is a **non-cellular** (acellular) infectious particle that can only reproduce inside a living host cell. Outside a host it is a chemically inert particle called a **virion**. Because a virus is not built from one or more cells, it breaks the first principle of the cell theory, and this single fact explains almost everything unusual about viruses.

- **Acellular:** no plasma membrane enclosing cytoplasm, no ribosomes, no organelles.
- **No metabolism:** a virus carries out no respiration and no protein synthesis of its own; it has no enzymes for generating ATP.
- **Obligate intracellular parasite:** it must enter a host cell and hijack that cell's ribosomes, enzymes, nucleotides and ATP to make new virions.
- **Not placed in the three domains:** viruses are excluded from Archaea, Bacteria and Eukarya because those domains contain only cellular organisms.

Are viruses alive?

This is a genuine, open debate and a favourite discussion question. Viruses show some characteristics of life but not others, so the answer depends on which definition of life you adopt.

Argument that viruses are alive	Argument that viruses are not alive
They possess genetic material (DNA or RNA) that is copied and inherited.	They cannot reproduce independently — only a host cell's machinery makes new virions.
They evolve by natural selection, adapting to hosts and to drugs.	They have no metabolism, no respiration and do not use energy of their own.
They reproduce (with help) and can be extremely host-specific, like parasites.	They are not cells and can be crystallised like a chemical, then remain inert indefinitely.

> **Exam tip:** A safe exam answer is that viruses occupy a *grey area* between living and non-living: they are best described as replicating biological entities that are only active inside a host. Give evidence on **both** sides before reaching a conclusion.

2. Structural features common to all viruses

Despite enormous diversity, every virus shares two features: a nucleic acid genome and a protein coat. A minority add a third: a lipid envelope.

Feature	Description	Always present?
Nucleic acid genome	DNA *or* RNA (never both), single- or double-stranded; carries the genes needed to make new virions.	Yes
Protein capsid	A coat built from many identical protein subunits called **capsomeres**; protects the genome and helps attach to host cells.	Yes
Lipid envelope	An outer membrane derived from the **host** cell's membrane as the virus buds out, studded with viral **glycoproteins** for host recognition.	No — enveloped viruses only

A virus that has a capsid but no envelope is called a **naked** virus. The genome plus capsid together is the **nucleocapsid**.

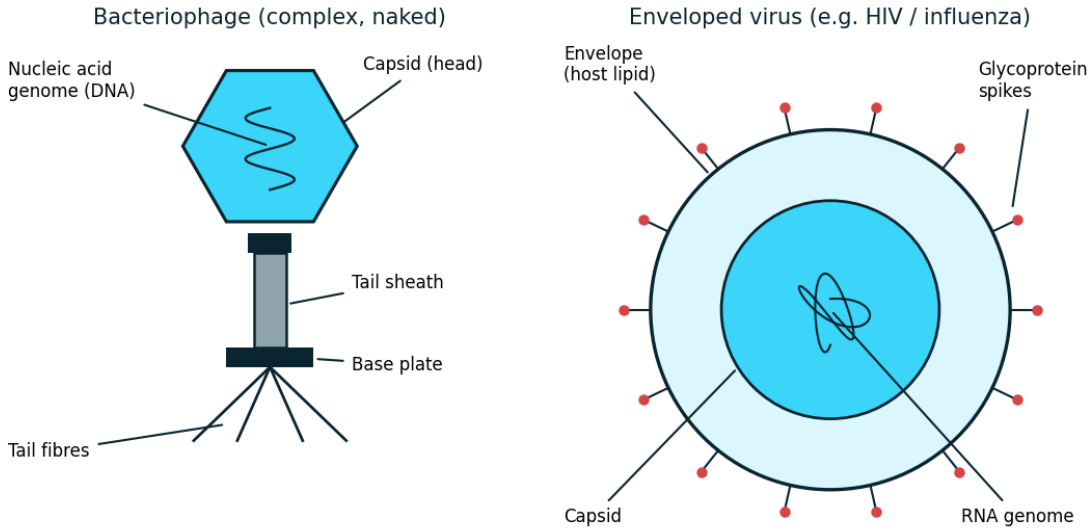

Figure 1. Two contrasting virus body plans: a complex bacteriophage (naked, DNA genome, tail apparatus) and an enveloped virus whose lipid envelope and glycoprotein spikes are derived from and recognise the host membrane.

What a virus does NOT have

- No cytoplasm and no organelles (no ribosomes, no mitochondria, no nucleus).
- No metabolic pathways and no ability to make its own proteins or ATP.
- No means of independent movement or growth.

