

# The Chemistry of Carbohydrates Found in Food

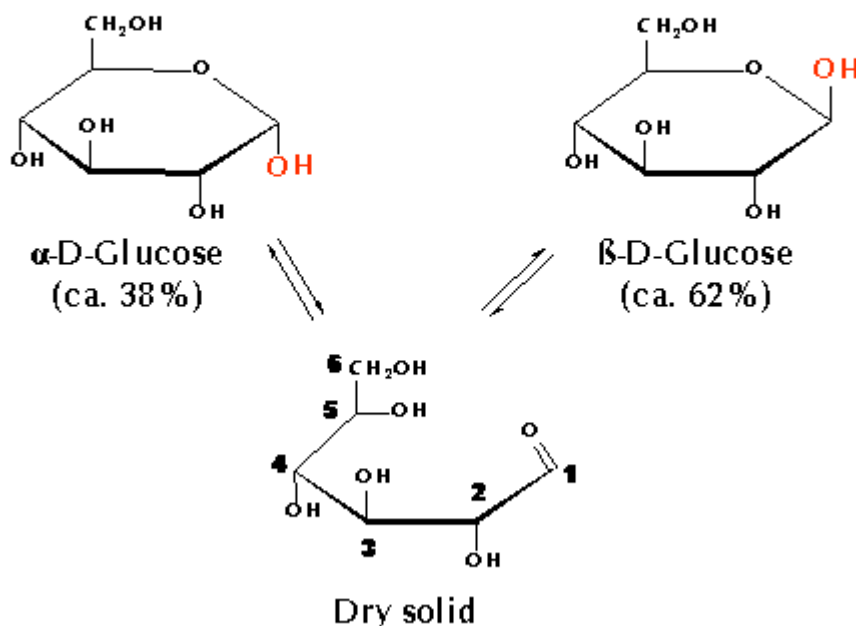
The carbohydrates we find in food fall into one of three groups; mono, di, or polysaccharides. The monosaccharides (and there are normally only three in our diet) are the building units of both disaccharides and polysaccharides. All biochemistry text books cover these topics in detail. I will only focus on some few points that are important to understand the fate and function of carbohydrates as an energy source in humans.

## Monosaccharides

### Glucose

The central actor in this game is glucose, known also as blood sugar and dextrose. Glucose is a "reducing sugar", that is, it is oxidized by ferric ( $\text{Fe}^{+++}$ ) and cupric ( $\text{Cu}^{++}$ ) ions yielding reduced metal ions. Glucose also reacts with itself, leading to formation of a "6-ring" (5 carbon atoms and 1 oxygen atom) seen in the figure. The really interesting thing with the ring form is that there are two forms of these,  $\alpha$ -D-Glucose and  $\beta$ -D-glucose. The first of these has

### Mutarotation of glucose



the C-1 hydroxyl group on one side of the ring and the 6th carbon in a side chain on the other side. In the beta form of glucose, both of these are on the same side of the ring. Did I hear you say "so what"? Just wait and you will see that this makes a huge difference in digestibility of polysaccharides made from these compounds.

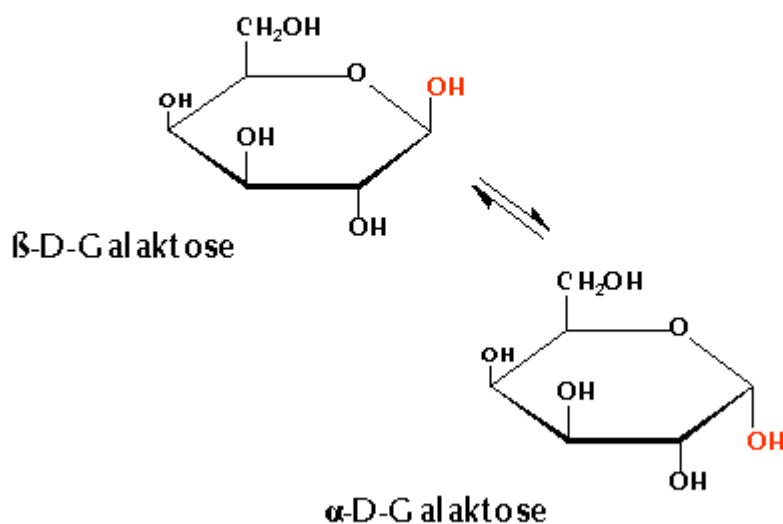
The carbonyl group in glucose also allows the sugar to interact with many other compounds. In the body this applies especially to various proteins. The level of glycosylated hemoglobin (HbA<sub>1c</sub>) is used as a measure of blood glucose levels over time. Much of the pathology seen in diabetes is thought to arise from reaction of glucose with the body's proteins. [Click here for more information about the toxic effects of glucose.](#)

## Galactose

The next of the three monosaccharides we should consider is galactose. This sugar is found in milk and milk products. Galactose is another "reducing sugar" and forms a "6-ring" when dissolved.

