Microbiology 305: Microbial Metabolism
Lecture 4
[Consetta Helmick]

Slide #: 1

Slide Title: WSU Online Title Slide

Title: Microbial Metabolism
Instructor: Consetta Helmick

[Image of WSU Cougar logo.]

Audio:
[Music playing in background.]

Slide #: 2

Slide Title: Microbial Metabolism

Microbial Metabolism

- Microbial Metabolism
  - Aerobic Cellular Respiration or in bacteria called the Embden-Meyerhof Pathway
  - Alternate Pathway
    - Pentose Phosphate Pathway
    - Entner-Doudoroff Pathway

Audio:
Lecture 4, Microbial Metabolism. Today’s lecture, we’re going to go over what organisms, including yourself, actually do with the macromolecules that you ingest. What do you do with glucose? How do bacteria produce proteins, nucleic acids, fats, all the components that they require. You gotta remember, bacteria don’t go up to McDonalds and order a hamburger. They get all their macromolecules from feeding off other lifeforms or decaying material, and then they have to take that material and make it into precursor molecules so that they can make all the components that they require for life. So we’ll be covering aerobic cellular respiration, or in bacteria it’s called the Embden-Meyerhof Pathway. We’ll also be talking about alternate pathways that bacteria have – the Pentose Phosphate pathway and the Entner-Doudoroff pathway.

Slide #: 3

Slide Title: A Glimpse of History

A Glimpse of History
Biologists had noticed that in vats of grape juice, alcohol and CO₂ are produced while yeast cells increase in number.
  - In 1850s, Louis Pasteur set out to prove
    - Simplified setup: clear solution of sugar, ammonia, mineral salts, trace elements
    - Added a few yeast cells – as they grew, sugar decreased, alcohol level increased
    - Strongly supported idea, but Pasteur failed to extract something from inside the cells that would convert sugar
  - In 1897, Eduard Buchner, a German chemist, showed that crushed yeast cells could convert sugar to ethanol and CO₂; awarded Nobel Prize in 1907

Audio:
If we go back and look at history, biologists, chemists, microbiologists have been observing these pathways for centuries and then eventually we finally figured them out. Biologists noticed that in vats of grapes juice, alcohol and carbon dioxide were produced while yeast numbers increased. What was going on? 1850, Louis Pasteur set out to prove it. Simplified set up, clear solution of sugar, ammonia, mineral salts, trace elements. Added a few yeast cells, voila, they grew. The sugar decreased, the alcohol levels increased, the organism increased, and we have metabolism. We also see that in 1897, Buchner a German chemist showed that crushed yeast cells could convert sugar into ethanol and carbon dioxide, and actually won a Nobel Prize in 1907 for this discovery.

Slide #: 4

Slide Title: Microbial Metabolism

Microbial Metabolism
  - All cells need to accomplish two fundamental tasks
    - Synthesize new parts
      - Cell walls, membranes, ribosomes, nucleic acids
    - Harvest energy to power reactions
    - Sum total of these is called [emphasized] metabolism
    - Human implications
      - Used to make biofuels
      - Used to produce food
      - Important in laboratory
      - Invaluable models for study
      - Unique pathways potential drug targets

[Image of several glasses of red and white wines.]

Audio:
Metabolism – microbial metabolism, eukaryotic metabolism – all cells need to accomplish 2 fundamental tasks. They need to synthesize new parts: cell walls, membranes, ribosomes, nucleic acids, everything that makes them, them. They need to harvest energy to power these reactions; they need to produce ATP. And the sum total of these reactions is called metabolism. In human implications, again we use this to make biofilm. We use these reactions to produce film – food. We use these reactions, again, in laboratory. They’re invaluable models for us to study. Because of their unique pathways, we look at potential drug targets, control mechanisms, and again, food production.

**Slide #: 5**

**Slide Title:** Principles of Metabolism

Principles of Metabolism
- Can separate metabolism into two parts
  - [emphasized] **Catabolism**
    - Processes that degrade compounds to release energy
    - Cells capture to make ATP
  - [emphasized] **Anabolism**
    - Biosynthetic processes
    - Assemble subunits of macromolecules
    - Use ATP to drive reactions
  - Processes intimately linked

*[Diagram depicting the processes of Catabolism and Anabolism.]*

*Image captions:*
- Catabolic processes harvest the energy released during the breakdown of compounds and use it to make ATP. The processes also produce precursor metabolites used in biosynthesis.
- Anabolic processes (biosynthesis) synthesize and assemble subunits of macromolecules that make up the cell structures. The processes use the ATP and precursor metabolites produced in catabolism.

**Audio:**
Principles of metabolism, broken into 2 parts: catabolism and anabolism. Catabolism is a process that degrades compounds to release energy. Cells capture to make, again, energy. So they take glucose and they make it into energy. Plants take photosynthesis and they make it into energy. Anabolism is a biosynthetic processing – assemble subunits of macromolecules. They use ATP to drive this reaction, so if you take glucose plus glucose plus glucose to make glycogen or again the cell wall, that’s anabolism. That’s gonna require energy produce the structures. The two of them are linked very closely together – so if you look at the illustration to the right, be aware of what’s happening as things are entering the cell, what the processes are, and how things are leaving the cell.

**Slide #: 6**
**Slide Title:** Energy

**Energy**
- Energy is the capacity to do work
- Two types of energy
  - [emphasized] Potential [end] stored energy (e.g., chemical bonds, rock on hill, water behind dam)
  - [emphasized] Kinetic [end] energy of movement (e.g., moving water)
- Energy in universe cannot be created or destroyed, but it can be converted between forms

[Image of a water dam.]

**Audio:**

Energy. Energy is the capacity to do work, or the ability to do work. And under energy we have 2 types. We have what is called the potential energy, or the stored energy – so this is kind of like the water behind the dam. This is the energy that’s stored in your muscles; this is the glycogen that stores glucose. Again, it’s potentially being ready to be used for energy. Then we have kinetic energy, and energy of movement. So if you go back to the dam, the water moving, the water moving out of the dam or running through a turbine to produce energy. You grab a baseball, you throw that baseball – that energy that has been stored in those muscles is now being made into energy that’s gonna allow the muscle to open up for the motion to be done, and for you to be able to throw that ball. So energy takes on a lot of different forms. If you also think about steam, you can take steam, put it into an engine, and you can run a locomotive. If you think about wind turbines, we’re capturing the energy from the wind, which would be the potential energy, putting it into a wind turbine, circulating those wind turbines and capturing energy, which would now be kinetic energy for electricity that could be used in your homes.