Small size

Viruses are far smaller than the cells they infect — typically 20–300 nm across, roughly 10–100 × smaller than a bacterium. Most are below the resolution limit of a light microscope, so they were only seen after the electron microscope was invented.

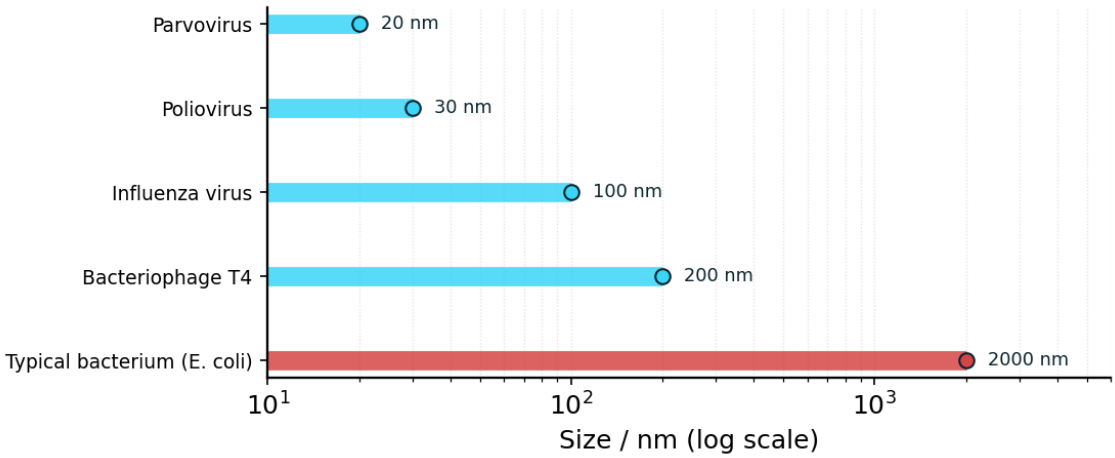

Figure 2. Characteristic sizes on a log scale: viruses (about 20-300 nm) are roughly 10-100 × smaller than a typical bacterium (about 2000 nm).

> **Key distinction:** The capsid is always **protein**; the envelope, when present, is **lipid + glycoprotein taken from the host membrane**. Confusing these two coats is a common exam error.

3. The diversity of viruses

Viruses vary more widely in their genetic material than any cellular group. Cells always store their genes as double-stranded DNA; viruses use every chemical possibility.

Diversity of genomes

Genome type	Meaning	Named example
dsDNA	Double-stranded DNA	Herpesvirus; many bacteriophages (e.g. T4)
ssDNA	Single-stranded DNA	Parvovirus
dsRNA	Double-stranded RNA	Rotavirus
ssRNA (+)	Single-stranded RNA that acts directly as mRNA	Coronavirus; poliovirus
ssRNA (–)	Single-stranded RNA that must first be copied into mRNA	Influenza virus; rabies virus
ssRNA (retro)	Single-stranded RNA copied into DNA by reverse transcriptase	HIV (a retrovirus)

Diversity of shape and size

The way capsomeres pack together gives viruses their characteristic shapes:

- **Helical:** capsomeres form a spiral tube around the genome (e.g. tobacco mosaic virus).
- **Icosahedral:** a roughly spherical 20-faced shell (e.g. adenovirus, poliovirus).
- **Enveloped:** a helical or icosahedral nucleocapsid wrapped in a host-derived membrane (e.g. influenza, HIV, coronavirus).
- **Complex:** more elaborate architecture — the classic bacteriophage has an icosahedral head, a protein tail and tail fibres.

Diversity of host range

Every type of cellular life has viruses that infect it. **Bacteriophages** infect bacteria; other viruses infect archaea, plants, fungi, animals and humans. Most viruses are highly **host-specific** because their attachment proteins must fit particular receptor molecules on the host surface — a lock-and-key match that also determines which tissues a virus can infect.

4. The lytic cycle (bacteriophage)

The lytic cycle is the standard way a virulent bacteriophage reproduces: it takes over the host, mass-produces new phages and then bursts the cell. Learn the five stages in order.

Stage	What happens
1. Attachment	Tail fibres of the phage bind to specific receptor molecules on the bacterial cell wall (host-specific).
2. Injection (entry)	The phage injects its nucleic acid genome into the host; the empty capsid stays outside.
3. Replication + synthesis	Host enzymes and ribosomes are hijacked to copy the viral genome many times and to make viral proteins (capsomeres, tail parts).