### Mutarotasjon av galaktose

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Galactose is, in fact, it is almost identical to glucose, the only exception being the position of the hydroxyl group on carbon 4. Once again, you will soon see that this "minor" difference has large

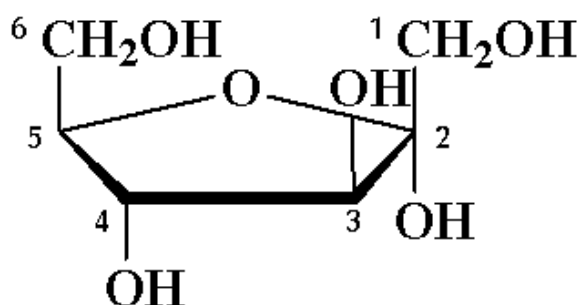
effects on metabolism and can lead to serious symptoms in some newborn babies. As with glucose, galactose undergoes mutarotation and has an alpha and a beta form. Only the beta form reacts with glucose to form the disaccharide lactose or milk sugar. Again, this has major effects on digestibility of lactose. We shall soon see that beta-linked disaccharides and polysaccharides are indigestible in humans. Lactose is the only exception to this rule. We have a specific enzyme, lactase, that catalyzes cleaving of lactose. While almost all new-born have this enzyme, most adults do not make lactase and are "milk intolerant". [You will find more about this by clicking here.](#)

## Fructose

Fructose is the third of the common sugars found in our diet. It has a unique structure giving rise to a "5-ring" where 4 carbon atoms and one oxygen atom are involved in the ring structure. As you can see, carbons one and six are not involved in the central ring and this affects both intestinal uptake and metabolism of fructose. Fructose is a natural but limited component of our diet, being found

## Fructose

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in limited amounts in many types of fruits and berries. Until about 150 years ago it played a minor role in human nutrition. Fructose is one of the two sugars that are found in sucrose or "table sugar". It was first in the 1800s that sugar plantations in the West Indies began to produce so much sucrose that this disaccharide became an important part of the western diet. With the increase in "table

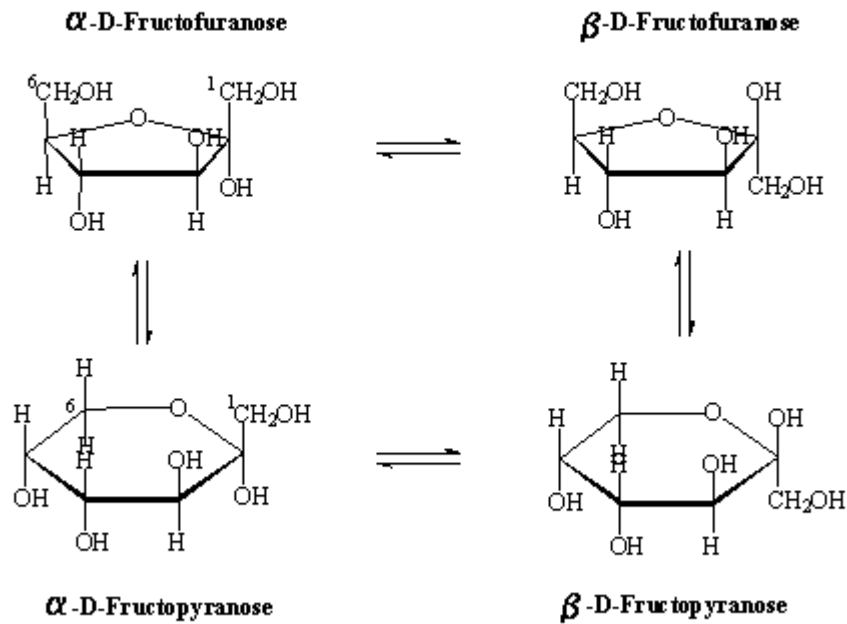
sugar" or sucrose, came a huge increase in the amount of fructose in our diet. While the consumption of sugar was some few kilograms per year around 1850, the normal annual consumption in most western lands is now around 40-50 kilograms. Monomeric fructose and glucose are now used in soft drinks in large quantities. As I have stated above, fructose is not handled as other monosaccharides in our bodies. I will come back to this under when I take up digestion of sucrose as well as under a discussion of the metabolism of monosaccharides. Fructose is sweeter than table sugar (sucrose). For this reason it has been suggested by many "health experts" that one can cut down on the calorie intake by replacing sucrose with fructose. Since fructose is 30-40% sweeter than sucrose, one should be able to eat 30-40% less sugar and get the same sweetening effect. This sounds logical, but is wrong.

Firstly, fructose has a different metabolism than glucose (the other half of sucrose and the same as blood sugar). The enzyme required to initiate fructose metabolism (fructokinase) is only found in the liver. Fructose is not a direct energy source for other tissues. Fructose metabolism is not controlled. It goes very quickly forward unrelated to hepatic energy utilization. This results in an increased synthesis of lipids and increased serum lipoproteins. Fructose is substrate "number one" for gluconeogenesis and gives a rapid rise in serum glucose levels.