**Slide #: 7**

**Slide Title:** Harvesting Energy

**Harvesting Energy**
- Photosynthetic organisms harvest energy in sunlight
  - Power synthesis of organic compounds of CO\(_2\)
  - Convert kinetic energy of photons to potential energy of chemical bonds
- Chemoorganothrophs obtain energy from organic compounds
  - Depend on activities of photosynthetic organisms

[Diagram depicting energy harvesting.]

[Image captions:]
- Photosynthetic organisms harvest the energy of sunlight and use it to power the synthesis of organic compounds from CO\(_2\). This converts radiant energy to chemical energy.
Chemoorganotrophs degrade organic compounds, harvesting chemical energy.

Audio:
When it comes to harvesting energy, there’s a couple of ways that organisms can do it. We have our photosynthetic organisms such as plants, our cyanobacteria, our photosynthetic bacteria, that have the ability to capture energy from sunlight and in the process of using carbon dioxide can produce that energy or ATP and then also get the products needed for their existence. Then we have our chemoautotrophics, which obtain again, energy from organic compounds, food. Again, our organisms that decompose a carcass, you that eats – this again is a way of producing energy from using a macromolecule, running it through certain steps, and then again producing ATP. So how an organism does it depends again on their existence, their life form, their habitat, their environment, and their overall existence in an ecosystem.

Slide #: 8

Slide Title: Components of Metabolic Pathways

- Metabolic pathways
  - Series of chemical reactions that convert starting compound end product
    - May be linear, branched, cyclical

[Flow chart depicting components of metabolic pathways.]

Audio:
The process of metabolism is a series of chemical reactions. You’re gonna take glucose, you’re gonna run it through an 11 step process, and you’re gonna produce pyruvate. You’re gonna take pyruvate, you’re gonna run it through a 2 step process, and you’re gonna make acetyl CoA. You’re gonna take that acetyl CoA, run it through the TCA cycle or Krebs cycle, and you’re gonna produce products. Those products are gonna be set to the electron transport chain, and you’re gonna produce energy. So each one of these steps require very specific enzymes, which will be seen later – a leads to b, b leads to c, c leads to d. Intermediate steps are gonna be very important, precursor molecules of bacteria are gonna be extremely important. But what we wind up doing is we’re gonna start with something, we’re gonna run through an intermediate, we’re gonna wind up with an end product. Then the end product is gonna be fed to another cycle, and our ultimate goal is to produce ATP.

Slide #: 9

Slide Title: Three types of Glucose metabolism

Three types of Glucose metabolism
- Aerobic Respiration Cellular Respiration
- Anaerobic Respiration
- Fermentation
### Table 6.3 ATP-Generating Processes of Prokaryotic Chemoorganoheterotrophs

<table>
<thead>
<tr>
<th>Metabolic Process</th>
<th>Uses an Electron Transport Chain</th>
<th>Terminal Electron Acceptor</th>
<th>ATP Generated by Substrate-Level Phosphorylation (Theoretical Maximum)</th>
<th>ATP Generated by Oxidative Phosphorylation (Theoretical Maximum)</th>
<th>Total ATP Generated (Theoretical Maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic Respiration</td>
<td>Yes</td>
<td>O₂</td>
<td>2 in glycolysis (net) 2 in the TCA cycle 4 total</td>
<td>34</td>
<td>38</td>
</tr>
<tr>
<td>Anaerobic Respiration</td>
<td>Yes</td>
<td>Molecule other than O₂, such as nitrate (NO₃⁻), nitrate (NO₂⁻), sulfate (SO₄²⁻)</td>
<td>Number varies; however, the ATP yield of anaerobic respiration is less than that of aerobic respiration but more than that of fermentation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermentation</td>
<td>No</td>
<td>Organic molecule (pyruvate or a derivative)</td>
<td>2 in glycolysis (net) 2 total</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

**Audio:**

There are 3 forms of glucose metabolism – aerobic cellular respiration, anaerobic respiration (which seems a contradiction of terms, because anaerobic usually means not in the presence of oxygen), and fermentation. So if we look at table 6.3, what we’re seeing is that it’s giving you these examples. Aerobic cellular respiration, again, as a final electron acceptor, uses oxygen; it has to have oxygen. We’re gonna see that it’s gonna generate ATP through the process of substrate level phosphorylation. It’s also gonna generate ATP through the processes of oxidative phosphorylation, and then again wind up with a total number of ATP molecules. One glucose molecule in a eukaryotic cell, such as yourself, will produce 36 ATPs. A prokaryote will produce 38 ATPs. And the reason is that a prokaryote does not have a mitochondria. When pyruvate crosses the mitochondrial membrane it uses energy, so this is the reason why a eukaryotic cell produces 2 less ATP molecules than a prokaryotic cell. Anaerobic respiration, like I said in contradiction to terms we always think of anaerobic as in the process of non-oxygen, and it is. What we’re gonna see is these organisms use a different final electron acceptor – they can use sulfate, nitrate. They can use phosphate; they can use a number of different, again, components. And then down to ATP, they’re gonna produce varies from 2 to 34. So again, it just depends on the organism itself. Fermentation, again no electron transport chain. We’re gonna go from glucose to pyruvate, and then that pyruvate is converted into lactic acid or alcohol, depending on the life form itself. Eukaryotes, lactic acid. Prokaryotes, alcohol. But you’ll get a grand total of 2 ATPs being produced during this process.

**Slide #: 10**

**Slide Title:** Overview of Metabolism in Bacteria

Overview of Metabolism in Bacteria
- Central metabolic pathways
  - Glycolysis
  - Pentose phosphate pathway
  - Tricarboxylic acid cycle
- Key outcomes
  - ATP
  - Reducing power
  - Precursor metabolites

[Flow chart overview of metabolism in bacteria.]

Audio:
Overview of metabolism in a bacteria – if we look at this, what we’re gonna see is in the 4 steps of aerobic cellular respiration we have glycolysis, the transition step or acetyl coa formation, glycolysis and electron transport chain. One of the things that bacteria can also do is they can have an additional pathway – they have what’s called a pentose phosphate pathway that will be using items from the aerobic cellular respiration to make them into precursor molecules which will become, again, parts that that organism actually requires. They also have the Entner-Doudoroff pathway, again that is also gonna go from glucose to pyruvate and we’re gonna be seeing a number of products being produced off of that pathway also.
If we look at a eukaryote, you, the only pathway you have is aerobic cellular respiration. So you take glucose to glycolysis to acetyl CoA, to the transition step, to the Krebs cycle or TCA cycle, and to the electron transport chain to produce again, energy.