Stage	What happens
4. Assembly	New genomes and capsid proteins self-assemble into many complete virions inside the host.
5. Lysis (release)	Viral enzymes break down the cell wall; the cell bursts (lysis), releasing progeny phages to infect new cells.

The result is the rapid destruction of the host and the release of many new virions — often within tens of minutes for a bacteriophage.

> **Sequence trap:** Keep the order right: attach → inject → replicate/synthesise → assemble → lyse. A common mistake is to describe assembly before enough genome copies and proteins have been made.

5. The lysogenic cycle

Some phages, called **temperate** phages, can take a quieter route. Instead of immediately destroying the host, the viral genome is integrated into the host chromosome and lies dormant, copied passively every time the bacterium divides.

Stage	What happens
1. Attachment + injection	As in the lytic cycle, the phage injects its genome into the host.
2. Integration	The viral genome is inserted into the host chromosome, where it is now called a **prophage**.
3. Replication with host	Each time the bacterium divides, it copies the prophage along with its own DNA, so the viral genes spread to all descendant cells without harming them.
4. Induction (switch)	A trigger such as UV light, chemicals or stress causes the prophage to excise itself and enter the **lytic cycle**, producing new virions and lysing the cell.

A dormant virus in this state can persist silently for many host generations. The lysogenic and lytic cycles are therefore two alternative pathways available to a temperate phage, not two separate viruses.

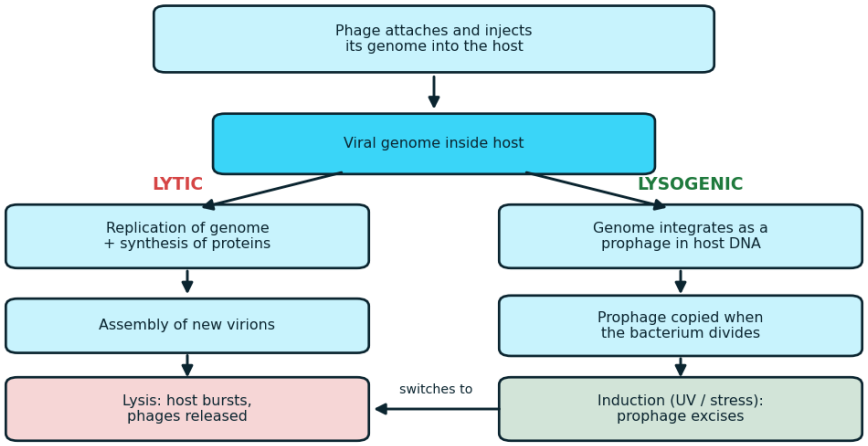

Figure 3. A temperate phage can follow either the lytic pathway (replicate, assemble, lyse) or the lysogenic pathway (integrate as a prophage, replicate with the host); induction switches lysogeny to lysis.

> **Link to disease:** A prophage can carry extra genes that change the host. Some bacteria only produce toxins (for example the diphtheria and cholera toxins) because a prophage in their genome codes for them — an example of how lysogeny alters the phenotype of the host.

6. Retroviruses — HIV

A **retrovirus** is an enveloped RNA virus that reverses the normal flow of genetic information. Instead of RNA being made from DNA, the virus makes DNA from its RNA genome using the enzyme **reverse transcriptase**, which it carries inside the capsid. HIV, the cause of AIDS, is the standard example.

Stage	What happens
1. Attachment + entry	Envelope glycoproteins bind receptors on a host cell (HIV targets helper T-lymphocytes / CD4 cells); the envelope fuses and the RNA + enzymes enter.
2. Reverse transcription	Reverse transcriptase copies the ssRNA genome into single- then double-stranded **DNA** (RNA → DNA, the reverse of transcription).
3. Integration	The enzyme integrase inserts the viral DNA into the host chromosome, where it is now called a **provirus** and may stay latent for years.
4. Transcription + translation	When active, the provirus is transcribed by the host into viral mRNA and new genome RNA; host ribosomes translate viral proteins.
5. Assembly + budding	New virions assemble and bud from the host membrane, taking a lipid envelope with them, then infect further cells.

Why this matters

The unusual replication cycle of retroviruses gives medicine several unique drug targets that human cells do not have:

- **Reverse transcriptase inhibitors** block the RNA → DNA step (e.g. the drug AZT/zidovudine).
- **Integrase inhibitors** stop the viral DNA joining the host genome.
- **Protease inhibitors** prevent the final processing of viral proteins.