That increased sweetness of fructose is a feature of the 5-ring. Now, it just happens that fructose in solution and at higher temperatures (tea and coffee, baking etc.) goes over to a 6-ring form. More correctly, the alpha and beta furanose forms (5-ring) are in equilibrium with the pyranose (6-ring) forms. The latter dominate in solution and the equilibrium reaction speeds up as the temperature increases. The pyranose forms of fructose are not sweeter than table sugar and one must use just as much fructose as sucrose in warm drinks and baked goods if equal sweetness is desired.

## Isomeric Forms of Fructose

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The message should be clear: increased fructose use, either from sucrose or the pure monosaccharide, is associated with increases in blood lipids (increased LDL and decreased levels of HDL) that are associated with cardiovascular disease. Fructose misses its sweetness when warmed and may not help to reduce caloric intake. Sorry, but fructose is not good for you! It's expensive too.

Let's look at some 3D models of these sugars.

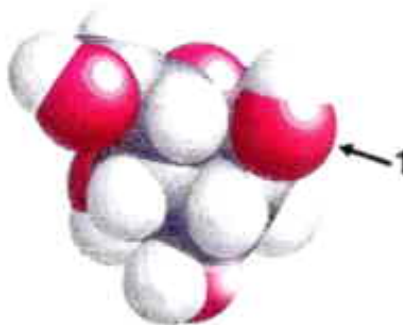
## Monosaccharides normally found in food

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Glucose



Galactose



Fructose



Here the red balls represent oxygen, the white hydrogen and the black, carbon. The black? Where are they? In the center of the sugar molecules! The ring structures are very compact. The hydroxyl groups, those with a white hydrogen on a red oxygen ball, dominate the surface of these molecules. Metabolic reactions involving large enzymes have to react with the easily reached hydroxyl groups. Look at glucose and galactose where the only difference is the position of the hydroxyl group on carbon 4. While the left side of galactose resembles that of glucose, something has happened at carbon 1. Here the hydroxyl group is turned upward

and is more accessible to enzymatic attack. We shall see that metabolism starts at carbon 1.

Compare the 5-ring fructose with the other sugars. It is really larger than both of the others and the hydroxyl groups on both carbon 1 and 6 are relatively open to enzymatic attack. Because of these "little" differences, both the intestinal uptake and metabolism of fructose differ from that of the other monosaccharides.

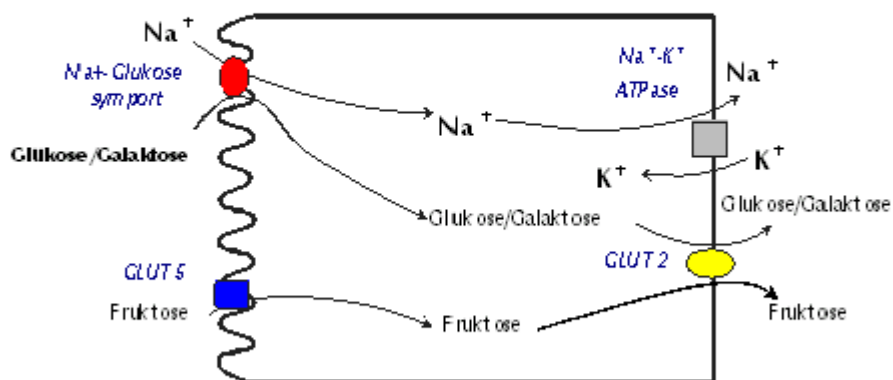
Metabolic derivatives of fructose have that 5-ring form. Perhaps that follows the more reactive -OH groups in the furanose forms of the sugar.

## Adsorption of sugars in the intestine

Adsorption of sugars in healthy persons occurs almost exclusively in the small intestine. Adsorption is limited to the monosaccharides glucose, fructose and galactose. These "mono-sugars" are large molecules and can only cross cell membranes when a "carrier protein" is present. These are very specific and do not react with and transport other sugars. This topic is very well discussed in most textbooks. I will take up just a few points here.

Note that uptake of glucose and galactose is through a  $\text{Na}^+$ -coupled symport driven by ATP. This is an active process. Uptake of these sugars is not dependent on a concentration gradient over the intestinal wall. Glucose and galactose are completely "sucked up" from the intestinal lumen and transferred over the mucosal cell to

### Monosakkaridtransport i Tynntarm



the intestinal circulation.

Fructose is not bound and moved by this active transporter. One of the glucose transport proteins (GLUT5) carries out this job. ([You can learn more about these transporters by clicking here](#)). GLUT5, just as the other members of the glucose transport protein family, is passive. It moves the sugar down a concentration gradient. That is, it requires that the fructose concentration in the intestinal lumen is higher than that in the mucosal cell. Transport from these cells to the circulation must also go "downhill". It is GLUT2, another glucose transport protein that carries fructose as well as glucose and galactose over the basolateral side of the intestinal cell. Why is the concentration of fructose in the portal blood so low that a concentration gradient is maintained during fructose uptake? The key to this is the liver's GLUT2 and fructokinase. These are very active and fructose is speedily removed from portal blood into the liver and trapped there as fructose-1-phosphate. This maintains the fructose concentration gradient over the intestinal cells in spite of the rapid absorption of the sugar.