Slide #: 11

Slide Title: Components of Metabolic Pathways

Components of Metabolic Pathways
- Roles of Enzymes
    - Highly specific: one at each step
    - Reactions would occur without, but extremely slowly

[Graph and flow chart showing metabolic pathways.]

Audio:
One of the most important components of metabolic pathways are enzymes. Remember enzymes have the ability to make or break chemical bonds. So we’re gonna take glucose, which is 6 carbon, we’re gonna break it down into the next form, and so forth and so forth. We’re gonna get through 10 steps of glycolysis which will wind us up with 2 pyruvate or
pyruvic acid molecules. Each of these 10 steps has its own enzyme. Enzymatic reactions are critical in aerobic cellular respiration, or any metabolic pathway. The other thing, that since enzymes are presences, enzymes are also catalysis. So they speed up the reaction – and by speeding up the reaction, we lower the activation energy. So if you think about it, A plus B to AB. If this takes a long time to generate that product AB, remember, all reactions are not 100% efficient; you’re gonna generate heat, and you’re gonna be generating heat through this process. But if I can take that same reaction and go [quickly] A plus B plus AB, product is gonna be quick. The reaction is sped up, we’re gonna see less, again, heat being generated and so we wind up again, activation energy is lower. So our enzymes make and break chemical bonds, and again, protect the biological system because they act as biological catalysts.

Slide #: 12

Slide Title: Energy Molecule

Energy Molecule
- Adenosine triphosphate (ATP)
  - Energy currency of cell
  - Three negatively charged phosphate groups repel
    - Bonds inherently unstable, easily broken
    - Releases energy to drive cellular processes
    - High energy phosphate bonds denoted by ~
    - ATP \( \rightarrow \) ADP + Pi

[Images showing molecular structures of phosphate groups and adenosine.]

Audio:
All life forms require energy – this is your gas, this is you fill up your cells. And if we look at this, you can see the importance of, again, our functional groups and our minerals. Adenosine triphosphate – three negatively charged phosphate groups repel. The bond is easily broken; it’s a high energy bond, so when the phosphate bond breaks it releases energy. We capture that energy and we use it for cellular energy, mechanical energy. So we’ll be seeing how this is gonna be produced through the process of metabolism. After the ATP bond is broken, we’re gonna be having ADP plus a phosphate bond – adenosine diphosphate. How do we go and make adenosine triphosphate? This is the process of metabolism – taking a glucose molecule, running it through aerobic cellular respiration, and again, producing ATP. Our next section of the material will be going into a lot of detail on metabolism and metabolic functions in prokaryotes and eukaryotes.

Slide #: 13

Slide Title: Slide 13

- Role of ATP
Adenosine triphosphate (ATP) is energy currency
- Composed of ribose, adenine, three phosphate groups
- Adenosine diphosphate (ADP) acceptor of free energy
- Cells produce ATP by adding P_i to ADP using energy
- Release energy from ATP to yield ADP and P_i

Three processes to generate ATP
- [emphasized] Substrate-level phosphorylation [end]
  - Exergonic reaction powers
- [emphasized] Oxidative phosphorylation [end]
  - Proton motive force drives
- [emphasized] Photophosphorylation [end]
  - Sunlight used to create proton motive force to drive

[Diagram showing unstable (high-energy) bonds.]

Audio:
As a cell goes through metabolism, there’s a various number of ways that they can produce, again, ATP – adenosine triphosphate. Again, your energy molecule. Adenosine triphosphate, again, is made up of ribose, adenine, and three phosphate groups. Adenosine diphosphate has, again, 2 phosphates attached. It can accept, again, free energy. And when those bonds are broken, it can release energy. So we’re recycling this product all the time; we start with ATP, break a bond, release energy, use that energy, and then through the process of metabolism we have to attach the high-phosphate bond back to the ADP to produce, again, a new ATP molecule. Cells can do this in 3 ways. We have what’s called substrate-level phosphorylation, this is a part that we’ll see during glycolysis and actually through the Krebs cycle. And then we have oxidative phosphorylation, which is proton motive force driven reaction, where we’ll be generating protons or hydrogens, running it through the electron transport chain – our high-energized electrons – and then again producing ATP. So this is where the bulk of our ATP will be produced. And then we have our photosynthetic organisms, again, that use photophosphorylation. So they’re gonna use sunlight to create, again, a proton motive force driven reaction also to produce ATP.

Role of Electron Carriers
- Energy harvested in stepwise process
  - Electrons transferred to [emphasized] electron carriers [end], which represent [emphasized] reducing power [end] (easily transfer electrons to molecules)
    - Raise energy level of recipient molecule
  - NAD⁺/NADH, NADP⁺/NADPH, and FAD/FADH₂
Table 6.1 Electron Carriers

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Oxidized Form (Accepts Electrons)</th>
<th>Reduced Form (Donates Electrons)</th>
<th>Typical Fate of Electrons Carried</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nicotinamide adenine dinucleotide (carries 2 electrons and 1 proton)</td>
<td>NAD$^+$ + 2 e$^-$ + 2 H$^+$</td>
<td>NADH + H$^+$</td>
<td>Used to generate a proton motive force that can drive ATP synthesis</td>
</tr>
<tr>
<td>Flavin adenine dinucleotide (carries 2 electrons and 2 protons; i.e., 2 hydrogen atoms)</td>
<td>FAD$^+$ + 2 e$^-$ + 2 H$^+$</td>
<td>FADH$_2$</td>
<td>Used to generate a proton motive force that can drive ATP synthesis</td>
</tr>
<tr>
<td>Nicotinamide adenine dinucleotide phosphate (carries 2 electrons and 1 proton)</td>
<td>NADP$^+$ + 2 e$^-$ + 2 H$^+$</td>
<td>NADPH + H$^+$</td>
<td>Biosynthesis</td>
</tr>
</tbody>
</table>

