BioInorganic Chemistry of Zinc
Chemistry 2211a

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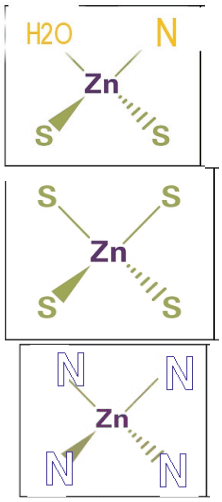
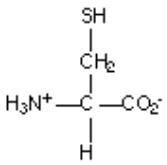
*d^{10} – no colour – zinc proteins are colourless unlike Fe & Cu proteins.

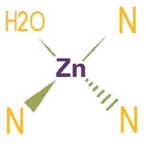
The role of zinc (an essential group 12 metal)



1. Zinc is everywhere in our environment
2. Zinc is a constituent of over 300 enzymes involved in numerous body functions, including enzymes involved in gene expression, wound healing, growth.
3. Deficiency impairs cell growth and repair of tissue injury; leads to poor growth, delayed wound healing, impairment of sexual development and decreased taste acuity.
4. Zinc is present in gustin, a salivary polypeptide that is necessary for the development of taste buds.
5. Its binding motifs are: Intermediate-Intermediate or S-I or H-I (ligand-metal order) – such a versatile metal!
6. HIS and CYS are favourite amino acids – plus water and carboxylic acids (GLU, ASP) in the 3rd and 4th position if chemistry takes place there. TETRAHEDRAL geometry – sometimes 5 groups but from 4 different ligands – ie the carboxylic group of GLU or when acting as a protease.

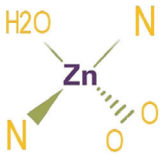
Proteins of interest:

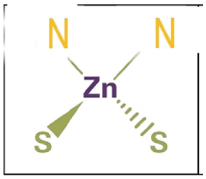


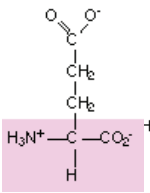


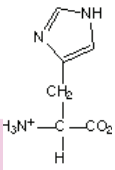
1) Carbonic anhydrase (CA) 3 HIS 1 water; - below
2) Carboxypeptidase A (CPA) 2 HIS; 1 GLU; 1 water; - below
3) Alcohol dehydrogenase (ADH) (2 Zn) 2 CYS; 1 HIS; 1 water; - below
4) Metallothionein (7 Zn) 4 CYS; -below
5) Zn – finger proteins typically - CYS-CYS HIS-HIS (C2H2 motif) - briefly below

(other motifs are known: 4CYS; - note donor atoms: CYS – SH HIS =N- or -NH-; GLU -OH & =O)









L-B	R-M	K-S	Problems to do
P 8-9; 22,23;178184;Ch 10 257-275;	Tables on: p. 4 – 6 –8-	Ch 12 242-266	See Qu 1 – p 279 L&B.

Zinc	A (high intake), calcium, copper, phosphorus	brewer's yeast, liver, seafood, soybeans, spinach, sunflower seeds, mushrooms	burn & wound healing, carbohydrate digestion, prostrate gland function, reproductive organ growth & development, sex organ growth & maturity, vitamin B1, phosphorus & protein metabolism	delayed sexual maturity, fatigue, loss of taste, poor appetite, prolonged wound healing, retarded growth, sterility

NOTE: For any treatment or diagnosis of illness see your physician. The use of certain dietary supplements may result in allergic reactions in some individuals, consult your physician. This Mineral chart is not intended to be diagnostic or prescriptive and therefore Swiss Herbal Remedies Ltd. assumes no responsibility.

KEY
*essential for proper
**equal dosage requir

Let's return to our chart from the first lectures:

2 g in a 70 g human – right up next to Fe.

RDA: for adults - males: 15 mg & females: 12 mg

Zinc Requirement and Effects of Deficiency

Zinc is essential in -

1. Development and functioning of the brain.
2. Zinc dependent enzymes and neurotransmitters play a role in the central nervous system, which may in turn affect cognition.
3. Important for healthy skin, a healthy immune system, and resistance to infection.
4. Wound healing with Zn ointments (from the ancient world).
5. Growth is dependent on Zn.