I mentioned above that this localized uptake has to do with healthy persons. Intestinal inflammation reduces uptake; the enzymes responsible for splitting of disaccharides are produced in the intestinal mucosal cells. Inflammation causes temporary loss of these and a reduced uptake of sugars. Leakage of mono and disaccharides over intestinal membranes can also take place when these are inflamed.

## **Other monosaccharides used as dietary supplements**

There is no uptake mechanism for other monosaccharides in the small intestine. As we shall soon see, lacking or reduced uptake in the small intestine leads to further transport of sugars to the large intestine. There, bacteria overtake digestion, giving gas formation, pain and diarrhea when the transfer of sugar to the large intestine exceeds around 4-5 grams daily. This lack of small intestine uptake for some monosaccharides has been used to give "calorie-free" sweetening agents.

## **Sweet Sorbitol**

Sorbitol is a monosaccharide found in our metabolism, being produced from glucose and further metabolized to fructose. It is readily oxidized and is should be a good source of energy. BUT, it is not taken up in the small intestine since no carrier is found here.

Sorbitol is used in chewing gum and some "drops" as a "non-fattening" sweetener. As long as one takes less than those 4-5 grams all is well. More can give "stomach pain" and diarrhea.

## Ribose

Ribose is an essential part of our metabolic system, being found in phosphorylated form in, among other things, ATP. The diet supplement industry has presented ribose as a strength and energy giving stuff.

Take a look at the next figure. In a way, the statement is correct, but the body builds all the ribose-5-phosphate it needs from glucose. Dietary ribose is completely unnecessary for ATP synthesis. And, ribose is not adsorbed in the small intestine! The label states that the daily dose should be around 4-5 grams, so the producer seems to know that this stuff is not taken up.



## Ribose

**The most elemental source of energy in the body is ATP (Adenosine Triphosphate). This cellular energy is required to power your workouts and to recover from intense training. Your body must produce enough Ribose before it can build ATP, and that can take many days. [REDACTED] D-RIBOSE enhances your body's ability to restore its ATP stores faster and more efficiently, for better recovery and muscle growth.**

A Norwegian weightlifter was disqualified at the Olympic Games in Australia a few years ago. He had taken ribose daily but stopped before the Olympics. He began to lose strength, he said, and began with ribose again. Ribose "worked" for him. But why? He was taken for doping with Nandrolon, an anabolic steroid. His ribose was found to be "contaminated" with the stuff. He has sued the producer for this. The bottom line: there is no need for dietary ribose and no intestinal uptake of this sugar!

## The Disaccharides and their digestion.

All good things come in "threes" when we study carbohydrates. First three monosaccharides, now three disaccharides, each synthesized from two of those simple sugars.

### The BOND

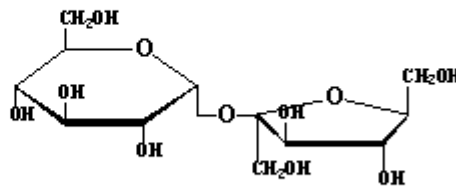
The first thing we must have straight is the nature of the bonds between the sugars in a disaccharide or polysaccharide. These ester bonds are formed through a dehydration of two hydroxyl

## Digestible Disaccharides in Food

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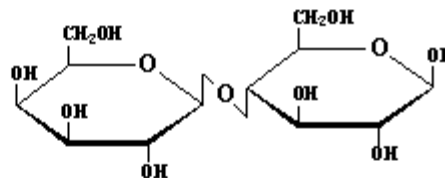
### Sucrose

(Glucose-fructose)



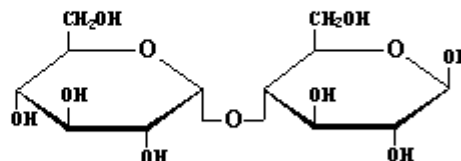
### Lactose

(Galactose-glucose)



### Maltose

(Glucose-glucose)



groups, one on carbon 1 and the other on carbon 4 of either glucose or galactose, or carbon 2 of fructose. If the carbon-1 hydroxyl group is in the beta position (same side of the ring as carbon 6), the resulting bond is a beta 1-4 glucosidic bond. If the hydroxyl group was under the ring (an alpha hydroxyl group) the resulting bond is called an alpha 1-4 or alpha 1-2 glucosidic bond. None of the enzymes that cleave glucosidic bonds in our digestive tract can

cleave beta 1-4 linkages. Well, there is ONE exception, lactase, which is specific for the beta 1-4 glucosidic bond in lactose, the sugar found in milk.