**Audio:**
There are a number of players involved in energy production from, again, ATP to ADP, high phosphate, reattach it to produce ATP. If it’s aerobic cellular respiration, then oxygen is gonna be required. If it’s anaerobic cellular respiration, the organism can use sulfate, nitrate, phosphate as the other final electron acceptor. But one of the more important items in this whole process is gonna be the electron carriers. So what we have is that we have NAD, which produces NADH. And we have NADP, which becomes NADPH. And then we have FAD that becomes NADH. These are basically electron baskets — if you think about it through the process of capturing energy or producing, again, the steps of aerobic cellular respiration, when we go from glucose to pyruvate, we’re gonna be generating some high-energized electrons. We’re also gonna be producing protons. We have to capture those high-energized electrons, put them in an electron carrier or a basket, and ship them off to the electron transport chain. Once the NADP delivers the high energized electrons and the protons, the NAD is now empty – it goes back to its original reaction site and picks up more protons and high energized electrons. If you look at table 6.1, basically what it’s showing you is NAD plus 2 electrons, plus 2 protons is gonna give you NADH plus a proton. And this is gonna be used to, again, generate proton motor force, reactions that are gonna eventually become ATP. We also have NAD plus 2 high energized electrons plus 2 protons, produces FADH. And again, this will be shipped off to the electron transport chain and we will be producing, again, energy. We also have NADP plus 2 electrons plus 2 protons which produce NADPH plus a proton – this is gonna be involved in biosynthesis and this is part of the Calvin cycle of our photosynthetic bacteria and our plants.

**Slide #:** 15

**Slide Title:** Aerobic cellular respiration Bacteria produce Precursor Metabolites

Aerobic cellular respiration Bacteria produce Precursor Metabolites
-Serve as carbon skeletons for building macromolecules

Table 6.2 Precursor Metabolites

<table>
<thead>
<tr>
<th>Precursor Metabolite</th>
<th>Pathway Generated</th>
<th>Biosynthetic Role</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Audio:
I’ve also mentioned precursor metabolites – now, precursor metabolites are only produced by bacteria, and during the steps of aerobic cellular respiration, glycolysis, acetyl CoA formation or the transition state, the Krebs cycle or the TCA cycle, bacteria can produce precursor molecules that are gonna be shipped off the become biosynthetic molecules. So if you look at the illustration in table 6.2, you have glucose 6-phosphate which is gonna be part of glycolysis. This can be biosynthetically made into the lipopolysaccharide layer – remember, that’s the grand-negative cell wall. Fructose 6-phosphate, again during glycolysis can become the peptidoglycan layer – the grand-positive cell wall. And if we continue with, again, the illustration, you can see where the precursor metabolites that are being produced during aerobic cellular respiration are gonna be extremely important because the bacteria has to be able to generate cell components, amino acids, and structural components so that, again, they have their existence. If we look at acetyl CoA during the transition step, that precursor molecule or metabolite is gonna become the fatty acids and those organisms again can use that for energy production. It would be very advisable to understand the precursor metabolites in, again, table 6.2 So this is an alternate pathway that we see with our prokaryotes that, again, have the ability to use aerobic cellular respiration and add additional steps so that they can produce components that they cannot attain from their food, and they have to internally generate.
- Glycolysis
- Pentose phosphate pathway
- Tricarboxylic acid cycle

- Key outcomes
  - ATP
  - Reducing power
  - Precursor metabolites

[Flowchart depicting metabolic pathways of bacteria.]

Audio:
We’ve seen this summary before, and again it’s very important to understand what’s going on with it, so it’d be advisable to look at this summary and to go back and think about what precursor molecules are actually being produced. And then we will be getting into the pentose phosphate pathway here in just a little bit.

Slide #: 17

Slide Title: Aerobic Cellular Respiration or Embden-Meyerhof Pathway in bacteria

Aerobic Cellular Respiration or Embden-Meyerhof Pathway in bacteria
- Requires oxygen as the final electron acceptor
- Produces 38 ATP’s in Bacterial and 36 ATP’s in Eukaryotic cells
- Prokaryotic cells produce precursor metabolites which become cellular components or macromolecules

Audio:
In summary again, aerobic cellular respiration or the Embden-Meyerhof pathway in bacteria – they both require oxygen as the final electron acceptor. They’re gonna produce 38 ATP’s in bacteria, 36 ATP’s in eukaryotic cells, due to the lack of mitochondria in a prokaryotic cell. Prokaryotic cells also, again, use this pathway to produce precursor metabolites which are gonna become structural components or macromolecules for their existence.

Slide #: 18

Slide Title: Slide 18

- Glycolysis
  - Converts 1 glucose to 2 pyruvates; yields net 2 ATP, 2 NADH
  - [emphasized] Investment phase: [end]
    - 2 phosphate groups added
    - Glucose split to two 3-carbon molecules
  - [emphasized] Pay-off phase: [end]
    - 3-carbon molecules converted to pyruvate
Generates 4 ATP, 2 NADP total

[Flowchart depicting the process of glycolysis.]

Audio:
If we go through the steps of aerobic cellular respiration, the first step is gonna be glycolysis. So whether we’re talking about a prokaryote or a eukaryote, it’s going to be the same. We’re gonna start with glucose, and eventually going through those 10 steps of glycolysis. One glucose molecule will become 2 pyruvates and in the process we will net yield of 2 ATP’s and 2 NADH’s. So remember these are electron baskets. Those will be shipped off to the electron transport chain. Go through these steps in detail, see what’s going on with them. Understand, again, the enzymes that are involved in it. So be sure to realize the importance of each step, the enzymes, where the addition of ATP, ADP is being produced, the phosphate groups being, again, exchanged. The glucose molecule being split into two 3-carbon molecules and then, again, our pay-off here at the end is we’re gonna start with our glucose molecule and convert it into 2 pyruvates to generate 4 ATP’s, spent 2 ATP’s, get a net total of 2 ATP’s, and produce, again, 2 NADH’s which will go off to the electron transport chain.