Emerging research on human models supports a beneficial role for zinc in human cognitive development and functioning

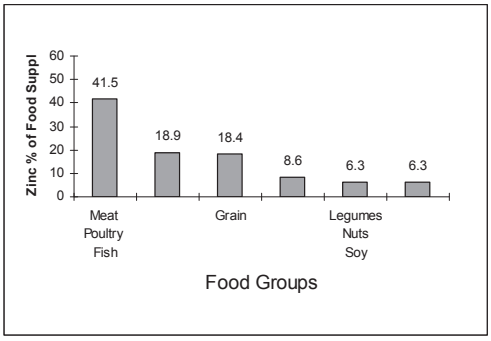
•Good sources meat, liver, eggs and seafood are good dietary sources, whereas zinc in vegetable sources (green leafy vegetables and legumes), and particularly in cereal grains, is less bioavailable.
Beef is a major source of iron and zinc for American children and adults – actually is the number one source of zinc

Supplement: no more than 40 mg (above this is considered toxic)

1 veggie hot dog	3.75 mg
1 cup cooked greens	0.8 mg
¼ cup peanuts.....	3.6 mg
½ cup pumpkin seeds	2.6 mg

Meat is much better as a source of Zn than cereals. High Zn is found in the fetus – developmental reasons?

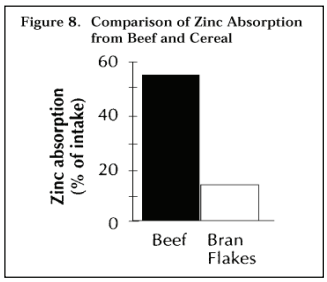
Mainly transported by the protein metallothionein (see below), which controls absorption



Zinc deficiency can lead to:

1. Hair loss,
2. Delayed wound healing
3. Dwarfism when there is major zinc deficiency due to poor diet – was the case in rural Iran in 1960's
4. Structural malformations in the brain
5. Changes in enzymes and proteins important for neurotransmission
6. Behavioural problems - reduced attention
7. Reduced memory - reduced ability to learn
8. Low zinc status during pregnancy may affect the development of the infant's nervous system and later cognitive functioning
9. In older adults (aged 65-90) dietary zinc is positively linked to cognitive function
10. Low levels of zinc in the blood and brain tissues of patients with Alzheimer's

Severe zinc deficiency is seen primarily in alcoholics (especially if they have developed cirrhosis), patients with chronic renal disease or severe malabsorption diseases



Zheng JJ, Mason JB, Rosenberg IH, et al. Measurement of zinc bioavailability from beef and a ready-to-eat breakfast cereal in humans: application of a whole-gut lavage technique. Am J Clin Nutr. 1993; 58: 902-907.

1999

Where are we in the Periodic Table?

Group 12 (recent numbering scheme for groups)

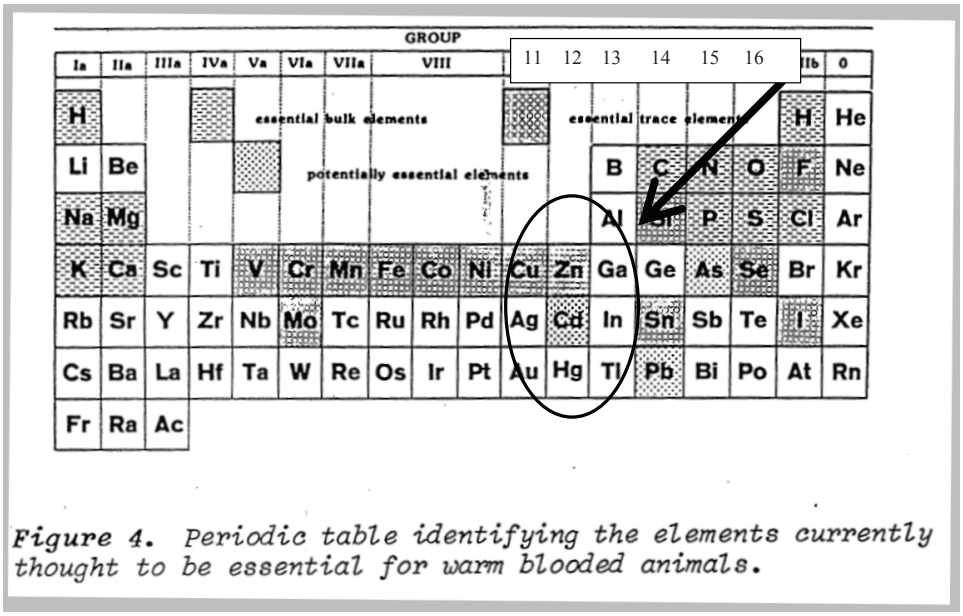


Figure 4. Periodic table identifying the elements currently thought to be essential for warm blooded animals.

All 2+ cations (well, Hg can be 1+: $[Hg_2]^{2+}$)

As 2+ cations, all are d^{10}

Become 'softer' down the triad

Need to memorize this triad

What is special about Zn(II)?

$3d^{10}$ – so no contribution to bonding – bonds form between s and p orbitals – empty now.

