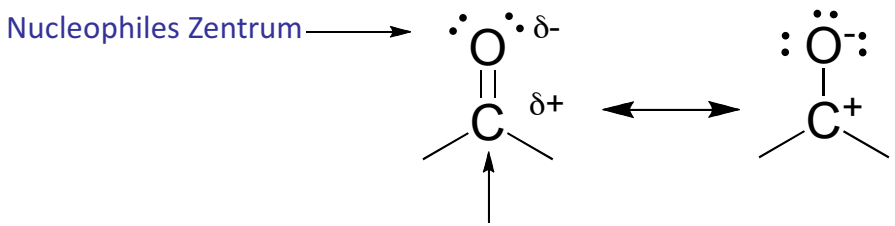
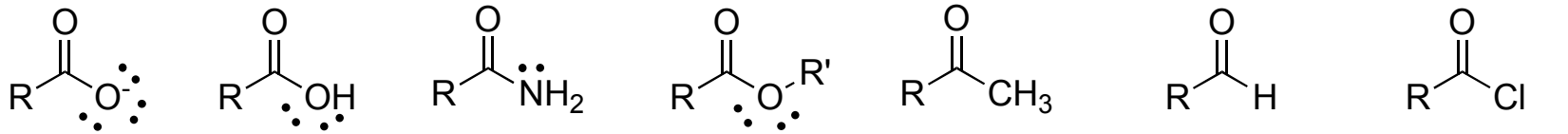
4.8. Carbonyle

Eine wichtige funktionelle Gruppe – die Carbonyl-Funktion

▪ Kohlenstoff und Sauerstoff sind sp^2-hybridisiert und durch eine Dopplebindung verbunden. Die drei Bindungen, die vom Kohlenstoff ausgehen liegen in einer Ebene und schließen einen Winkel von ca. 120° ein.





Carboxylat (Salz einer Carbonsäure) → nicht mehr elektrophil am C !

Carbonsäure

Carbonsäureamid

Carbonsäureester

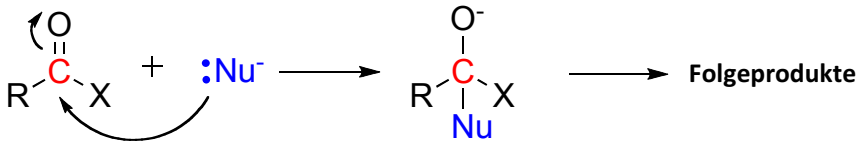
Keton

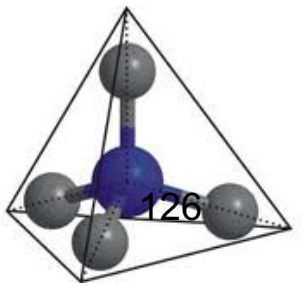
Aldehyd

Carbonsäurechlorid

Steigende Reaktivität – durch höhere Elektrophilie am C-Atom → d.h. elektronenziehende (wie Chlor) erhöhen Reaktivität.

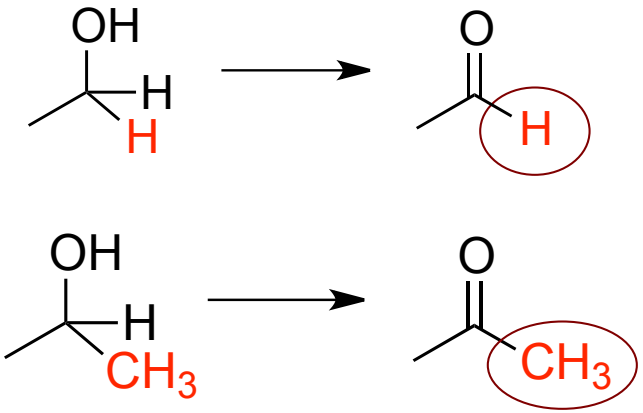
▪ Nucleophile Addition an Carbonyl-C führt zu tetrahedraler (sp^3) Zwischenstufe (Anmerkung: tetrahedral = die vier Atome bilden einen Tetraeder):



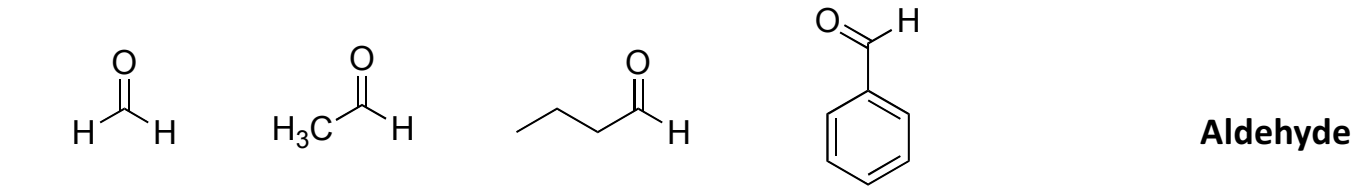


Aldehyde und Ketone

- Aldehyde (***Al****cohol* ***dehyd****rogenatus*) und Ketone sind durch Oxidation von Alkoholen zugänglich:



- Aldehyde tragen die Endung **-al**, Ketone **-on**



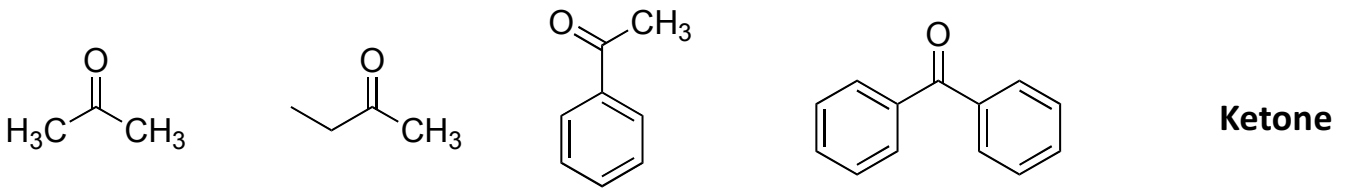
Formaldehyd
Methanal

Acetaldehyd
Ethanal

Butanal

Benzaldehyd

Aldehyde



Aceton
Propanon

Butan-2-on

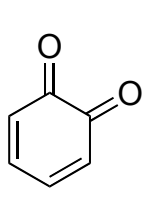
Acetophenon
Methylphenylketon

Benzophenon

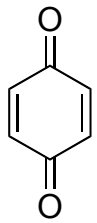
Ketone

Chinone

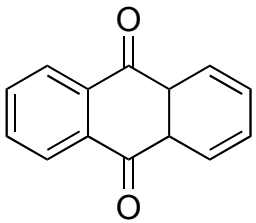
- **Chinone** nennt man Verbindungen, die **zwei Carbonyl-Funktionen in cyclischer Konjugation** enthalten:



ortho-Benzochinon



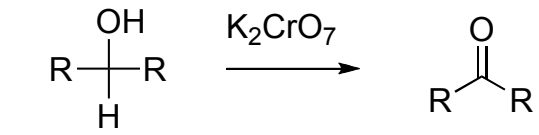
para-Benzochinon



9,10-Anthrachinon

Herstellung von Aldehyden und Ketonen

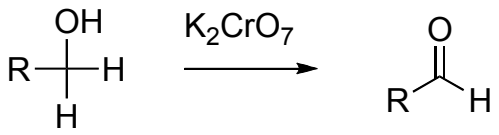
- Oxidation von Alkoholen



R = Alkyl-Rest

SEKUNDÄRER Alkohol

KETON



R = Alkyl-Rest

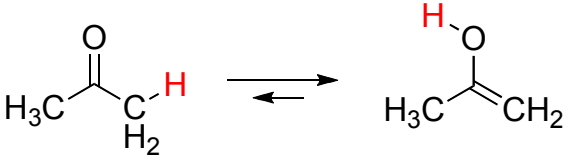
PRIMÄRER Alkohol

ALDEHYD

Eigenschaften

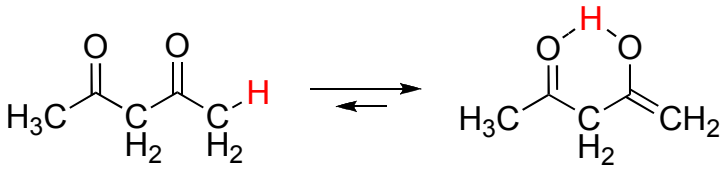
- **keine H-Brücken** → tieferer Siedepunkt als Alkohol, niedere Aldehyde und Ketone sind wasserlöslich.

- **Keto-Enol-Tautomerie:** tautomeres Gleichgewicht = Tautomere sind durch Wanderung eines H-Atoms ineinander überführbar.



Aceton
Keto-Form:
99.9997 %

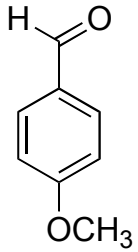
Aceton
Enol-Form:
0.0003 %



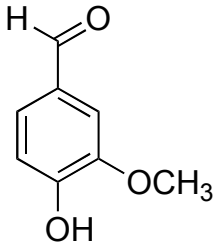
Keto-Form:
15 %

Enol-Form:
85 %

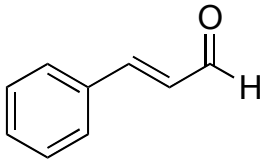
Biologisch relevante Carbonylverbindung



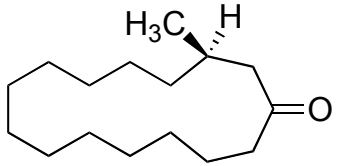
Anisaldehyd



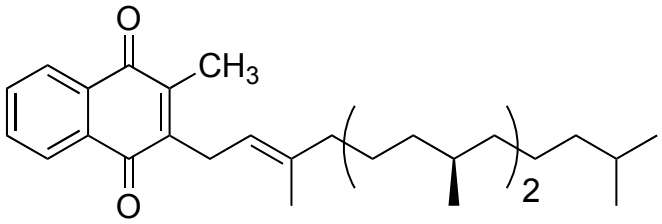
Vanillin



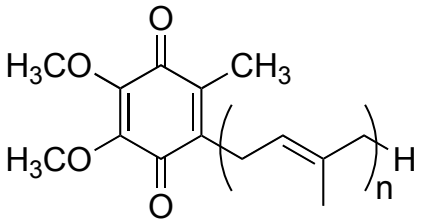
Zimtaldehyd



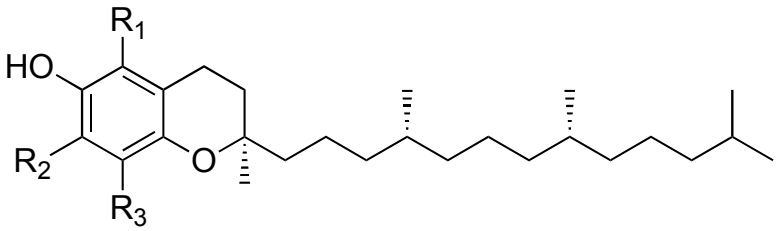
Muscon: Moschus Geruch



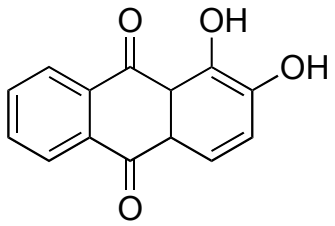
Vitamin K1: Blutgerinnung



Ubichinone: Oxidationen in Mitochondrien



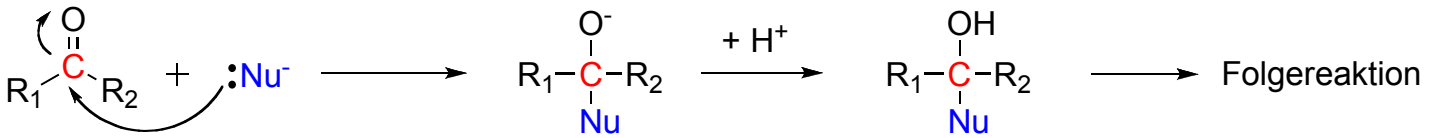
Tocopherole: Vitamin E-Reihe - Radikalfänger