Because these enzymes are viral rather than human, antiretroviral drugs can attack the virus with relatively little harm to the patient's own cells. Combining several such drugs (antiretroviral therapy) makes it far harder for the fast-mutating virus to become resistant to all of them at once.

> **Common confusion:** Reverse transcriptase makes **DNA from RNA** — the opposite of ordinary transcription. The integrated form of a retrovirus is a **provirus** (in a eukaryotic host); the integrated form of a bacteriophage is a **prophage**. Keep the two terms apart.

7. Why viruses evolve so rapidly

Viruses evolve faster than almost any other biological entity. Three factors combine to make this happen, and RNA viruses are the fastest of all.

- **High mutation rate:** RNA viruses copy their genomes with RNA-dependent polymerases that lack **proofreading**, so replication errors are frequent and are passed on. (DNA viruses proofread and mutate more slowly.)
- **Very short generation times:** a single infected cell can release hundreds of new virions in hours, so an enormous number of genome copies — and mutations — are produced quickly.
- **Recombination and reassortment:** when two different strains infect the same cell, they can swap or mix genome segments, creating new combinations in a single step.

Antigenic drift and shift (influenza)

Process	Mechanism	Consequence
Antigenic **drift**	Gradual accumulation of small point mutations in the genes for surface proteins.	Surface antigens change slowly; the flu vaccine must be updated most years.
Antigenic **shift**	Sudden reassortment of whole genome segments between strains (e.g. human + avian flu in one host).	A major new surface protein appears at once; the population has little immunity, so a **pandemic** can follow.

Consequences for vaccines and pandemics

- Rapidly changing surface antigens mean existing antibodies (from past infection or vaccination) may no longer recognise the virus.
- Vaccines must be reformulated frequently (influenza) or may be evaded by new variants (SARS-CoV-2).
- Fast mutation also drives the evolution of **drug resistance**, which is why combination therapy is used against HIV.
- A genuinely novel antigen (antigenic shift, or a spillover from an animal host) can spread through an immunologically naive human population and cause a pandemic.

8. The origin of viruses

Because viruses are so different from cells, their evolutionary origin is uncertain and probably not the same for every virus. Three main hypotheses are discussed; these are conceptual and you should be able to outline and evaluate them.

Hypothesis	Core idea	Support / difficulty
Escaped-gene (progressive)	Viruses arose from fragments of genetic material (e.g. plasmids or transposons) that 'escaped' from cellular genomes and gained the ability to move between cells.	Fits the close resemblance between some viral and host genes; explains host specificity.
Regressive (reduction)	Viruses are the remnants of once free-living cells that became parasites and lost all structures except their genes over time.	Some large complex viruses hint at cellular ancestors; but viruses lack any cellular remnants such as ribosomes.
Virus-first (co-evolution)	Self-replicating nucleic acids existed before, or alongside, the first cells and evolved in parallel with them.	Consistent with an early RNA world; but modern viruses depend completely on host cells, which is hard to reconcile.

How to answer: No single hypothesis explains all viruses, and the three are not mutually exclusive — different virus groups may have different origins. In an essay, outline each idea, give one point of support and one difficulty, then conclude that the evidence is currently inconclusive.

9. Worked exam explanations

Explanation 1 — Compare the lytic and lysogenic cycles

Command term: compare (give similarities *and* differences).

Similarities: both begin with attachment and injection of the phage genome into a bacterial host; both ultimately depend on the host's machinery; a lysogenic infection can convert into a lytic one.

Differences: in the **lytic** cycle the genome is immediately copied and expressed, new virions are assembled and the host is destroyed by lysis — it is fast and kills the cell. In the **lysogenic** cycle the genome integrates as a **prophage**, is replicated harmlessly with the host for many generations, and only later switches to the lytic cycle after induction. Lysis releases progeny in the lytic cycle; no new virions are made during lysogeny itself.

Explanation 2 — Explain why RNA viruses evolve rapidly

Their genomes are copied by RNA polymerases that lack **proofreading**, so mutations occur at a high rate and are inherited by progeny virions. Generation times are very short and each infected cell releases many virions, so a huge number of mutant genomes arise quickly. Co-infection allows **recombination or reassortment**, mixing genome segments in one step. Natural selection then favours variants that escape immunity or resist drugs. The overall consequence is frequent new strains, the need to update vaccines, drug resistance and the potential for pandemics.