No redox chemistry possible – it's Zn(II) all the time. So why Zn(II)? That's the point – it can help make changes in organic molecules without being involved. It acts as a tether. Most important changes the acid-base properties of ligands so that acid-base chemistry takes place that shouldn't at pH 7 – see CA mechanism below.

L-B	R-M	K-S	Problems to do
1-2; 9	2	4	See the questions at the end

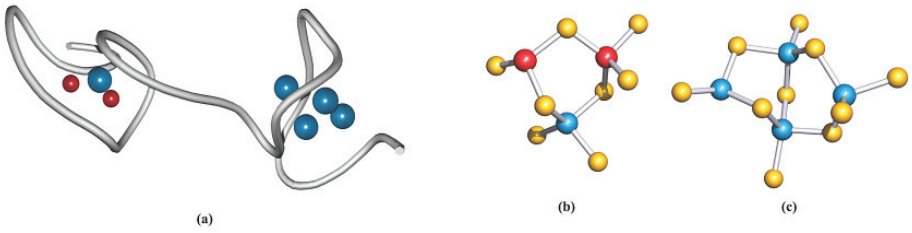
Zinc containing proteins and enzymes:

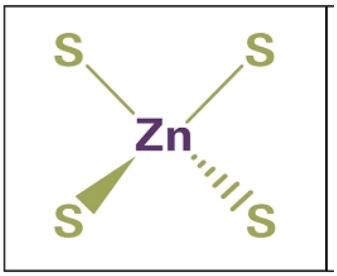
1) Metallothionein (MT)- 7 Zn (and Cd) 4 CYS ligands each metal – tetrahedral coordination solely by CYS

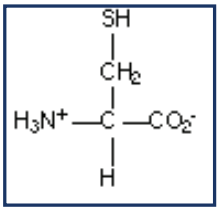
7 METALS – 20 CYS

2 domains some CYS are shared – see (b) and (c) for the structures of the metal binding sites.

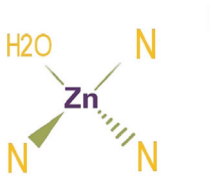
Major zinc binding protein – acts as a storage site. Essentially no free zinc in a cell. $K_F = \beta_7 = 10^{11}$ for 7 Zn(II).

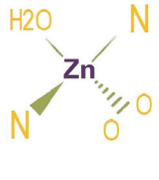






In enzymes very many examples, we will select:





1) carbonic anhydrase (CA)

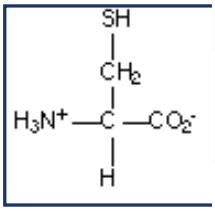
2) matrix metalloproteases (MMPs), secreted by cells – wound healing

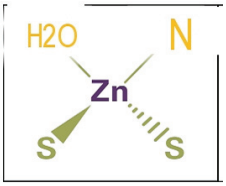
3) carboxypeptidase A (CPA)

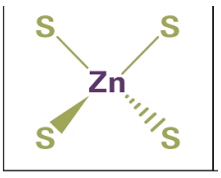
4) alcohol dehydrogenase (ADH) – from liver = LADH

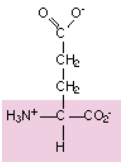
5) zinc finger DNA-binding-proteins (and A1)

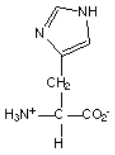
6) Superoxide dismutase (ZnCuSOD)











ZINC in catalytic roles binds readily to HIS, CYS, GLU, ASP, and water.

Zn^{2+} acts as a Lewis Acid – so, is an electron acceptor – binds anions – so the ligand usually becomes charged – the effect is a reduction over several orders of magnitude of group (makes the group dramatically more acidic) – the pKa of the

BUT HAS TO HAVE A VACANT SITE. As an enzyme – **major role is activating water** (or ROH or $R_2C=O$) – making the water (and other groups) far more acidic – that is changing H_2O almost into OH^-.

BUT Binds to 4 cys – or 2 cys & 2 his in structural roles

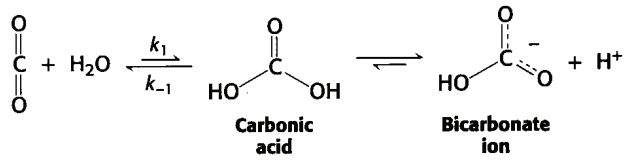
1) Carbonic anhydrase - CA

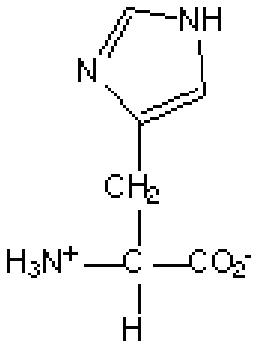
Zn^{2+} activation of H_2O in carbonic anhydrase