Alizarin: Färbestoff

Reaktionen von Aldehyden und Ketonen

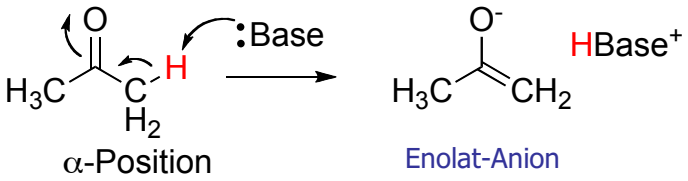
▪ **Addition** von **Nucleophilen** an die **Carbonyl-Gruppe**:



R_1, R_2 = Alkyl KETON
R_1 = Alkyl, R_2 = H ALDEHYD

→ Elektrophiles Carbonyl-C wird von Nucleophil angegriffen
→ verschiedenste Nucleophile sind möglich: z.B. Stickstoff (N)-, Sauerstoff (O)- oder auch Kohlenstoff (C)- Nucleophile.

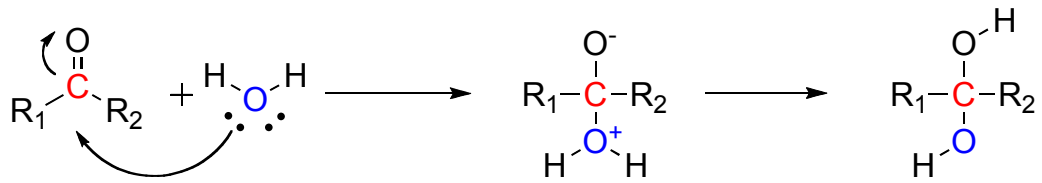
▪ **Bildung von Enolat-Anionen**:



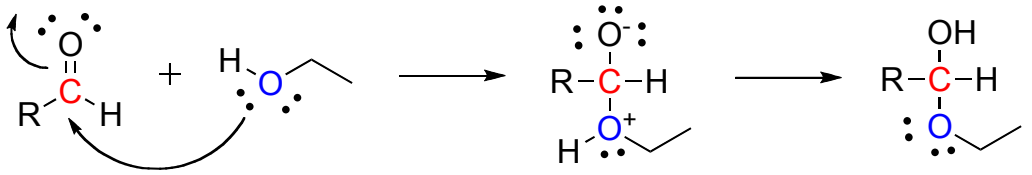
→ Proton kann von α-Kohlenstoff relativ leicht abstrahiert werden unter Bildung eines Enolat-Anions.

Addition von Sauerstoff (O) - Nucleophilen

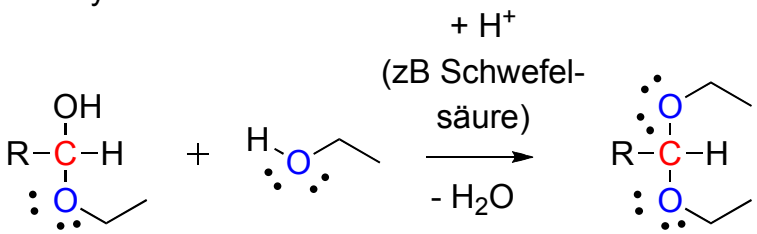
- **Addition** von **Wasser (H_2O)** an die **Carbonyl-Gruppe**:



- **Addition** von **Alkoholen (HO-R)** an die **Carbonyl-Gruppe** → Bildung von **Acetalen**:

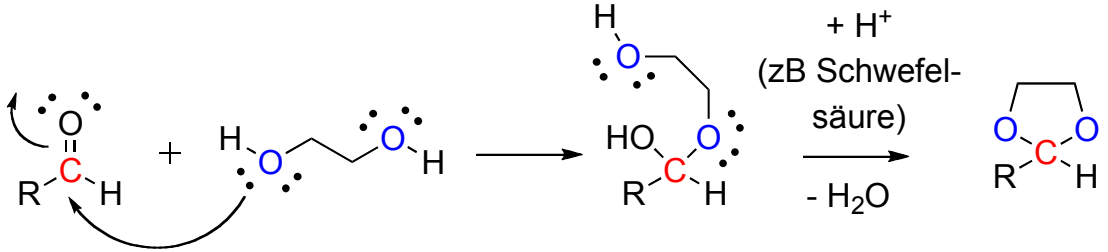


Aldehyd Halbacetal



Halbacetal Acetal

→ **Acetale** sind im **Sauren NICHT stabil**, im **Basischen stabil**.



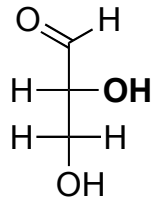
Aldehyd Ethylenglykol (1,2-Ethandiol) cyclisches Acetal

Cyclisches Acetal bei Diolen

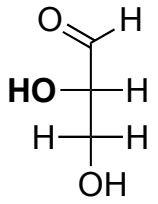
Exkurs: Kohlenhydrate - Zucker

▪ Kennen **Alkohole** und **Aldehyde** → **Zucker** sind **Polyakohole** mit einer **Aldehyd-** (**Aldosen**) oder **Keton**- (**Ketosen**) **funktion**:

▪ Man unterscheidet: **Mono-** (**eine Zuckereinheit**) , **Oligo-** (**2-6 Monosaccharide**) und **Poly-** (**> 6 Zuckereinheiten**) -saccharide.