Explanation 3 — Explain how a retrovirus replicates

A retrovirus enters a host cell after its envelope glycoproteins bind specific receptors. Its enzyme **reverse transcriptase** copies the single-stranded RNA genome into double-stranded DNA (RNA → DNA). The enzyme integrase inserts this DNA into the host chromosome as a **provirus**, which may remain latent. When activated, the host transcribes the provirus into viral mRNA and new genomic RNA and translates viral proteins; virions assemble and bud from the cell, gaining a lipid envelope. HIV is the standard example, and reverse transcriptase and integrase are targets for antiretroviral drugs.

10. Common pitfalls

- Calling a virus a cell. Viruses are **acellular** — they have no cytoplasm, membrane-bound organelles or ribosomes.
- Saying the envelope is made by the virus. The envelope is **host membrane** the virus takes as it buds out; only the glycoproteins in it are viral.
- Describing the capsid as made of lipid or nucleic acid. The capsid is always **protein** (capsomeres).
- Claiming viruses belong to a domain or kingdom. They are placed **outside** the three domains.
- Saying reverse transcriptase makes RNA. It makes **DNA from RNA** — the reverse of transcription.
- Muddling **prophage** (integrated bacteriophage) with **provirus** (integrated retrovirus).
- Stating flatly that viruses are alive or not alive. Examiners want the **debate**, with evidence on both sides.

11. Quick reference

Term	Meaning
Virion	A complete virus particle outside a host cell; inert.
Capsid / capsomere	Protein coat / the identical protein subunits that build it.
Envelope	Host-derived lipid membrane with viral glycoproteins (enveloped viruses only).
Bacteriophage	A virus that infects bacteria; often complex-shaped.
Lytic cycle	Attach → inject → replicate/synthesise → assemble → lyse; host destroyed.
Lysogenic cycle	Genome integrates as a prophage, replicates with host, later switches to lytic.
Temperate phage	A phage able to use either the lysogenic or the lytic cycle.

Term	Meaning
Retrovirus	RNA virus using reverse transcriptase to make DNA that integrates as a provirus (e.g. HIV).
Reverse transcriptase	Enzyme that makes DNA from an RNA template (RNA → DNA).
Antigenic drift / shift	Slow point mutation vs sudden reassortment of surface-antigen genes.

12. Test yourself

Attempt these without notes; full answers follow.

1. State three structural features common to all viruses.

2. Explain why viruses are described as obligate intracellular parasites.

3. Distinguish between a naked virus and an enveloped virus, and state where the envelope comes from.

4. List, in order, the five stages of the lytic cycle of a bacteriophage.

5. Explain what a prophage is and how it can later cause the death of the host cell.

6. Explain the role of reverse transcriptase in the replication of HIV, and why it is a useful drug target.

7. Explain, using the terms drift and shift, why a new influenza vaccine is often needed each year.

8. Outline one hypothesis for the origin of viruses and give one problem with it.

Answers

1. A nucleic acid genome (DNA or RNA); a protein capsid made of capsomeres; very small size (about 20–300 nm). (Some, but not all, also have a lipid envelope.)

2. They have no ribosomes, no metabolism and cannot make their own proteins or ATP, so they can only reproduce by entering a living host cell and using its machinery — hence 'obligate' (must) and 'intracellular' (inside a cell).

3. A naked virus has only a capsid around its genome; an enveloped virus has an additional outer lipid membrane studded with glycoproteins. The envelope is derived from the **host cell's membrane** as the virus buds out.

4. Attachment → injection/entry of the genome → replication of the genome and synthesis of viral proteins → assembly of new virions → lysis/release.

5. A prophage is a bacteriophage genome integrated into the host chromosome during the lysogenic cycle; it is copied harmlessly with the host DNA. If induced (e.g. by UV or stress) it excises and enters the lytic cycle, making new virions and lysing (bursting) the cell.

6. Reverse transcriptase copies HIV's single-stranded RNA genome into DNA (RNA → DNA), which integrase then inserts into the host genome as a provirus. Because human cells have no equivalent enzyme, inhibiting reverse transcriptase blocks viral replication with little effect on the patient's own cells, making it a specific drug target (e.g. AZT).

7. Influenza surface antigens change constantly. **Antigenic drift** is the gradual build-up of point mutations, so antibodies from previous years no longer match well; a reformulated vaccine is needed most years. **Antigenic shift** is sudden reassortment producing a major new antigen, against which the population has little immunity, risking a pandemic.

8. For example, the **regressive hypothesis**: viruses are reduced descendants of once free-living cells that lost all structures except their genes. Problem: viruses retain no cellular remnants such as ribosomes, so there is little direct evidence of a cellular ancestor. (Other acceptable answers: escaped-gene or virus-first hypotheses with an appropriate difficulty.)