## Sucrose

The disaccharide sucrose is composed of glucose and fructose joined by an alpha 1-2 bond. As mentioned above, sucrose is a relative "new-comer" in our diet. It is actually not especially sweet, and we use large amounts to get the taste we desire in breakfast cereals, soft drinks, cakes and sweets. Just imagine using the same amount of salt in a recipe! Sugar has become a major energy contributor. A year's consumption of around 50 kilograms of sucrose calculates out to about 500-600 kilocalories per day (our total requirement is around 2000-2500 kcal/day). The problem is that we use sugar as though it was a spice, while we pile on a lot of empty calories in the process! See the later chapter about weight regulation.

Sucrose is readily cleaved by sucrase, one of the enzymes produced by and bound to the mucosa cells of the small intestine (for details see Marks, Marks and Smith, Basic Medical Biochemistry or another of the popular and good text books covering medical biochemistry). An important point to remember here is that the activity of sucrase does not normally limit the rate of absorption of the monosaccharides that result from cleavage of sucrose (glucose and fructose). There is ample enzymatic activity to digest the amounts of sucrose usually consumed by adults. However, intestinal infections or inflammation may well give rise to a temporary loss of mucosa cells with a loss of enzyme activity. Any carbohydrate that reaches the large intestine will serve as a substrate for bacteria there. The resulting gas formation coupled with release of two and three-carbon products from bacterial metabolism can give pain and perhaps diarrhea. We see the same phenomena in children who eat and drink too many sweets. They simply take in more sucrose than they manage to digest. The resulting tummy ache is the result of bacterial gas formation in the large intestine.

## Lactose

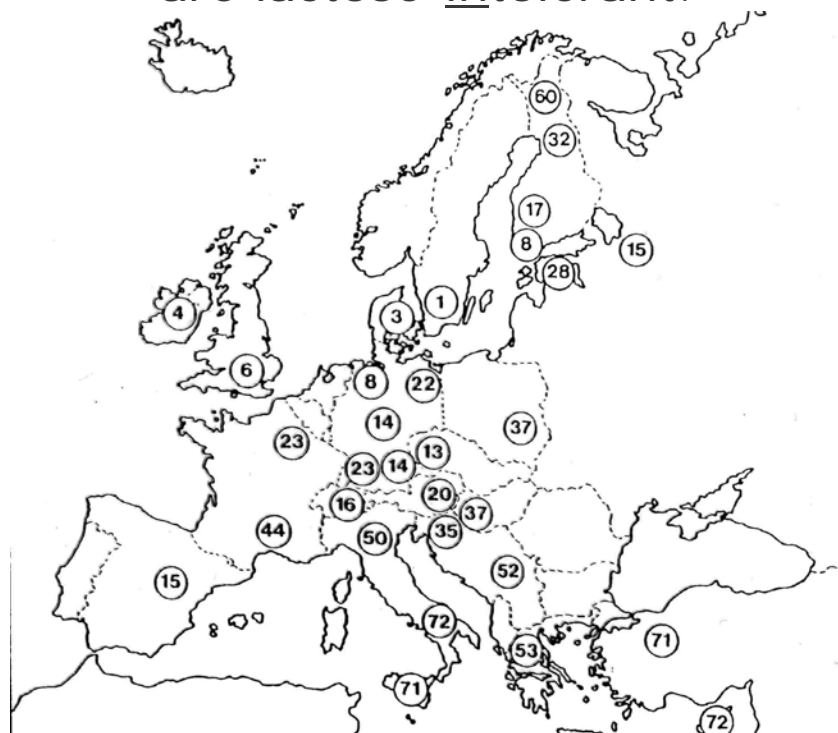
Lactose (or milk sugar) is a disaccharide composed of galactose and glucose. The enzyme responsible for synthesis of lactose is specific for the beta form of glucose and the result is a beta 1-4 glucosidic bond between the two monosaccharides. Lactose is the only substance with such a bond that can be digested in the human

intestine. This requires the presence of lactase, another of the enzymes involved in carbohydrate digestion that is produced and bound to the mucosal cell membrane. In contrast to sucrase and isomaltase, lactase production is restricted and can limit the digestion of lactose. Do you remember Mom who said "you mustn't drink milk when you have a tummy ache"? She "knew" that lactase production was reduced when the intestinal mucosa was enflamed. The result of drinking milk and other fresh dairy products in the absence of lactase is the transport of the sugar to the large intestine. Bacterial digestion of this leads to gas production. In addition will bacteria produce two and three carbon compounds that increase the osmotic pressure of the intestinal contents, thus retaining water. The result; "explosive diarrhea".

Lactase is usually found in the intestine at birth in all human races. In a global prospective one can state that production begins to decrease at the one to two-year stage and is all but lacking from the age of five years. Lactase-deficient adults can utilize milk products without discomfort if they are cultured with bacteria or yeast before ingestion. Culture milk, sour cream, yogurt and many cheeses are typical products in which microorganisms are allowed to digest lactose for us.

Lactose deficiency in adults is quite rare in Scandinavia. Examine this map.