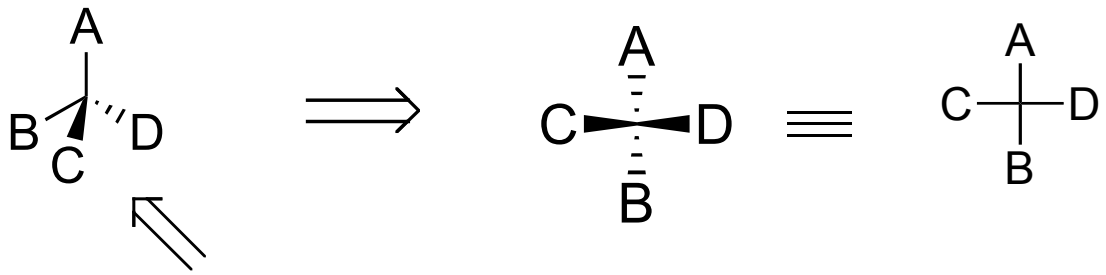


D-Glycerin-Adehyd (**OH Gruppe rechts, Dexter = lat. rechts**)

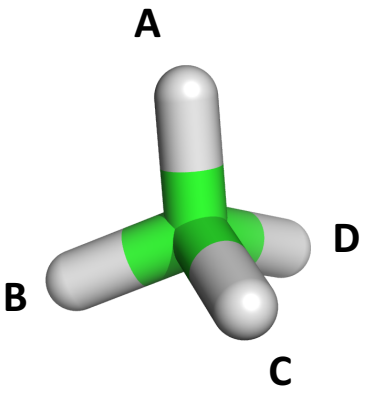


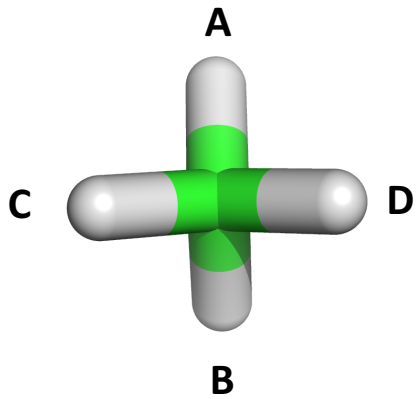
L-Glycerin-Adehyd (**OH Gruppe links, Laevus = lat. links**)