Slide #: 19

Slide Title: Bacterial Alternative Pathway

Bacterial Alternative Pathway
- Also breaks down glucose
- Important in biosynthesis of precursor metabolites
  - Ribose 5-phosphate, erythrose 4-phosphate
- Also generates reducing power: NADPH

Precursor metabolites
- Glucose molecules can have different fates
- Can be completely oxidized to CO₂ for maximum ATP
- Can be siphoned off as precursor metabolite for use in biosynthesis

Audio:
Also during these steps you have to realize too that the bacteria can also run the pentose phosphate pathway, and during the pentose phosphate pathway they can break down glucose and they can biosynthesize a number of precursor molecules. They can, at this time, produce the ribose 5-phosphate component of our nucleic acids, our nucleotides. They can also produce, again, ATP; they can also produce amino acids. This particular pathway also, again, can produce NADPH. So they start, again, with the precursor molecules of glucose, but it has a different fate than going from glucose to pyruvate and then eventually to the electron transport chain. So it’s kind of a spinoff of this particular aerobic cellular respiration so that they have the ability to produce additional components that they require for life.

Slide #: 20
Slide Title: 6.10. Anabolic Pathways – Synthesizing Subunits from Precursor Molecules

6.10 Anabolic Pathways – Synthesizing Subunits from Precursor Molecules

[Flowchart depicting anabolic pathways.]

Audio:
This illustration also, again, shows you the synthesizing of the precursor metabolites and what they’re gonna be used for, along with table 6.1 – it’s very advisable that you understand both of these tables. Where do these precursor metabolites generate from? And what will they biosynthetically become? Again, [inaudible] excellent illustration showing you all the steps and what those components do become.

Slide #: 21

Slide Title: Slide 21

- Transition step
  - CO₂ is removed from pyruvate
  - Electrons reduce NAD⁺ to NADH + H⁺
  - 2-carbon acetyl group joined to coenzyme A to form acetyl-CoA
  - Takes place in mitochondria in eukaryotes

[Diagram depicting transition step, captioned as follows:]
Transition Step: CO₂ is removed, a redox reaction generated NADH, and coenzyme A is added.
1. The acetyl group is transferred to oxaloacetate to start a new round of the cycle
2. A chemical rearrangement occurs
3. A redox reaction generates NADH and CO₂ is removed.
4. A redox reaction generates NADH, CO₂ is removed and coenzyme A is added
5. The energy released during CoA removal is harvested to produce ATP.
6. A redox reaction generates FADH₂.
7. Water is added
8. A redox reaction generated NADH.

Audio:
If we go back and think about aerobic cellular respiration, remember there’s 4 steps. So we from glycolysis, glucose, to 2 pyruvates. The transitional step or again acetyl CoA, that 3-carbon acetyl will now again go through the transition stage. And what we’re gonna do is we’re gonna move a carbon dioxide and so it’ll be a 2-carbon molecule. And in the process we’re gonna add a CoA, and when we add the CoA to this we’re gonna generate ATP. And we’re also gonna generated carbon dioxide. We’re also gonna generate some NADH which will go off to the electron transport chain. Advisable again, to write these steps out – let’s see what’s going on with each one of these steps. In a eukaryotic cell, again, these processes take
place in the mitochondria. So glycolysis occurs in the cytoplasm of the cell, and then the pyruvate crosses into the mitochondrial matrix. So again, loses a little bit of energy during this step. And then we’ll see the TCA or Krebs cycle occurring and then the electron transport chain will actually be in the mitochondrial membrane. In a prokaryote, everything occurs in the cytoplasm. So glycolysis occurs in the cytoplasm, and then again our transitional step, acetyl CoA formation, TCA or the Krebs cycle, and then eventually the electron transport chain will occur in the cell membrane. Remember, prokaryotes do not have a mitochondria but they do go through the same 4 steps as, again, our eukaryotic cells.

**Slide Title: Slide 22**

- **Tricarboxylic Acid (TCA) Cycle**
  - Completes oxidation of glucose
- **Produces**
  - 2 Co₂
  - 2 ATP
  - 6 NADH
  - 2 FADH₂
  - Precursor metabolites

[Diagram depicting transition step same as the previous slide.]

**Audio:**

This is the TCA cycle, or the Krebs cycle. Either one of them is interchangeable; Dr. Krebs is the individual who discovered it, figured it out and actually won a noble prize for it. But basically what we’re seeing is that we’ve gone from glucose to pyruvate, pyruvate now gets converted into acetyl CoA. The acetyl CoA now enters the TCA cycle – it’s the only molecule that can. Think of this as a paddle wheel. So as acetyl CoA is running through this cycle, it’s cycling through, reactions are occurring. We’re taking off the CoA molecule which will be recycled back up to the transition step. We’re going from a 2 carbon to a 6 carbon. We’ll be breaking those carbons down, producing carbon dioxide. We’ll be generating ATP through substrate level phosphorylation. We’re gonna generated some more high-energized electron and protons. Build those electron baskets, NADH. This time we’re gonna generate a new electron basket or carrier – FADH₂, and those will be shipped off to the electron transport chain. And in the process we’re gonna generate some water, and then so by the time we continue this whole paddle wheel, we started with a 2-carbon molecule, we’ve made it into a 6-carbon molecule and eventually it’ll go back to a 4-carbon molecule. Each one of these steps, again, are enzymatic driven. Be aware of the steps, look at what the steps all entail and what we’re producing at the end. So with each turn of the paddle wheel, one acetyl-CoA entering, you’re gonna end up with 2 carbon dioxides, 2 ATP’s, 6 NADH’s, 2 FADH₂’s, and precursor metabolites, if you’re a bacterial cell.

**Slide #: 23**
Once the NADH and the FADH$_2$ have been produced, they’re gonna be shipped off to the electron transport chain. This is where the majority of our ATP is actually gonna be produced. So in the next couple of illustrations we’ll be looking at it in the eukaryotic cell, which is basically the electron transport chain which is in the mitochondria. In a prokaryotic cell the electron transport chain is in the cell membrane. But they operate very, very similar. They’re a series of cytochromes, complex proteins that are embedded in the membranes themselves.