Carbonic Anhydrase was the first enzyme identified that contained a zinc atom

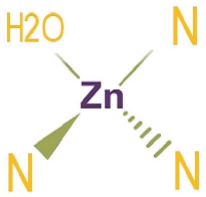
In CA, Zn^{2+} is bound to the enzyme through 3 Histidines + water – see the next pages for more details about the reaction = NOT a structural role-

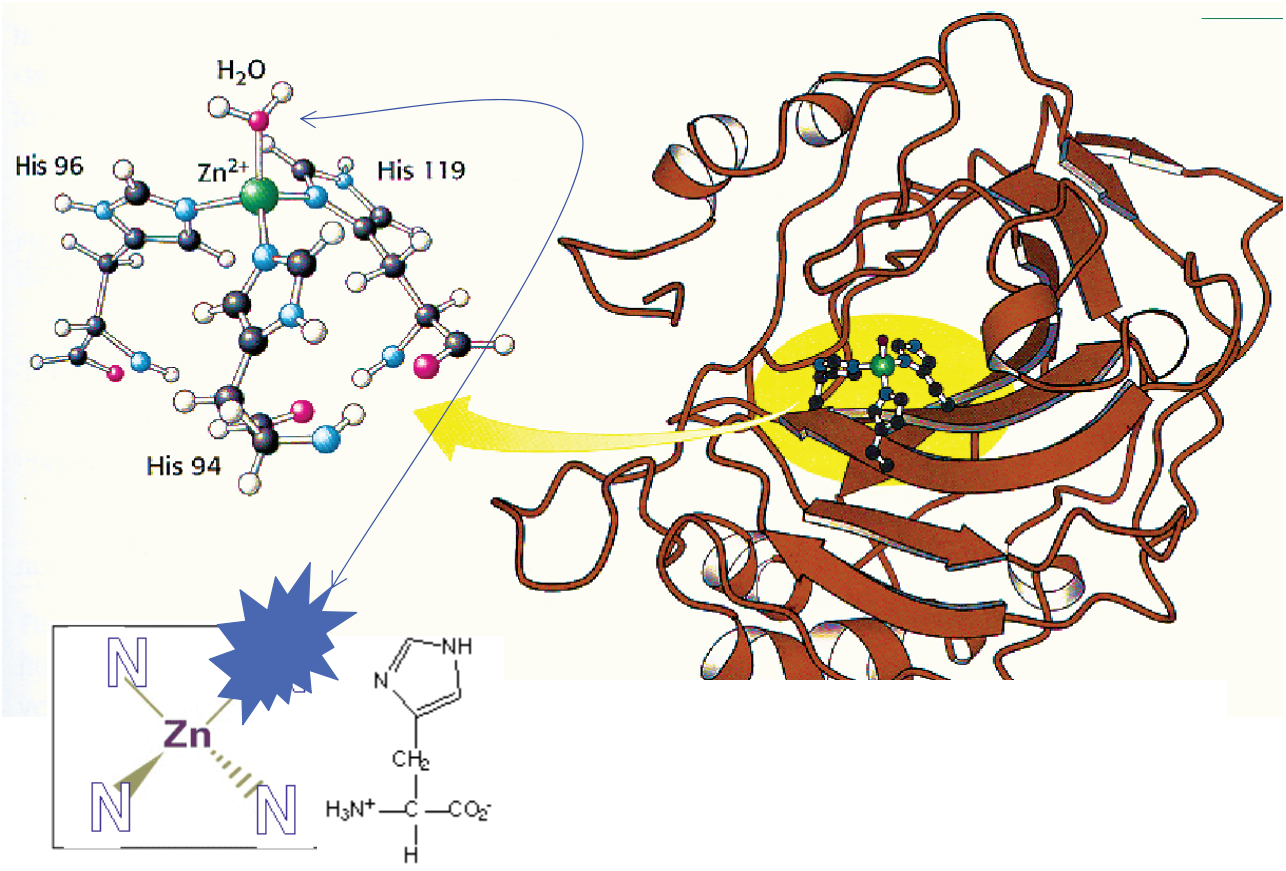
The overall reaction catalysed:



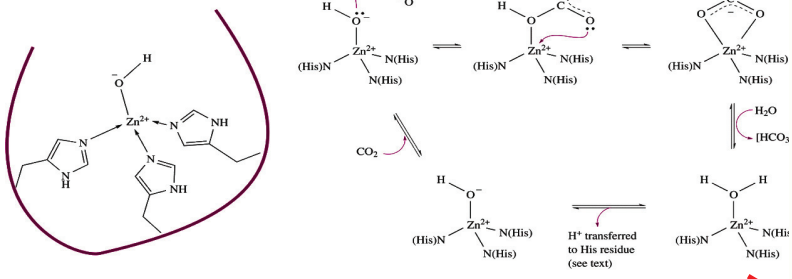


How does it do this? And what is special about the zinc coordination site? It's all to do with the histidine/imidazole nitrogen Intermediate ligand on an Intermediate metal – not a soft ligand like??). See next 2 pages..1st the Zinc binding reaction