▪ **Fischerprojektion**

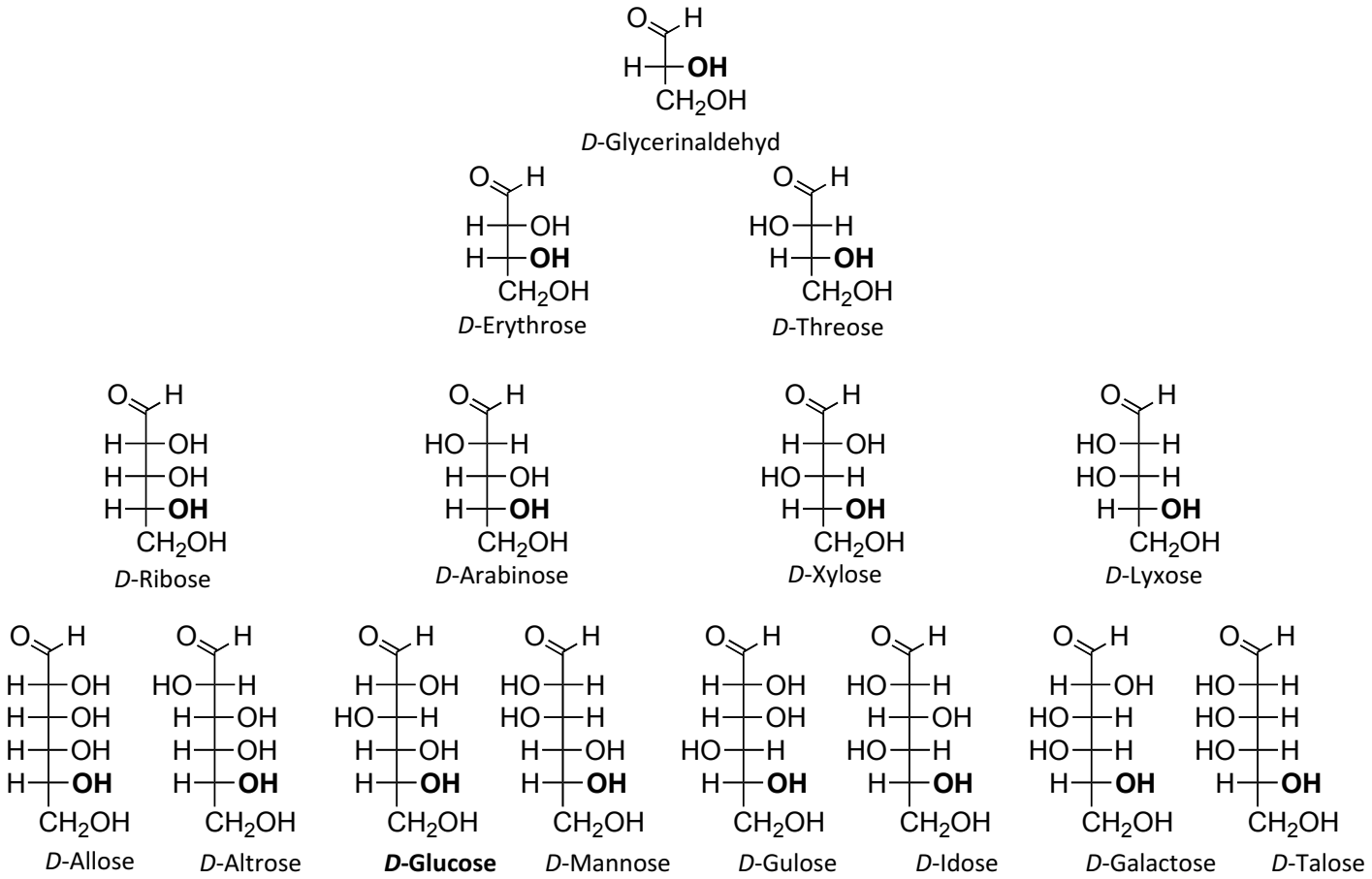


Blickrichtung

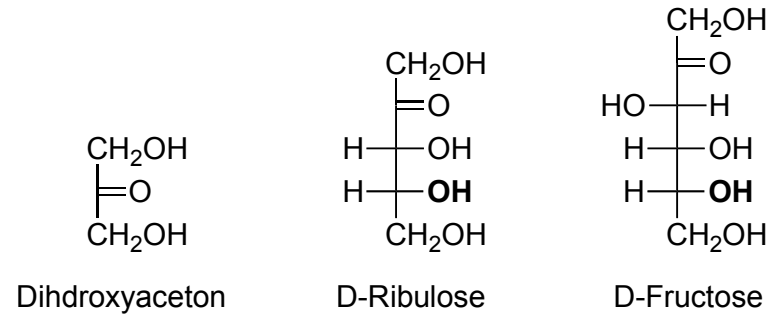




Stammbaum der *D*-Aldosen



Ketosen



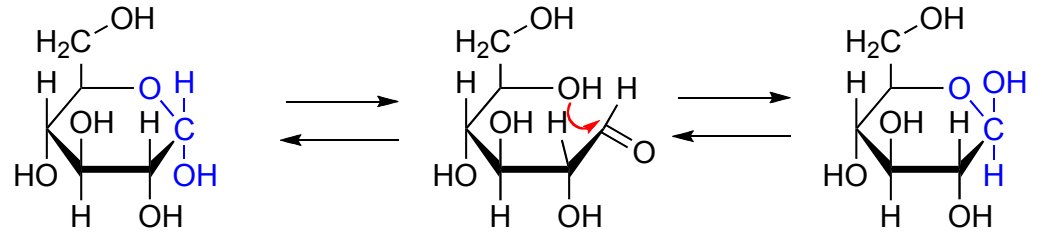
Konformationen der Monosaccharide

▪ **Zucker** liegen nur zu einem **geringen Teil in der offenen Form** vor, überwiegend bilden sich ***fünf- bzw. sechsgliederige Ringe*** durch ***intramolekluare Acetalbildung***.

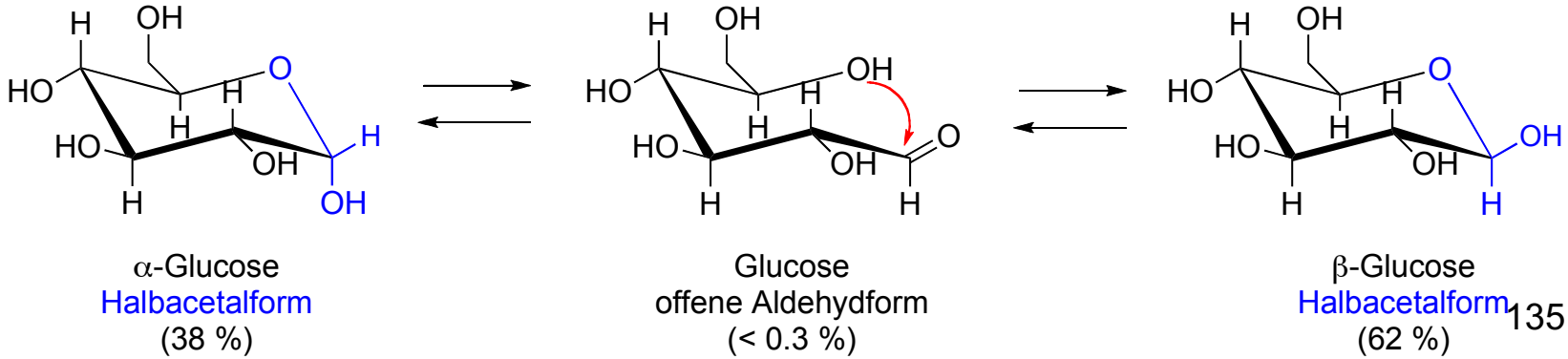
▪ durch die Acetalbildung bildet sich das sogennannte **anomere Zentrum** (assymmetrisches C-Atom). Man unterscheidet 2 Formen: schaut die **OH Gruppe** am anomeren Zentrum **nach oben → β-Form**, schaut die **OH Gruppe** am anomeren Zentrum **nach unten → α-Form.**

Darstellung der Zucker in der Ringform

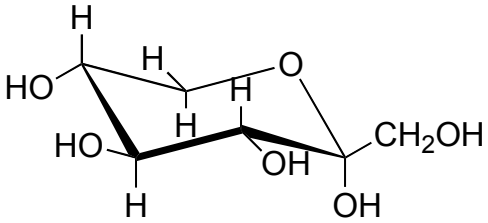
1. *Haworth*-Ringformel



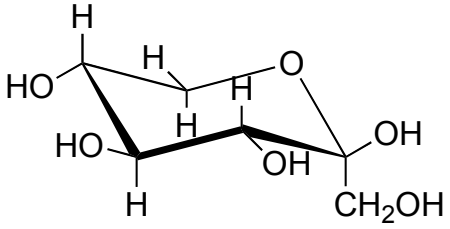
2. Konformations-Ringformel (vgl. Cyclohexan)



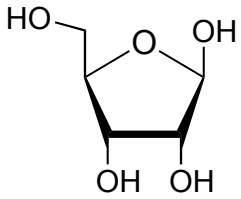
Weitere Monosaccharide



α-Fructopyranose



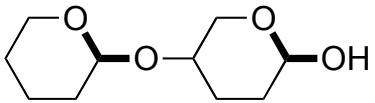
β-Fructopyranose



β-Ribofuranose

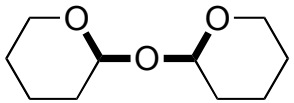
Disaccharide

reduzierende Zucker

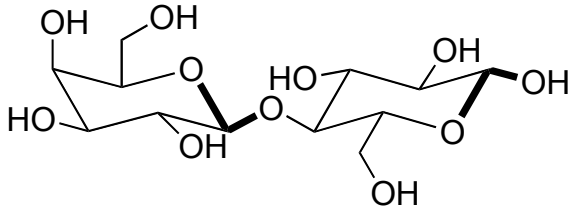


-osyl -ose

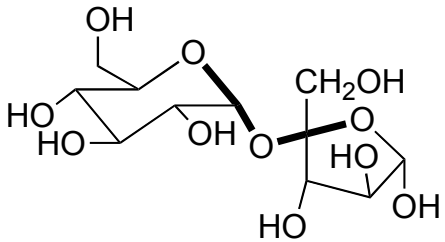
nicht-reduzierende Zucker



-osyl -osid



Lactose
(Milchzucker)