### Percent of the adult population who are lactose-intolerant.



Most of the people in Sweden, Denmark, England, Ireland, Norway (not shown but about 5% intolerant) and northern Germany have lactase activity as adults. In southern Europe the percent of the population that is lactose-intolerant is much larger. Asians, many tribes in Africa, Jews and many others lack lactase as adults.

## A theoretical explanation distribution of adult lactase in Europe.

Glaciers covered Scandinavia during the last ice age. Migration to this largely uninhabited region began about 10,000 years ago as the ice began to retreat. Hunters followed the ice and reindeer and established a growing colony on the newly uncovered land. A mutation leading to life-long production of lactase must have occurred in the Scandinavian population at sometime during the these 10,000 years. Otherwise, we would have expected an even distribution of this gene and enzyme in Europe. Where do we find milk-tolerant people in Europe? In the UK, Ireland, Spain and along the rivers of Central Europe; areas of exploitation and commerce during the Viking period. Looks like things then were just about the same as in modern times! Strangely, the "gene" did not wander to Finland. H'mm.

This mutation can well have occurred several times as lactose-tolerant groups are also found in Africa.

## Espen



Meet Marianne and Espen. He is a happy Norwegian boy who is now about 9 years old. As a newborn he was not quite as happy. He was a typical colic-child who screamed and cried after every feeding and had an

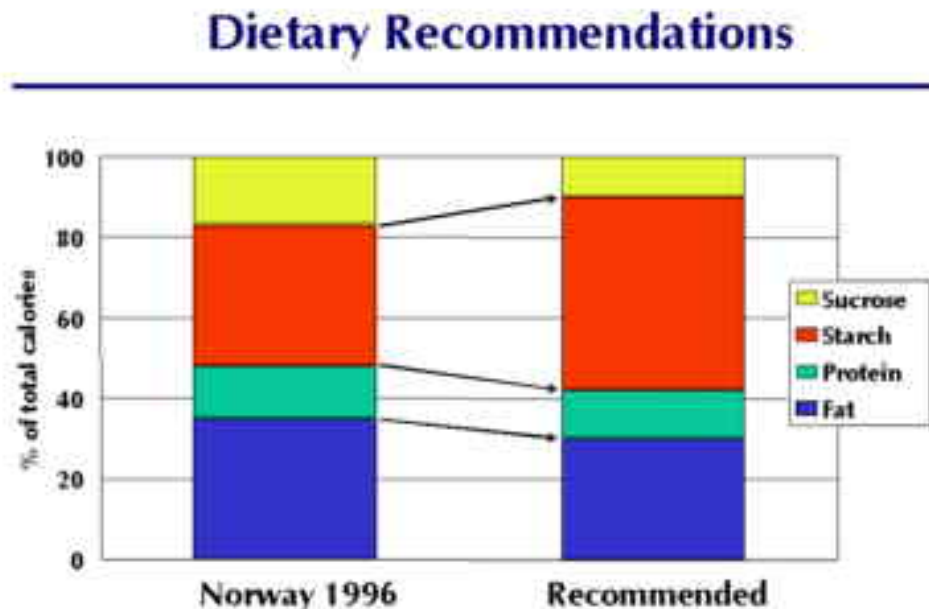
almost constant diarrhea. It was not until he was about 18 months old that it was discovered that he had a lactase-deficiency. Lactase deficiency is extremely rare in newborn, but it does occur. A lactose-free diet cured all of his problems. Today he can drink one glass of milk without symptoms, but after two...

## Maltose

Maltose and isomaltose are not major components of our diet but are formed from polysaccharides in the intestine through the action of amylase. These disaccharides are glucose dimers and are digested by maltase and isomaltase that are produced by and bound to the mucosal cell. The glucose formed is then readily adsorbed.

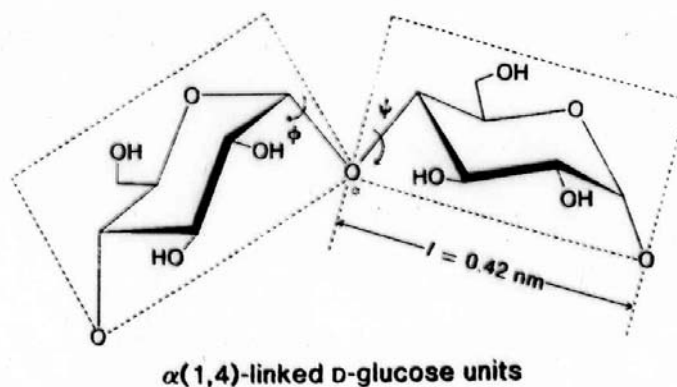
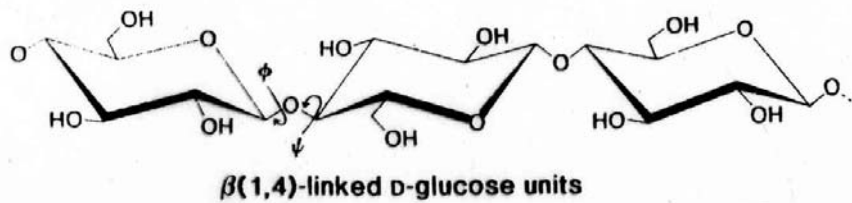
## Polysaccharides