Mechanism of Carbonic Anhydrase



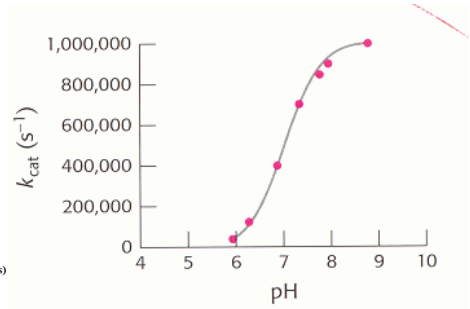
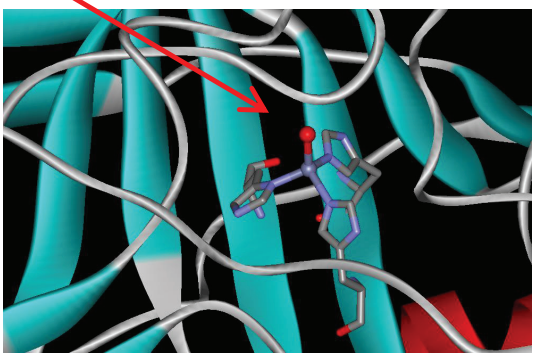


FIGURE 9.23 Effect of pH on carbonic anhydrase activity. Changes in pH alter the rate of carbon dioxide hydration catalyzed by carbonic anhydrase II. The enzyme is maximally active at high pH.

We can see the mechanism in more detail here:

Key – activation of the CO_2 by the negatively charged OH on the zinc. Then the now negatively charged O on the CO_2 (the new Lewis base) binds to the zinc(II) – it's the Lewis acid. Now we have a Glu-like binding pattern. Incoming water displaces the HCO_3^- product.



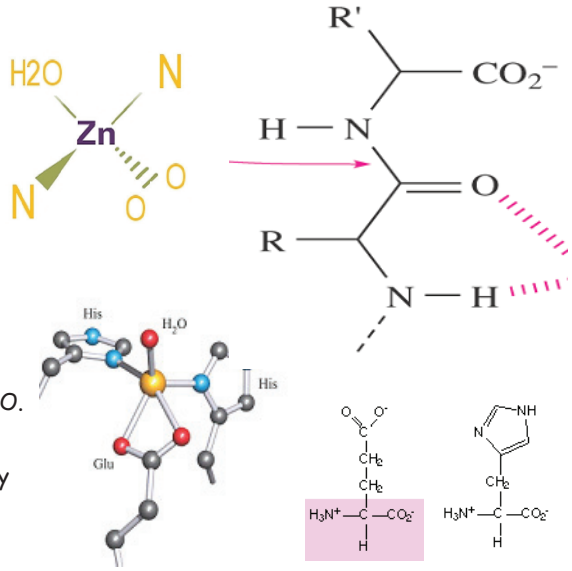
CA – primarily a β pleated structure

2) Zinc proteases (metalloproteases) include:

digestive enzymes – eg carboxypeptidase A CP-A

matrix metalloproteases (MMPs), secreted by cells

The zinc-binding motif at the active site of a metalloprotease includes: TET - 2 His residues whose imidazole side-chains are ligands & 1 Glu with 2 oxygens = catalysis NOT a structural role



During catalysis, the Zn^{2+} promotes nucleophilic attack on the carbonyl carbon by the oxygen atom of a water molecule at the active site. The active site base (Glu in Carboxypeptidase) facilitates this reaction by extracting H^+ from the attacking H_2O.

3) Carboxypeptidase A – a pancreatic digestive enzyme that cleaves the carboxyl terminal amino acid from a peptide chain by hydrolysing the amide link:

Example: LEU-GLU-PHE ➔ LEU-GLU + PHE

This is the reverse of the peptide chain expansion reaction

Mass: 34,500, 1 Zn, the Zn is bound in a crevice with almost 5 coordination –

HIS HIS GLU (both O's) and water - catalysis NOT a structural role

To cleave, break up, digest the peptide chain, hence a peptidase.

The organic chemistry says: nucleophilic attack of the C=O should work, but what with?

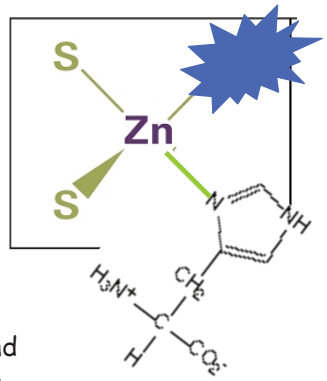
Needs an OH^- - where do we get that from?

