

Conjugation, Transduction & Transformation

The Three Routes of Horizontal Gene Transfer in Bacteria | Microbial Genetics Study Notes

1. Horizontal Gene Transfer — Evolution Without Reproduction

Bacteria don't only inherit genes vertically from a parent cell at division — they can also acquire entirely new genes sideways, from other bacteria or from the environment, in a single generation. This is **horizontal (lateral) gene transfer (HGT)**, and it is the single biggest reason bacterial evolution can be so fast: a beneficial gene (say, for antibiotic resistance) can spread through a population in one step, without waiting for mutation and selection to build it from scratch. Bacteria accomplish this through three distinct mechanisms, each defined by how the donor DNA physically reaches the recipient:

- **Transformation** — the recipient takes up naked, free DNA directly from its surroundings.
- **Transduction** — a bacteriophage (bacterial virus) accidentally packages and delivers bacterial DNA.
- **Conjugation** — two cells physically connect and DNA passes directly through a mating bridge.

The common thread

In every case, the incoming DNA must be either replicated as a self-sustaining unit (like a plasmid) or physically **recombine** into the recipient's own chromosome to be inherited by future generations — otherwise it is simply diluted out or degraded.

2. Transformation

Transformation is the uptake of free (“naked”) DNA fragments from the environment by a recipient cell, followed by their stable incorporation into the genome. It was the very first mechanism of gene transfer ever discovered — **Frederick Griffith's 1928 experiment** showed that heat-killed, virulent *Streptococcus pneumoniae* could transfer a “transforming principle” to live, non-virulent bacteria, converting them to virulent forms. Oswald Avery, Colin MacLeod, and Maclyn McCarty later identified that principle as DNA itself (1944), providing some of the earliest direct evidence that DNA is the genetic material.

2.1 Natural Competence

Only cells in a physiological state called **competence** can take up DNA efficiently. Some bacteria (e.g. *Streptococcus pneumoniae*, *Bacillus subtilis*, *Neisseria gonorrhoeae*) become naturally competent at particular points in their growth cycle, expressing surface DNA-binding receptors and an uptake channel. Many others are not naturally competent at all under normal conditions; laboratories induce **artificial competence** in these species using calcium chloride treatment plus heat shock, or by electroporation, to force DNA across the membrane — the basis of everyday genetic-engineering DNA cloning.

Transformation — Uptake of Naked (Free) DNA by a Competent Cell

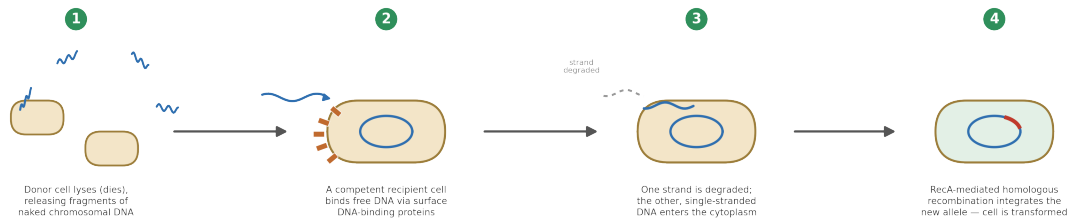


Fig. 1 — Transformation: DNA released from a lysed donor is bound by a competent recipient, taken up as a single strand while the complementary strand is degraded, and recombined into the chromosome by RecA-mediated homologous recombination.

2.2 Mechanism, Step by Step

- A donor cell dies and lyses, releasing fragments of double-stranded chromosomal DNA into the surroundings.
- A competent recipient's surface DNA-binding proteins bind a fragment, usually with little sequence specificity in most species.
- One strand is degraded by a membrane-associated nuclease as the fragment is taken up; the other enters the cytoplasm as single-stranded DNA.
- The RecA protein coats this single strand and searches the chromosome for a homologous region, catalysing strand invasion and recombination — replacing (or adding to) the resident allele.

2.3 Why It Matters

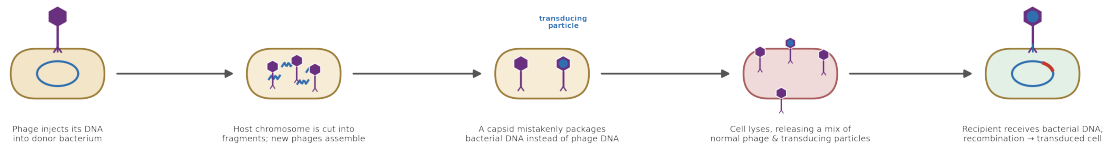
Natural transformation lets bacteria pick up useful genes — including antibiotic-resistance genes — straight from dead relatives or from the environmental DNA pool, contributing to the spread of resistance in clinical settings. Artificially induced transformation is also the routine, everyday first step of recombinant DNA technology — how a plasmid carrying a gene of interest is introduced into a laboratory *E. coli* strain.