As you can see from the illustration here, we have NADP coming up to the first complex 1, it will deliver, again, those high energized electrons and the protons. What the high-energized electrons are doing is they’re energizing – they’re releasing energy and they’re forcing the proton across the membrane. So what we’re gonna do is we’re gonna generate a proton gradient. Every NADH that comes up there is gonna force the proton across the membrane; every FADH$_2$ that comes up there is also going to force their protons across the membrane. And that’s what the high energized electron does. So as the electron tumbles through the electron transport chain, it loses energy. And every time it goes through another complex or cytochrome, it releases energy; we force both protons across the membrane. Now what we’re doing is, again, generating a proton gradient in the inter-membrane space of the mitochondria. Eventually the electron will get old, it’ll wear out, it’ll lose all its energy, and it has to leave the complex. And so at the end here of complex 4, it will leave the electron transport chain, re-enter again the mitochondrial matrix. Well you can’t have an electron bouncing around, not being captured. So it’s this time that oxygen is required. So you’re gonna have 2 hydrogens plus half an oxygen plus this electron, and when this complex comes together, you’re forming water. So oxygen has to be at the end of the electron transport chain so that, again, it can capture those electrons. The proton gradient – if you think about it, an increase in hydrogen equals acidic. So we’ve now dropped the Ph in the inter-membrane space, which is an irritant. And we will see is that the protons will travel to the ATP synthetase. So this is a very complex molecule that sits in the mitochondrial membrane. As the protons enter the ATP synthetase, they will literally start to rotate. And as this thing rotates and gains speed, it will produce energy. So think about the fireworks on the 4th of July. Kaboom! Huge blast of energy is gonna be produced. The proton that enters ATP synthetase will be shot off to the side, the kaboom energy that’s gonna be produced at this time, the explosion will now take ADP, reattach that high energy bond of phosphate and generate ATP. So we’re generating, again, NADH which we’re carrying protons and high-energized electron FADH$_2$ to be delivered to the electron transport chain, set up the proton gradient, capture the spent electron at the end of the electron transport chain with oxygen. Again, produce water, run those protons through ATP synthetase, take ADP plus the
phosphate bonds, and create ATP. Amazing system, again, if you really think about it. Just unbelievable.

**Slide #:** 24

**Slide Title:** The Electron Transport Chain -

The Electron Transport Chain –

[Diagram depicting the electron transport chain and use of proton motive force in a prokaryotic cell.]

**Audio:**

Alright, now let’s look at the same process of the electron transport chain in a prokaryotic cell. The only thing that is different is the prokaryotic cells have a little bit different composition of cytochromes. The process is gonna be the same. The location will be different, since prokaryotes do not have mitochondria, this whole process will occur in the cell membrane. And we’ll be creating that proton gradient in the inner cell membrane space between the cell membrane and the cell wall. Again, same kind of thing. NADH is gonna come up to the first cytochrome, and in the presence of NADH dehydrogenase, again an enzyme. The electron will enter the electron transport chain, the proton will be shoved into the inner cell membrane space, the electron tumbles, again, through the electron transport chain, releasing energy, forcing more protons over, releasing energy, forcing more protons over and eventually creating that proton space or a proton gradient. The electron has to leave after it’s been de-energized. Oxygen will be sitting there to, again, capture it. And we will produce water. Prokaryotes also, again have ATP synthetase, the same process. Run the protons through ATP synthetase, create that big kaboom of energy, take ADP, reattach the phosphate and produce ATP. We also can see that if you think about, when we thought of talked about flagella. Remember the flagella has a rotational capacity – it sits in the cell membrane, and this is what allows organisms to move, that rotational capacity. Now if you think about it also at this time, a phenomenal place to produce ATP – that high-energized reaction that is occurring. So our ATP, our electron transport chain is gonna be in close proximity with again rotation of the flagella. Also, organisms just like you have to get things across their cell membrane – the process of active transport requires energy. So what a slick evolutionary design – produce ATP at that location, use it for active transport, or again use it for the rotation of the flagella itself.

**Slide #:** 25

**Slide Title:** The Electron Transport Chain

The Electron Transport Chain

- Electron transport chain is membrane-embedded electron carriers
  - Pass electrons sequentially, eject protons in process
  - [emphasized] Prokaryotes: [end] in cytoplasmic membrane
- **Eukaryotes**: in inner mitochondrial membrane
- Energy gradually released
- Release coupled to ejection of protons
- Creates electrochemical gradient
- Used to synthesize ATP
- Prokaryotes can also power transporters, flagella

*Diagram depicting stair stepping process of the electron transport chain.*

**Audio:**
This illustration again is summarizing the electron transport chain. So if you’re a eukaryotic cell, it’s embedded in the mitochondrial membrane. If you’re a prokaryote, it’s embedded in the cell membrane. Basically doing the same thing – we’re delivering those electron carriers NADH, FADH$_2$ to this location. The highly energized electron is entering the cytochrome which is specific, again, for the prokaryote or the eukaryote. The electron is gonna be tumbling through the cytochromes, releasing energy, capturing protons, forcing them across the membranes, creating a proton gradient. Once that proton gradient is produced, you get acidic environment. Those protons will go over to the ATP synthetase, get shot through the ATP synthetase, take ADP plus phosphate and create ATP. Also again in prokaryotes, remember that the flagella and transport proteins for active transport are also located in these areas so that they can capture that energy as it comes off and be used again as their energy source.

**Slide #: 26**

**Slide Title:** The Electron Transport Chain

The Electron Transport Chain
- ATP Yield of Aerobic Respiration in Prokaryotes
  - Substrate-level phosphorylation:
    - 2 ATP (from glycolysis; net gain)
    - [emphasized] 2 ATP (from the TCA cycle) [end]
    - 4 ATP (total)
  - Oxidative phosphorylation
    - 6 ATP (from reducing power gained in glycolysis)
    - 6 ATP (from reducing power gained in transition step)
    - [emphasized] 22 ATP (from reducing power gained in TCA cycle) [end]
    - 34 (total)
- Total ATP gain (theoretical maximum) = 38

**Audio:**
If we look at the total number of ATP’s being produced during aerobic cellular respiration in a prokaryote, during the process of substrate level phosphorylation which occurs in glycolysis and the Krebs cycle or the TCA cycle, you’re gonna generate a grand total of 4 ATP’s. During
the process of oxidative phosphorylation, this is where you’re generating your NADH baskets or electron carriers and your FADH$_2$ baskets or electron carriers that are being delivered to the electron transport chain and again generating ATP. So from glycolysis, again, you’re gonna generate 6 ATP’s, you generate 2 NADH’s times 3 ATP’s each equals 6 ATP’s. During, again, acetyl CoA you’re also gonna generate 2 NADH’s that are gonna be worth 3 ATP’s each, 3 times 2 is 6 so you wind up again with a grand total of 6 ATP’s. And during the process of Krebs cycle, you will generate 6 NADH’s that are gonna be worth 3 ATP’s each which gives you 18 ATP’s, you’re gonna generate 2 FADH’s that are gonna be worth 2 ATP’s each so you’re gonna generate a grand total of 4 ATP’s. So 18 times [sic] 4 equals 22. So during that process you’re gonna create a grand total of 34 ATP’s. You’re add in your substrate level phosphorylation, ATP generation and you wind up with a grand total of 38 ATP’s for one glucose molecule.