We need one bound to a Zn(II), but at pH 7 – not many OH^- around, we have plenty of water though.

4) LIVER ALCOHOL DEHYDROGENASE LADH

A 2-zinc-containing dimeric enzyme (=4 Zn), uses a coenzyme (NAD^+)and ethanol.

A zinc metalloenzyme that oxidizes alcohols to aldehydes or ketones – a member of the oxidoreductase family of enzymes – a redox enzyme – shuttles electrons.



The catalytic zinc is bound to two CYS, 1 HIS and water; the 2nd zinc is bound to four CYS = a structural role..

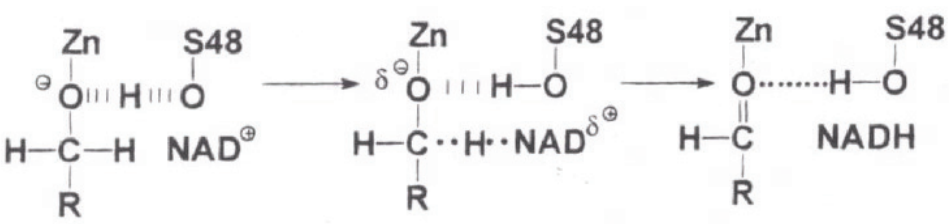
In humans, the enzyme is contained in the lining of the stomach and in the liver. It catalyzes the oxidation of ethanol to acetaldehyde:

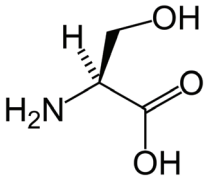
$CH_3CH_2OH + NAD^+ \rightarrow CH_3CHO + NADH + H^+$

It is important to note that the aldehyde is more toxic than the alcohol and water is being used - so dehydration occurs – hence the hang-over – luckily aldehyde is broken down more rapidly… hmmmm

This allows the consumption of alcoholic beverages, but its evolutionary purpose is probably the breakdown of alcohols naturally contained in foods or produced by bacteria in the digestive tract.

Humans have at least six slightly different alcohol dehydrogenases. Serine (S48) provides the route for the proton, above.



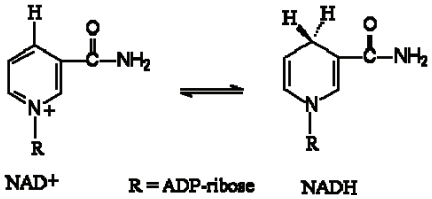


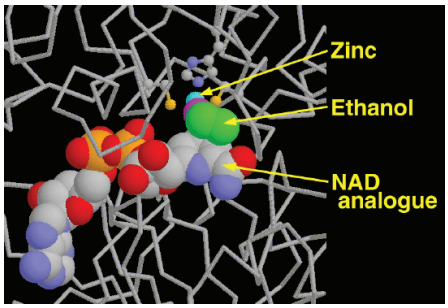
Up to 30% of alcohol is oxidized in the stomach – class IV rxn.

The rate-limiting step is the availability of the coenzyme, NAD^+.

We only have enough enzyme so that, for an average size person, it will take about 90 minutes to metabolize 1 drink (typical oxidation rate is 100 mg ethanol/kg/hr = 11 ml/hr/70 kg).

The liver is the major site of this oxidation, as well as the site of major destruction (cirrhosis) due to excessive amounts of alcohol.





The overall reaction catalyzed (Class I) is the oxidation of alcohol to aldehyde with the concomitant reduction of the coenzyme NAD+ to NADH:

$RCH_2OH + NAD^+ \rightarrow RCHO + NADH + H^+$

We can see how the enzyme works as follows:

•Enz + NAD^+ ➔ Enz-NAD^+

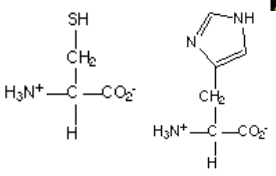
•Enz-NAD^+ + ETOH ➔ Enz-NAD^+-ETOH

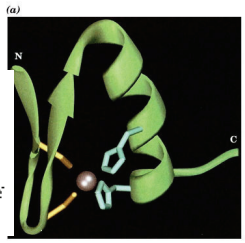
•Enz-NAD^+-ETOH ➔ Enz-NADH + aldehyde (RCHO)

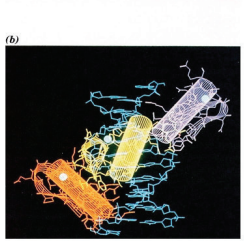
AND then •Enz-NADH ➔ Enz + NADH

Ethanol metabolism in humans follows zero-order kinetics; unfortunately, not inducible (which means cant improve the rate rink). The rate-limiting step is the availability of the coenzyme, NAD^+. `tep 4 – the release of NADH to cycle round to the 1st step. We only have enough enzyme such that, for an average size person, it will take about 90 minutes to metabolize 1 drink (typical oxidation rate is 100 mg ethanol/kg/hr = 11 ml/hr/70 kg individual). The liver is the major site of this oxidation, as well as the site of major destruction (cirrhosis) due to excessive amounts of alcohol.