3. Transduction

Transduction is gene transfer mediated by a **bacteriophage** — a bacterial virus unwittingly acts as a courier, packaging host DNA instead of, or along with, its own genome, and delivering it into the next bacterium it infects. There are two mechanistically distinct forms, tied to the two alternative lifestyles of a phage.

Transduction — Bacteriophage-Mediated Gene Transfer

Generalized Transduction (lytic cycle — any gene can be transferred)



Specialized Transduction (lysogenic cycle — only genes flanking the prophage)

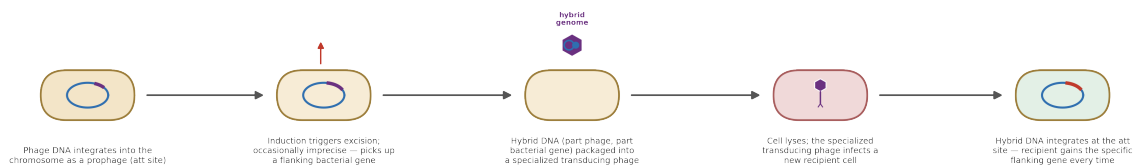


Fig. 2 — Generalized transduction (top): during the lytic cycle, a phage capsid occasionally mispackages random bacterial DNA instead of its own genome. Specialized transduction (bottom): imprecise excision of a lysogenic prophage carries specific flanking bacterial genes along with it.

3.1 Generalized Transduction

This occurs during a phage's **lytic cycle**. After infection, the phage degrades the host chromosome into fragments while replicating its own DNA and building new capsids. Packaging enzymes are not perfectly selective: occasionally a capsid mistakenly packages a fragment of bacterial DNA instead of the phage genome, producing a **generalized transducing particle**. Because packaging errors are essentially random, *any* bacterial gene can potentially be transferred this way — though each transducing particle carries only host DNA (no phage genes), so it cannot itself cause a new infection or lysis; the DNA it injects simply sits in the recipient until it recombines into the chromosome (or is lost).

3.2 Specialized Transduction

This occurs only in **temperate phages** capable of **lysogeny** — phages that integrate their genome into the host chromosome at a specific attachment (*att*) site and lie dormant as a **prophage**. Upon induction (e.g. UV damage, stress), the prophage normally excises itself precisely and re-enters the lytic cycle. Occasionally, however, excision is imprecise, and the phage carries away one or the other adjacent bacterial gene in place of some of its own DNA, forming a hybrid phage-bacterial genome. Because this always involves the specific genes flanking the fixed *att* site, specialized transduction can only transfer a small, predictable set of bacterial genes — in sharp contrast to the essentially random gene set of generalized transduction.

Generalized vs specialized — the key distinction

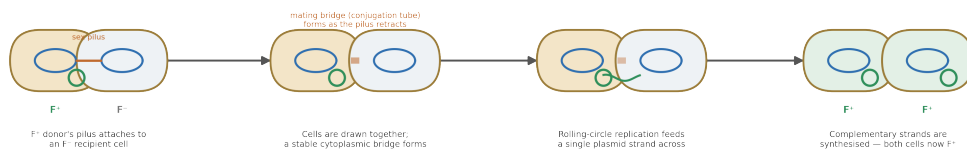
Generalized: lytic cycle, random packaging error, *any* gene can be transferred, particle carries only bacterial DNA. **Specialized:** lysogenic cycle, imprecise prophage excision, only genes *next to the att site* are transferred, particle carries a phage-bacterial hybrid genome.

4. Conjugation

Conjugation is the only one of the three mechanisms that requires **direct cell-to-cell contact**. A donor cell carrying a conjugative plasmid (classically the **F (fertility) factor** of *E. coli*) extends a thin proteinaceous appendage called a **sex pilus**, which attaches to a suitable recipient and retracts, drawing the two cells together into a stable mating pair joined by a cytoplasmic bridge.

Conjugation — Direct, Contact-Dependent Plasmid & Chromosomal DNA Transfer

$F^+ \times F^-$ Conjugation (plasmid transfer — recipient becomes F^+ too)



$Hfr \times F^-$ Conjugation (F factor integrated — chromosomal genes transferred)

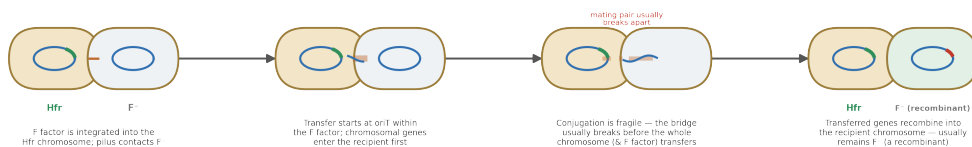


Fig. 3 — $F^+ \times F^-$ conjugation (top) transfers only the F plasmid, converting the recipient to F^+ . $Hfr \times F^-$ conjugation (bottom) transfers chromosomal genes from an integrated F factor, but the fragile mating bridge usually breaks before the whole chromosome — and the F factor itself — can transfer.