In a eukaryote you’re gonna see the exact same thing happening, except that the NADH’s that are produced during glycolysis will only be worth 2 ATP’s each, because as those NADH’s cross the mitochondrial membrane they lose a little bit of energy. So instead of those particular ATP’s being worth 6 ATP’s each, they’re gonna be worth 4, and then we’re gonna wind up, again, with 34 plus 2 ATP’s which is gonna equal 36 ATP’s as a grand total for your eukaryotic cell.

Slide #: 27

Slide Title: ATP Yield of Aerobic Respiration in Prokaryotes

ATP Yield of Aerobic Respiration in Prokaryotes

[Diagram depicting ATP yield of aerobic respiration in prokaryotes.]

Audio:
So just an extra illustration, again walking you through the steps of glycolysis, the transition step and the Krebs cycle, showing you where all the FADH’s, NADH’s and ATP’s are being generated. Same thing would be occurring, again, for a eukaryotic cell except for our grand total would be 1 glucose equals 36 ATP’s. Prokaryotes, 1 glucose equals 38 ATP’s.

Slide #: 28

Slide Title: Anaerobic environments

Anaerobic environments

- Prokaryotes unique in ability to use reduced inorganic compounds as sources of energy
  - E.g., hydrogen sulfide (H$_2$S), ammonia (NH$_3$)
    - Produced by anaerobic respiration from inorganic molecules (sulfate, nitrate) serving as terminal electron acceptors
    - Important example of nutrient cycling
Table 6.7 – Metabolism of Chemolithotrophs

<table>
<thead>
<tr>
<th>Common Name of Organism</th>
<th>Source of Energy</th>
<th>Oxidation Reaction(s) (Energy Yielding)</th>
<th>Important Feature(s) of Group</th>
<th>Common Genera in Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen bacteria</td>
<td>H₂</td>
<td>H₂ + ½ O₂ → H₂O</td>
<td>Can also use simple organic compounds for energy</td>
<td>Hydrogenomonas</td>
</tr>
<tr>
<td>Sulfur bacteria (non-photosynthetic)</td>
<td>H₂S</td>
<td>H₂S + ½ O₂ → H₂O + S S + 1½ O₂ + H₂O → H₂SO₄</td>
<td>Some members of this group can live at a pH of less than 1.</td>
<td>Acidithiobacillus, Thiobacillus, Beggiotoa, Thiothrix</td>
</tr>
<tr>
<td>Iron bacteria</td>
<td>Reduced Iron (Fe^{2+})</td>
<td>2 Fe^{2+} + ½ O₂ + H₂O → 2 Fe^{3+} + 2 OH⁻</td>
<td>Iron oxide present in the sheaths of these bacteria</td>
<td>Sphaerotilus, Gallionella</td>
</tr>
<tr>
<td>Nitrifying bacteria</td>
<td>NH₃</td>
<td>NH₃ + 1½ O₂ → HNO₂ + H₂O</td>
<td>Important in the nitrogen cycle</td>
<td>Nitrosomonas</td>
</tr>
<tr>
<td></td>
<td>HNO₂</td>
<td>HNO₂ + ½ O₂ → HNO₃</td>
<td>Important in the nitrogen cycle</td>
<td>Nitrobacter</td>
</tr>
</tbody>
</table>

Audio:
We also said that bacteria can produce energy through the process of anaerobic respiration in anaerobic environments. So they have they unique ability to reduce inorganic compounds as a source of energy; so their final electron acceptor can be something besides, again, oxygen. So we have organisms that can use, again, hydrogen as their final electron acceptor. We have some that can use sulfur as their final electron acceptor, iron as their final electron acceptor, carbonate as their final electron acceptor, nitrates, nitrites as their final electron acceptor. So table 6.7 is an excellent illustration, showing you these organisms that have the ability to exist in an anaerobic environment, can use a different final, again, electron acceptor. So be aware of the groups that can do this, what electron acceptor that they actually do. And when organisms use anaerobic respiration, they can produce anywhere from 2 to 36 ATP’s, depending on the organism itself. These are also very important in the nutrient cycles. We talked about nitrogen cycle; we talked about sulfur cycle; we talked about the phosphorous cycle. These organisms that can use, again, different final electron acceptors, cycle the nutrients through the systems through life through ecosystems, and again allow them to survive through ecosystems and again allow them to survive and exist.

Slide #: 29

Slide Title: The Electron Transport Chain

The Electron Transport Chain

  - Harvests less energy than aerobic respiration
    - Lower electron affinities of terminal electron acceptors
  - Some components different
  - Can synthesize terminal oxidoreductase that uses nitrate as terminal electron acceptor
- Produces nitrite
  - [emphasized] E. coli [end] converts to less toxic ammonia
- Sulfate-reducers use sulfate (SO\textsubscript{4}\textsuperscript{2-}) as terminal electron acceptor
  - Produce hydrogen sulfide as end product

Audio:
If we look at some examples of organisms, remember E. coli is a facultative anaerobe. It can exist in oxygenated environment, it can be a true anaerobic bacteria, or it can be a facultative anaerobe which means it can actually use a different final electron acceptor. This process again usually harvests less energy. Some of the components are a little bit different: terminal oxidoreductase again can use nitrates as a terminal electron acceptor, again instead of oxygen. E. coli can convert less toxic ammonia. We also see sulfate reducers, again, that can use sulfate as their final electron acceptor, and we saw this with our nutrient cycling. And this is where you get your rotten egg smell, because again it’s using hydrogen sulfite as its end product.