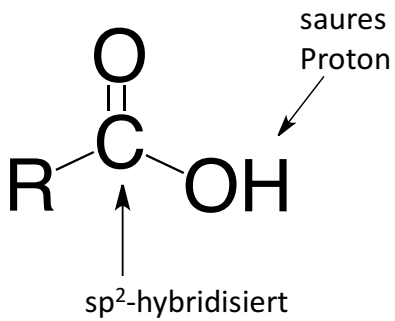


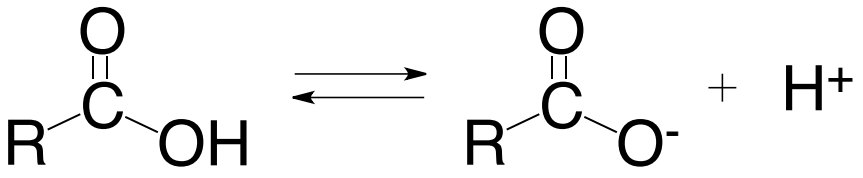
Saccharose
(Rohrzucker)

4.9. Carbonsäuren und Derivate

Carbonsäuren

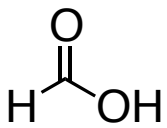
- Carbonsäuren können durch Oxidation von Aldehyden erhalten werden. Sie enthalten eine Carboxyl-Gruppe (-**COOH**).



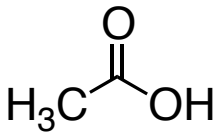


Carboxyl — Carboxylat — Proton

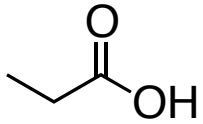
- **Beispiele**



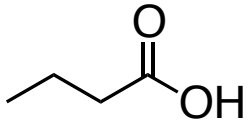
Ameisensäure



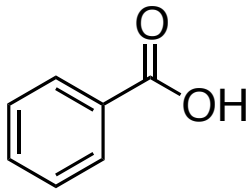
Essigsäure



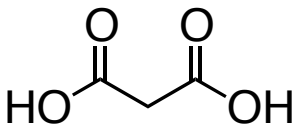
Propionsäure



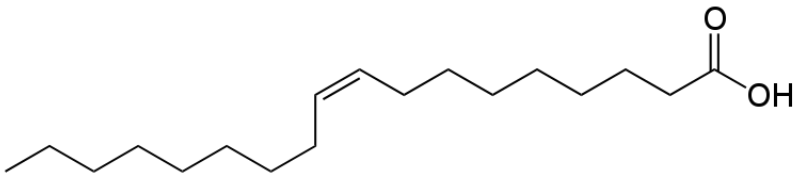
Buttersäure



Benzoesäure

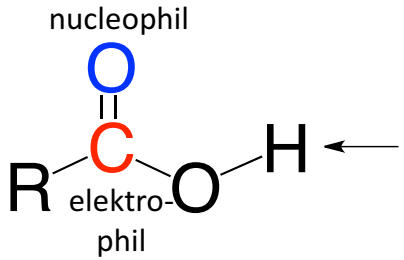


Malonsäure



cis-9-Octadecensäure
(ungesättigte Fettsäure)

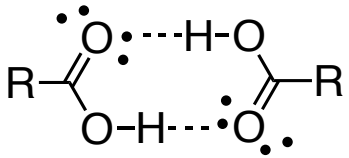
Eigenschaften von Carbonsäuren



saures (leicht abspaltbares) Proton

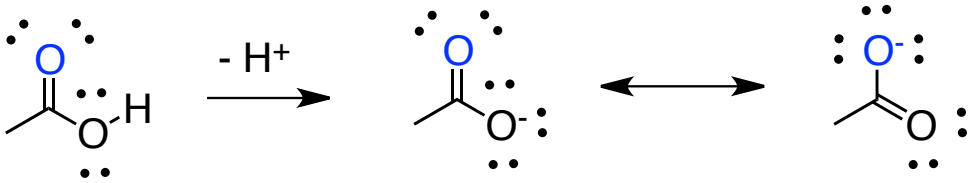
- Carbonsäuren besitzen eine POLARISIERTE C=O Bindung. Das **C-Atom** ist **elektrophil**, es kann duch Nucleophile angegriffen werden. Die C-gebundenen **Sauerstoffe** sind **nucleophil**.

H-Brückenbildung



- Carbonsäuren können Wassterstoffbrücken-Bindungen bilden, sie können z.B. Dimere bilden.

- Die höhere Acidität (im Vergleich zu anderen Vernidnugen wie Alkohole) beruht auf der Mesomerie-Sabilisierung der konjugierten Carboxylat-Base.

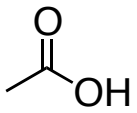


Mesomeriestabilisiertes Caroboxylat

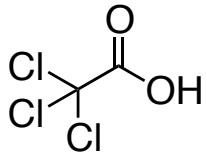
Substitutenteneinflüsse auf die Säurestärke I

- **Elektronenziehende Effekte (-I –Effekt)**

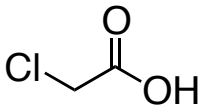
Elektronenziehende Substituenten (z.B. Halogene, -CN, $-NO_2$ oder auch –COOH) bewirken eine Zunahme der Acidität. Die Stärke des –I Effektes ist kurzreichweitig, aber additiv.