4.1 $F^+ \times F^-$ — Plasmid-Only Transfer

When the F factor exists as an independent, circular plasmid, the donor cell is called F^+ and the recipient (lacking F) is F^- . After the mating bridge forms, **rolling-circle replication** nicks one strand of the plasmid at the origin of transfer ($oriT$) and feeds it, 5' end first, across the bridge into the recipient. Both donor and recipient then synthesise a complementary strand to restore a double-stranded circle. Because the entire F plasmid transfers efficiently and quickly, **both cells end up F^+** — conjugation spreads plasmids, and any genes they carry (very often antibiotic-resistance genes), rapidly through a bacterial population.

4.2 $Hfr \times F^-$ — Chromosomal Gene Transfer

The F factor can also integrate into the host chromosome by homologous recombination between matching insertion-sequence elements, creating a **high-frequency recombination (Hfr)** strain. Conjugation still begins at $oriT$, but now that origin sits within the integrated F factor — so as rolling-circle transfer proceeds, it drags a copy of the adjacent **chromosomal DNA** across the bridge ahead of the rest of the F factor. The mating bridge is mechanically fragile and normally breaks well before transfer finishes (complete transfer of the ~100-minute *E. coli* chromosome is rare), so the recipient typically receives only a partial piece of chromosome and rarely the complete F factor — it becomes a **recombinant but usually remains F^-** . The transferred DNA is a linear fragment, not a self-replicating circle, so it must recombine into the recipient's own chromosome (again via RecA) to be inherited.

4.3 F' Plasmids

Occasionally an Hfr's integrated F factor excises imprecisely, taking a piece of adjacent chromosomal DNA with it back into an autonomous plasmid — producing an **F' (F-prime) plasmid**. A cell carrying F' can transfer both the F factor and its captured chromosomal genes together, efficiently and as a package, to an F⁻ recipient (a process sometimes called sexduction). This is directly analogous to how a specialized transducing phage captures nearby bacterial genes.

5. Comparison at a Glance

Feature	Transformation	Transduction	Conjugation
DNA source	Free DNA from the environment	Packaged inside a bacteriophage	Direct transfer from a live donor cell
Vector / carrier	None — naked DNA	Bacteriophage (virus) particle	Conjugative plasmid / sex pilus
Cell contact required?	No	No (phage acts as intermediary)	Yes — direct mating-pair contact
Recipient requirement	Must be competent	Must have the phage receptor	Must lack the plasmid (e.g. F ⁻)
Genes transferred	Any, from nearby lysed cells	Generalized: any. Specialized: only genes flanking the att site	Plasmid genes (F ⁺); or chromosomal genes near oriT (Hfr)
Discovered by	Griffith (1928); Avery, MacLeod & McCarty (1944)	Zinder & Lederberg (1952)	Lederberg & Tatum (1946)

6. Why These Three Mechanisms Matter

- **Antibiotic resistance spread:** all three mechanisms move resistance genes between bacteria, including across species — conjugative plasmids are especially notorious for rapidly disseminating multi-drug resistance.
- **Bacterial evolution & pathogenicity:** virulence factors (toxins, adhesins) are frequently acquired by HGT, sometimes packaged in “pathogenicity islands” transferred by phages or plasmids.
- **Tools of molecular biology:** artificial transformation (heat-shock/electroporation) is the standard way to introduce plasmids into lab strains; phage-based cloning vectors exploit transduction-like packaging; conjugative plasmids are engineered for targeted gene delivery.
- **Classic genetics experiments:** Hfr conjugation with timed interruption (the “interrupted mating” technique of Wollman & Jacob) was used to map the entire *E. coli* chromosome before DNA sequencing existed.

7. Quick Revision Points

- Three routes, one test question: **Transformation** = free DNA; **Transduction** = phage-carried DNA; **Conjugation** = direct cell contact via pilus.
- Transformation needs a **competent** recipient; uptake is single-stranded; integration needs **RecA**-mediated homologous recombination.
- Generalized transduction = lytic cycle, random gene, packaging error. Specialized transduction = lysogenic cycle, fixed genes near the *att* site, imprecise excision.
- F⁺ × F⁻ transfers only the plasmid — recipient becomes F⁺. Hfr × F⁻ transfers chromosomal genes — recipient usually stays F⁻ (a recombinant).
- F' plasmids arise from imprecise excision of an integrated F factor — the conjugation parallel to specialized transduction.
- All three ultimately require the incoming DNA to **replicate autonomously** (as a plasmid) or **recombine into the chromosome** to be stably inherited.

Study notes compiled for revision purposes — cross-check with your prescribed textbook (e.g. Prescott's Microbiology; Snyder & Champness, Molecular Genetics of Bacteria) before an examination.