Polysaccharides are the basis of the agriculture-based diet. When we examine the recommendations from the Norwegian Council for Nutrition and most other official agencies, we see that about 55-

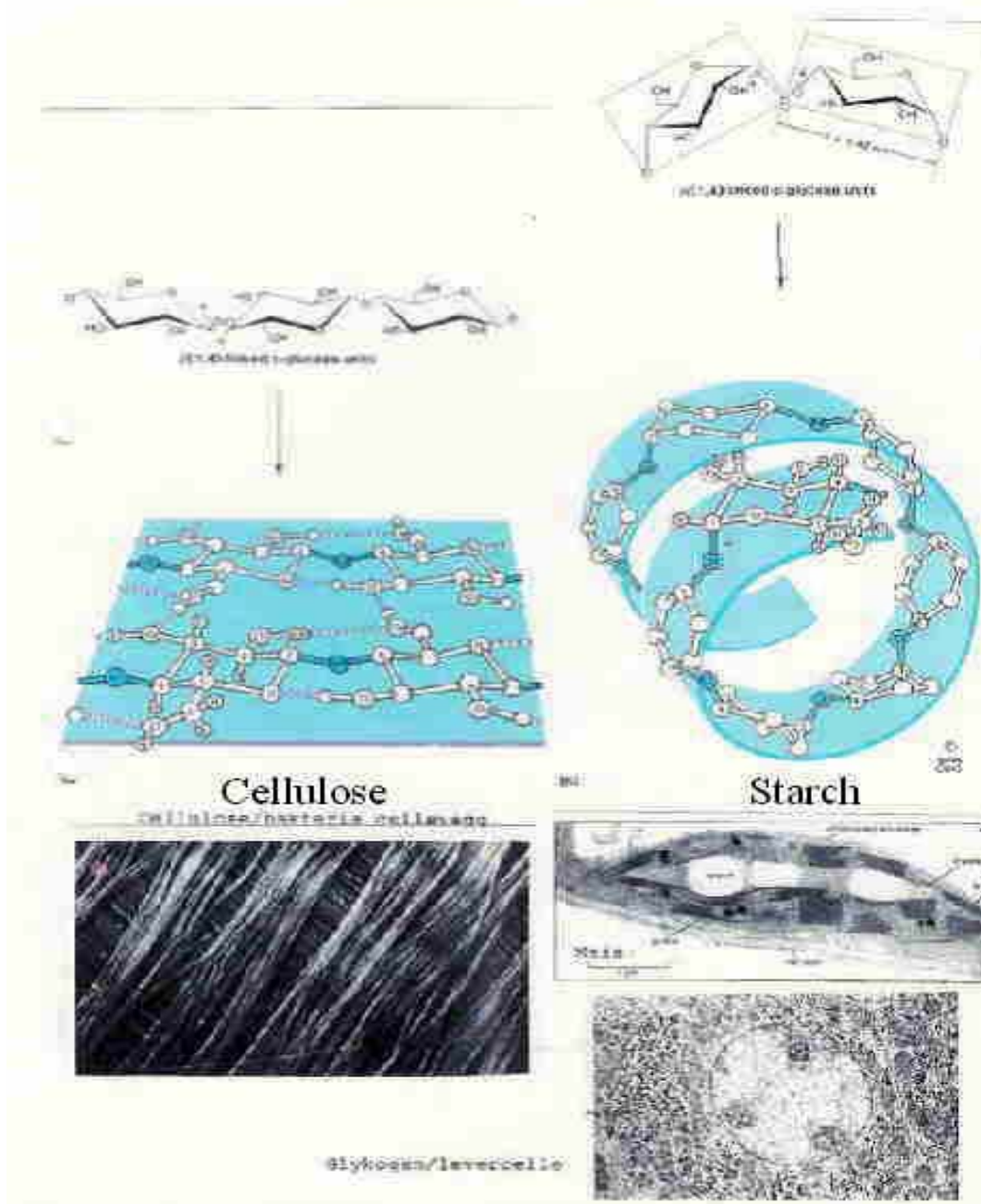


60% of the energy supplied should come from carbohydrates. Further, that most of these should come from starch and not sugar. That big increase in fructose consumption really appears to lead to CVD and overweight. Most medical and official dietary recommendations agree with this standard.