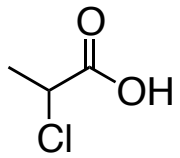
$pK_a = 4.76$



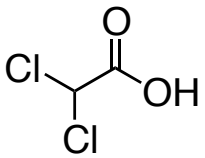
$pK_a = 0.65$



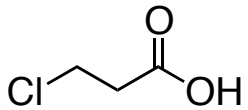
$pK_a = 2.81$



$pK_a = 2.80$



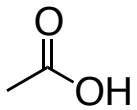
$pK_a = 1.30$



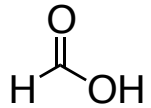
$pK_a = 4.10$

- **Elektronengebende Effekte (+I –Effekt)**

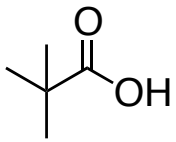
Elektronengebende Substituenten (z.B. Alkyl-Subsituenten) bewirken eine Abnahme der Acidität.



$pK_a = 4.76$



$pK_a = 3.77$

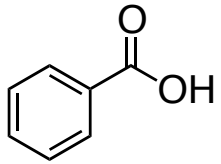


$pK_a = 5.05$

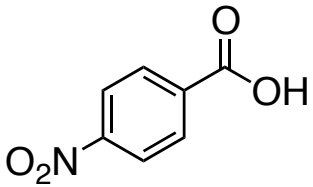
Substitutenteneinflüsse auf die Säurestärke II

- **Mesomerer Effekt**

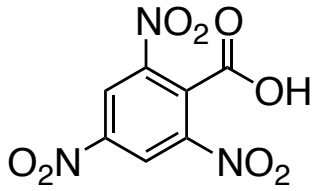
Elektronenziehende bzw. elektronendichte-verringernde Substituenten am Aromaten (z.B. Halogene, -CN, -NO_2 oder auch –COOH) bewirken eine Zunahme der Acidität.



pK_a = 4.22



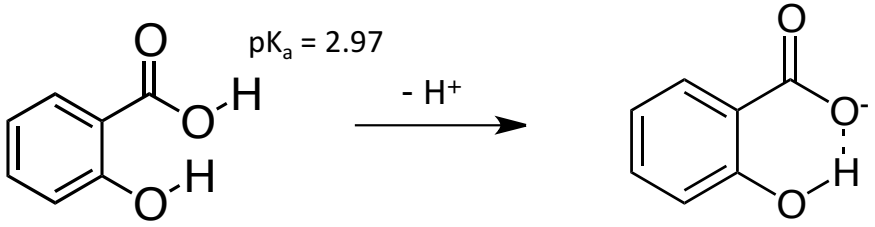
pK_a = 3.42



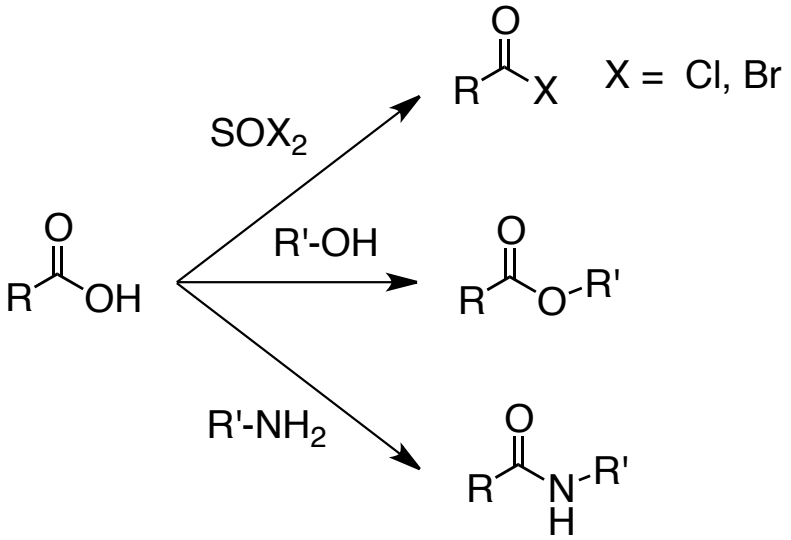
pK_a = 0.65

- **H-Brückenbildung**

H-Brücken können das entstehende Carboxylat-Anion stabilisieren, zB Salicylsäure (Vorläufer von Aspirin©)