5) …but what about the zinc fingers? CYS CYS HIS HIS – generally –

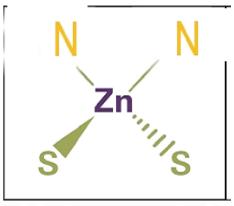






Zn^{2+} 4 CYS or 2CYS and 2HIS for structural jobs – no empty or reactive sites left.

Zinc-finger DNA binding protein family

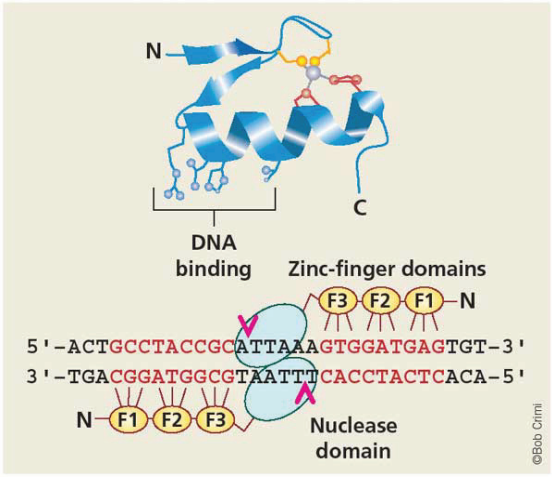


The DNA-binding motif is found as part of transcription regulatory proteins.

Zinc finger proteins were first discovered as transcription factors. (SEE BELOW for details)

Zinc finger proteins are among the most abundant proteins in eukaryotic genomes.

Their functions are extraordinarily diverse include DNA recognition, RNA packaging, transcriptional activation, regulation of apoptosis, protein folding and assembly, and lipid binding. Zinc finger structures are as diverse as their functions. One of the most abundant DNA-binding motifs. Proteins may contain more than one finger in a single chain.



Two common types: His_2ZnCys_2, Cys_4Zn Always TETRAHEDRAL. H2C2 and C4

What do Zinc-Finger proteins do?

Zn finger proteins are DNA-binding proteins

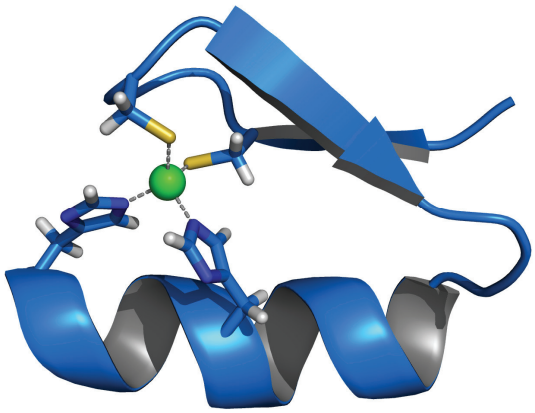
They all exhibit the same motifs of 2 antiparallel beta sheets and a alpha helix linked together by the Zn.

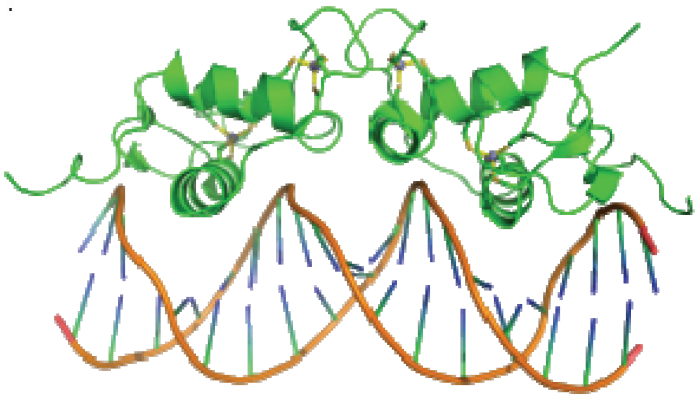
The key is that the Zn holds the whole protein together and stabilizes the structure.

There is always the beta-beta-α structures in each finger.

Because each finger binds to 2 or 3 bases the recognition becomes more precise by reading more of the DNA sequence and the binding strength increases making binding more efficient.