There is one area that I do wish to consider: the differing structures of the digestible and indigestible polysaccharides. We have seen that glucose units (the building stones of the polysaccharides in nature) can be connected with either alpha 1-4 or beta 1-4 bonds. This is dependent upon the specificity of the enzyme that catalyses formation of these polysaccharides. Some require alpha glucose, others beta glucose. The bonds formed arrange the connected glucosyl groups at differing angles to each other. As you can see, beta 1-4 linked glucosyl units lie in a single plane while alpha 1-4 bonded glucosyl groups lie at an angle to each other. This "minor" difference results in entirely dissimilar 3-dimensional structures. Beta 1-4 linked glucosyl groups form sheets that pack together to form the rigid structure we know as cellulose. This is the major polysaccharide of grass, leaves and trees and is said to include around 50% of all biological carbon found on our planet. Digestion of cellulose is entirely dependent upon intestinal flora in herbivores. The anatomy of our digestive system precludes the presence and function of these organisms. Cellulose is, however, of importance in human nutrition in that fiber (good old indigestible cellulose) is an essential part of our diet, giving bulk to our food and promoting intestinal motility.



As you can see from the next figure , starch in plants or glycogen in in

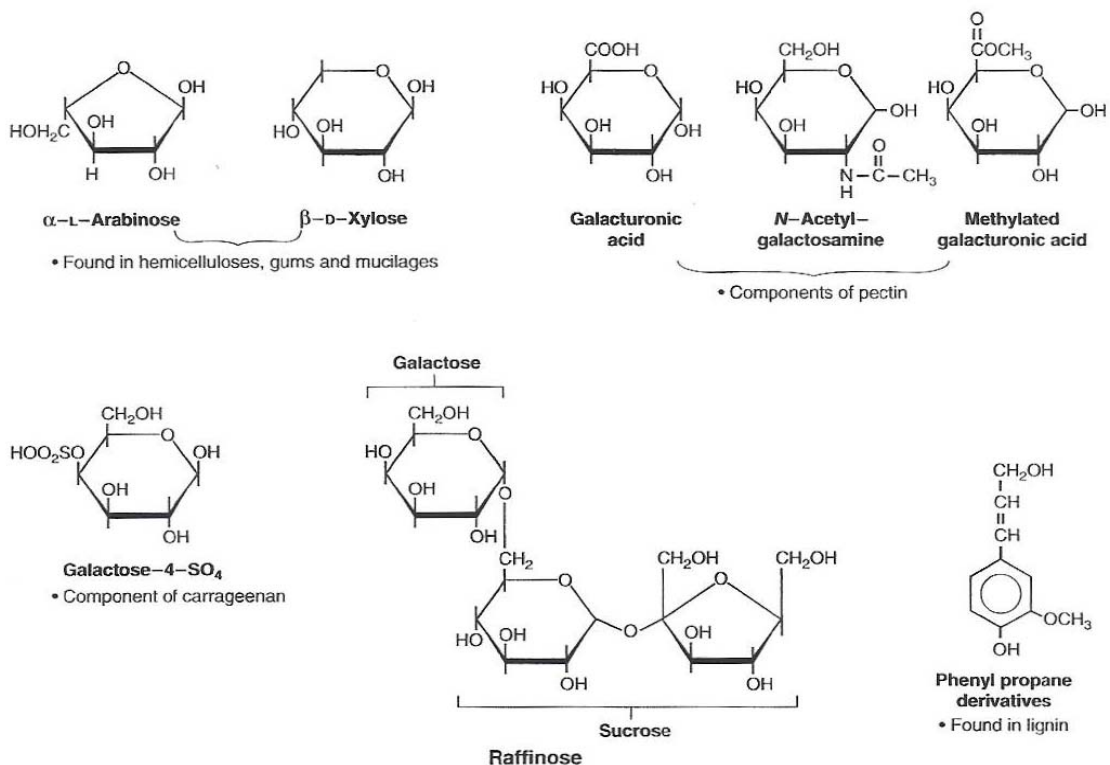


us has a completely different structure. The  $\alpha$ (1–4) glucosyl groups in these polysaccharide form structures with thousands of glucosyl groups bound together in a spiral. These are found packed together in granules. The granules bind water and the enzymes necessary for their synthesis and catabolism, providing a compact system for very rapid rates of synthesis and breakdown of starch and glycogen.

**These two figures are modified from Geoffrey L. Zubay's excellent book, Biochemistry, 4. edition.**

## Soluble fiber

There are many other carbohydrates found in varying amounts in our diet, many of which can neither be digested or absorbed in the small intestine. These migrate further to the large intestine where they serve as substrates for the intestinal flora. We have all observed the effects of eating large portions of pea soup, baked beans and other legumes. These have a variety of mono-, di- and trisaccharides that cannot be digested in humans. They are sometimes called antinutrients because on their tendency to lead to gastrointestinal disturbances. Some of these are shown in the following figure, taken from Basic Medical Biochemistry, Marks, Marks and Smith.



Here are a variety of mono, di and trisaccharides that are not digested by our intestinal enzymes but are substrates for the bacterial flora of the large intestine. As in the case of lactose intolerance, the metabolism of these compounds leads to formation of gas and varying degrees of discomfort. Note especially pectin (found in apples) and raffinose (found in legumes-beans). Most of us have experienced the effects of these compounds.