Slide #: 30

Slide Title: Fermentation

Fermentation
  - Fermentation end products varied; helpful in identification, commercially useful

- Ethanol
- Butyric acid
- Propionic acid
- 2, 3-Butanediol
- Mixed acids

<table>
<thead>
<tr>
<th>Pryruvate</th>
<th>Fermentation pathway</th>
<th>Microorganisms</th>
<th>End products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lactic acid</td>
<td>Ethanol</td>
<td>Butyric acid</td>
<td>Propionic acid</td>
</tr>
<tr>
<td>Streptococcus</td>
<td>Lactobacillus</td>
<td>Saccharomyces</td>
<td>Clostridium</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>Ethanol CO\textsubscript{2}</td>
<td>Butyric Acid Butanol Acetone Isopropanol CO\textsubscript{2} H\textsubscript{2}</td>
<td>Propionic acid Acetic acid CO\textsubscript{2}</td>
</tr>
<tr>
<td>[Images of pickles, yogurt, and sauerkraut.]</td>
<td>[Images of wine and beer.]</td>
<td>[Image of can of acetone.]</td>
<td>[Image of cheese.]</td>
</tr>
</tbody>
</table>
The process of fermentation, again, is another way of organisms to exist and produce energy, but they only usually produce about 2 ATP’s. But in the process of fermentation they produce by-products or end-products. So this is where you get the production of cheese, yogurt, depending again on what the organism uses, they can produce different by-products through the process of fermentation. So if we look at the illustration below, we have pyruvate that can be converted into lactic acid. Our organisms are gonna be streptococcus, lactobacillus, and we wind up with lactic acid and the production of foods. Pickles, yogurt, sauerkraut, cheeses. We talked about this from the lecture before. Some organisms can produce ethanol – so our organism saccharomyces which is yeast can again go through fermentation and they will produce ethanol and carbon dioxide. Some organisms also again can produce butyric acid, so again, we have our clostridiums that can produce butanol, acetone, butyric acid again as they go through the process of fermentation. Then we have other organisms, again, that can produce propionic acid, acetic acid, carbon dioxide. They can produce cheese, fingernail polish removal for women that use acetone, and again, acetic acid. Acetic acid is vinegar. We have mixed acids, again, E. coli can make a variety of different types of acids as their byproduct of the process of fermentation. So a lot of it depends on the organism itself, but we use these byproducts extensively in industry and in the food industry as a way of producing products that we require.

Audio:

So in summary, we’ve talked about aerobic cellular respiration, we have talked about anaerobic cellular respiration, and again, fermentation. So let’s look at what’s going on with these processes, and let’s look at it more from the alternate processes or pathways of the bacteria itself. If we start with aerobic cellular respiration in the bacteria, you can see the 4 steps of ACR – glycolysis, acetyl CoA, Krebs cycle and electron transport chain. So again, it’s gonna produce 36 ATP’s in a prokaryote and 36 ATP’s in a eukaryote.

Slide #: 31

Slide Title: Aerobic Cellular Respiration (ACR) in Bacteria summary

Aerobic Cellular Respiration (ACR) in Bacteria summary

- Glycolysis Glucose to pyruvate
  - Produces: 2 NADH, 2 ATP’s and 6 precursor metabolites
- Acetyl CoA or Transitional step
  - Produces: 2 NADH, 2 CO2 and 1 precursor metabolite
- TCA or Krebs cycle
  - Produces: 6 NADH, 2 FADH, 2 ATP’s, 4 CO2 and 2 precursor metabolites
- Electron Transport Chain
  - Produces: 38 ATP’s
- Oxygen required
  - Examples of Bacteria: E. Coli and Staph species
**Slide #: 32**

**Slide Title:** Summary

Summary

- Aerobic cellular respiration (ACR)
  - Or Embden-Meyerhoff Pathway in bacteria
- Pentose Phosphate Pathway
- Entener-Doudoroff Pathway

**Audio:**
If we look at aerobic cellular respiration or again the Embden-Meyerhoff pathway in bacteria, they have 2 pathways that they can also take. The pentose phosphate pathway or the Entener-Doudoroff, again pathway. So we will be looking at the summary of both these in just a second.

**Slide #: 33**

**Slide Title:** Pentose Phosphate Pathway Summary

Pentose Phosphate Pathway Summary

- Glucose to pyruvate
  - Produces:
    - 5 carbon sugar to intermediate products
    - Nucleic acids, nucleotides and amino acids
    - 1 ATP
    - 2 NADPH (Calvin cycle) Photosynthetic bacteria
    - Products to ACR, Anaerobic respiration and Fermentation
    - Example of bacteria are E. Coli and Bacillus Sp.

**Audio:**
We look at the pentose phosphate pathway, we got glucose going to pyruvate, and the organism in addition to producing glucose to pyruvate which could eventually go to produce ATP, if it’s an oxidative environment. They’re also going to produce 5 carbon sugars, which are gonna be in intermediate products. These 5 carbon sugars can be used for nucleic acids and nucleotides, they can also be used for, again, amino acids. They will generate 1 ATP. If it’s a photosynthetic organism, they will produce 2 NADPH’s which will be used, again, for the process of the Calvin cycle to produce photosynthetic byproducts. Products can go to ACR, anaerobic respiration, or fermentation, depending on what the organism is producing. Some of our organisms in this category are gonna be E. Coli and the Bacillus species.

**Slide #: 34**

**Slide Title:** Entner-Doudoroff Pathway summary
Entner-Doudoroff Pathway summary

- Glucose-pyruvate
- Produces:
  - 1 ATP
  - 1 NADH
  - 1 NADPH (Calvin cycle)
  - Products can go to ACR, Anaerobic respiration or Fermentation
  - Can process Glucose independent
    - EX Pseudomonas Sp, E. Coli, Bacteroides Sp.
    - Only Gram negative can use

Audio:
If we look at the Entner-Doudoroff pathway again, we’re gonna start with glucose, it’s gonna go to the pyruvate and it’s gonna produce 1 ATP, 1 NADH, 1 NADPH. Products can go to ACR, anaerobic respiration or fermentation. They can process glucose independently – so some of our organisms under this category will be the pseudomonas, E. Coli, and the bacteroides. Usually gram negative ones are the only one uses this pathway. So if we think about the process of metabolism – taking glucose, running it through 4 steps of aerobic cellular respiration and then again winding up with ATP. Our bacteria have the alternate pathways. So during aerobic cellular respiration, they also produce the precursor molecules or metabolites that they have to have so that they can produce structures. During, again, the pentose phosphate they can produce a variety of precursor molecules that will be used for other, again, cellular components and also again during the Entner-Doudoroff pathway. A lot of this depends on the organism itself: its adaptivity, how it’s evolved in its environment, what it’s required to produce so that it can, again, exist. So if you look at metabolism from the standpoint of a bacteria, they are so much more evolved than a eukaryotic cell. We require oxygen and, again, a food source. But they can pretty much get away with pseudomonas and anaerobic or a different organism so that they can exist in their habitat also.