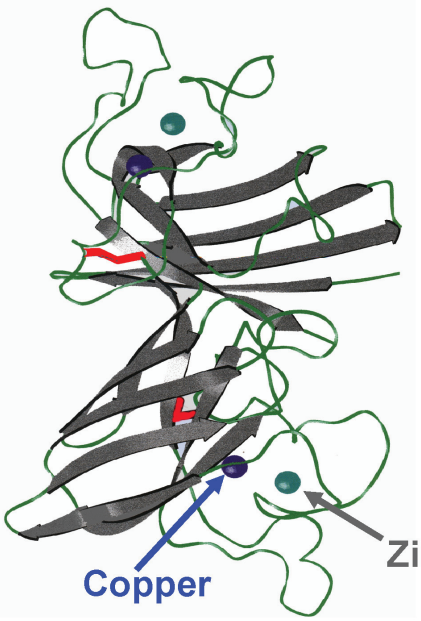
Transcription factors use the Zn-finger on the DNA as a trigger. The α-helices of the Zn-finger wrap around the DNA.



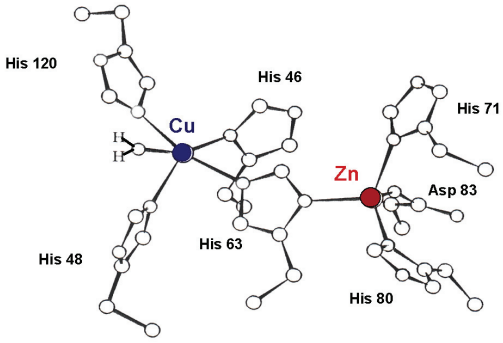


6) Superoxide dismutase (the binding of the Cu(I) and Zn(II) can be rationalised in terms of our models in the inorganic unit and here) – SOD – implicated in ALS disease due to muscle and nerve degeneration. Note – the O_2^- reaction was described in the inorganic unit. Here, one of a great many, CuZnSOD. Note – needs catalase (Fe(III-IV)-heme enzyme) to decompose the

$$2\,O_2^- + 2H^+ \longrightarrow O_2 + H_2O_2$$



H_2O_2 product.



The chemistry requires both metals. SOD activity first described in a series of famous papers by Fridovich & McCord in 1969 The link to Amyotrophic Lateral Sclerosis (als) was reported in 1993

$$Cu^{2+} + O_2^- \longrightarrow Cu^+ + O_2$$

$$Cu^+ + O_2^- + 2\,H^+ \longrightarrow Cu^{2+} + H_2O_2$$

$$2\,O_2^- + 2H^+ \longrightarrow O_2 + H_2O_2$$

Key points from this unit	
1	Relationship of Zn to other metals – what is its role? Why was the change from anaerobic to aerobic atmosphere not significant for zinc? Common binding site combinations for Zn – check out p 2 – what are the amino acids involved? What are the binding sites of Zn as a catalyst and zinc as a structural metal? Why the difference? What makes Zn such a good catalyst? Why so much Zn do you think? Zn deficiency is hard to achieve (is that a real sentence or thought?) but with not enough Zn – problems like Pb excess (is Pb excess possible?) So, Zn deficiency – cognitive problems – where is Zn deficiency really found? Liver disease – from? List, name , 3 Zn-containing enzymes – and 1 Zn structural-required protein
2	Metal distribution comes from natural and man-made sources – know the cycle- but is Zn toxic? No!! A major played in the transport of Zn is metallothionein – 7 Zn(II) per molecule, bound only to CYS – we see this protein later as a major played for Cd metabolism and toxicity.
3	So, how does Zn act in enzymes? It is its Lewis acid properties – which are what? Carbonic anhydrase – key is CO_2 is polarised – OH^- from water attacks CO_2 – the key is that H_2O is made much wore acidic by the Zn. What are the other ligands in CA? Know the cycle shown on p 16.

	Carboxypeptidase – works the same way – know the key step of attack of C=O by O attached to Zn. – see p. 17 Alcohol dehydrogenase – see p 24 – here the alcohol binds to the Zn –and the aldehyde is formed – how does NAD^+ enter the reaction? What is it called? Recognise it's structure.
4	Zinc finger proteins bind to DNA – how? What does the Zn do?
Study questions from the lectures: What is a Lewis acid? How does it differ from a protonic acid? Why is Zn called a Lewis acid? Name a Lewis base. What is the key property of Zn that is exploited in the zinc- enzymes? How?	
Lectures	
Study questions from the books (S-L; R-M; K-S) and study questions for exams	
L-B Housecroft & Sharpe	Read several pages on Zn enzymes. K&S see ch. 12. Metallothionein binds zinc and cadmium in what sort of way? What is the only ligand known to date? See p 854 for a discussion of Zn as a Lewis acid