Reaktionen von Carbonsäuren – Derivate von Carbonsäuren

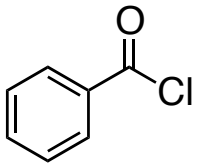


Carbonsäurehalogenide

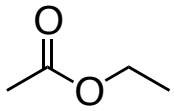
Carbonsäureester

Carbonsäureamide

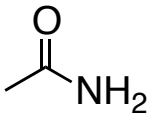
- **Beispiele**



Benzoesäurechlorid

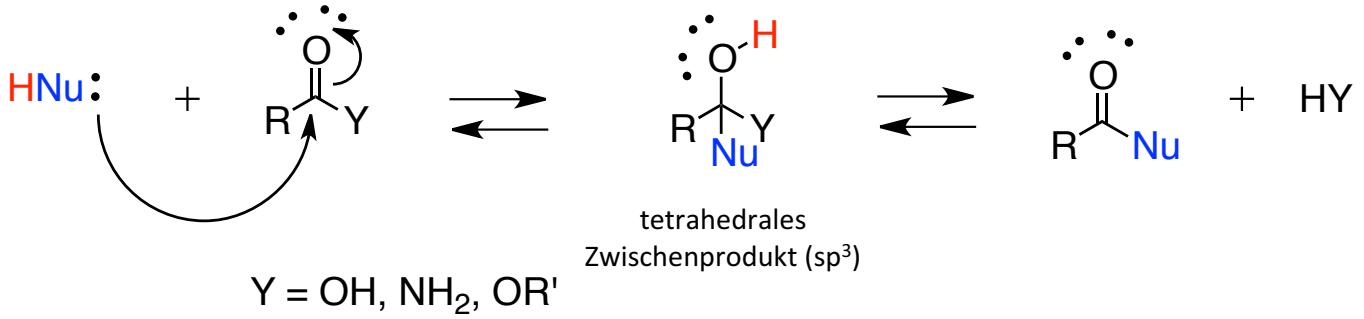


Essigsäureethylester



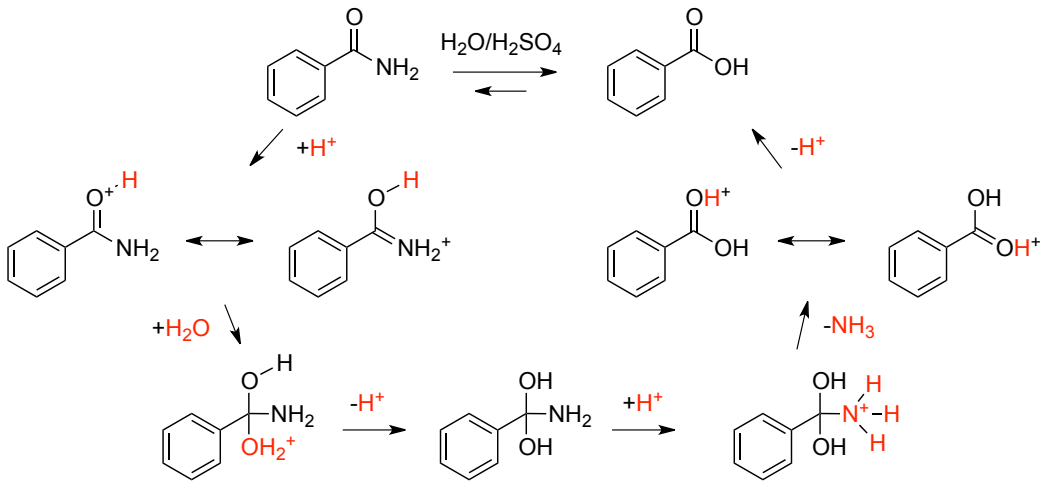
Acetamid

Reaktionen von Carbonsäuren mit Nucleophilen

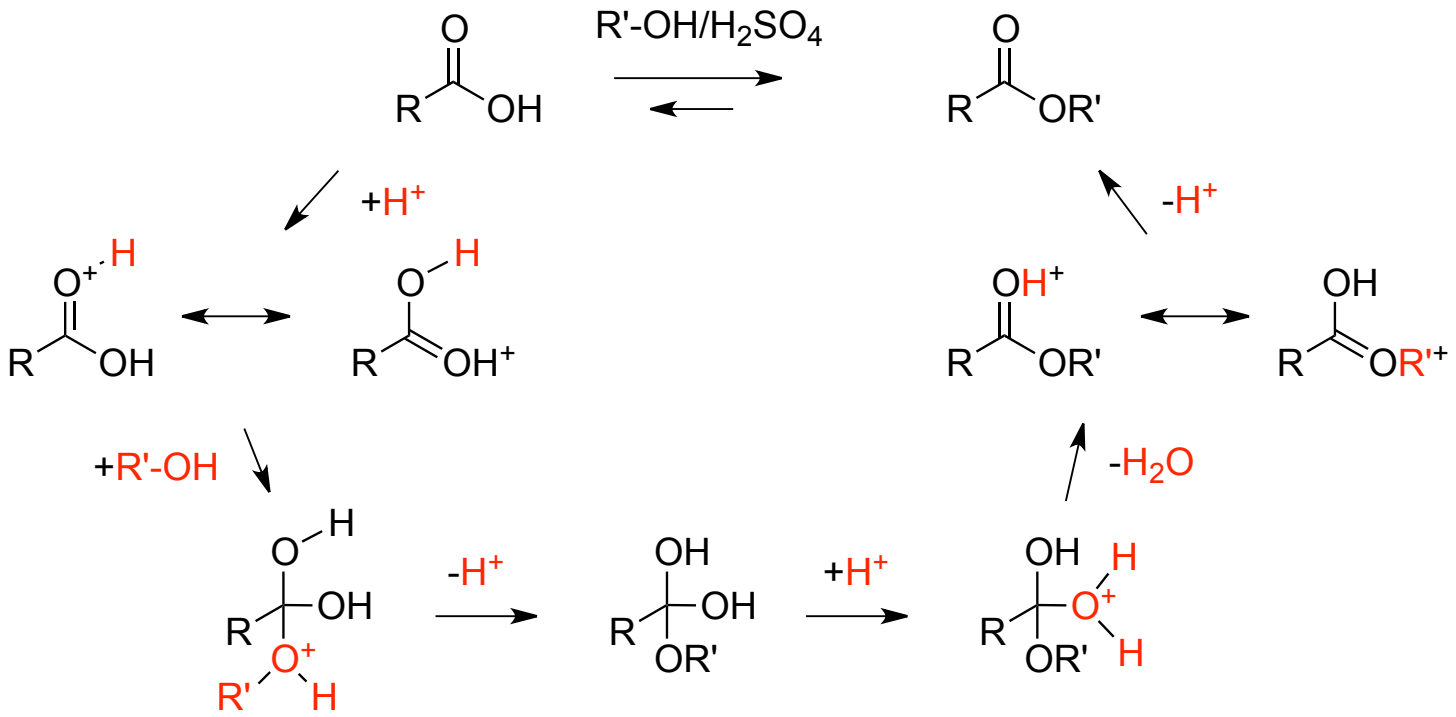


→ **Additions-Eliminations-Reaktion:** in der Regel Gleichgewichtsreaktionen, Reaktion durch Säuren (Protonierung der Carboxylgruppe) und Basen (Deprotonierung des Nucleophils) beschleunigbar.

Beispiel: Hydrolyse von Carbonsäurederivaten zu Carbonsäuren



Herstellung von Carbonsäureestern

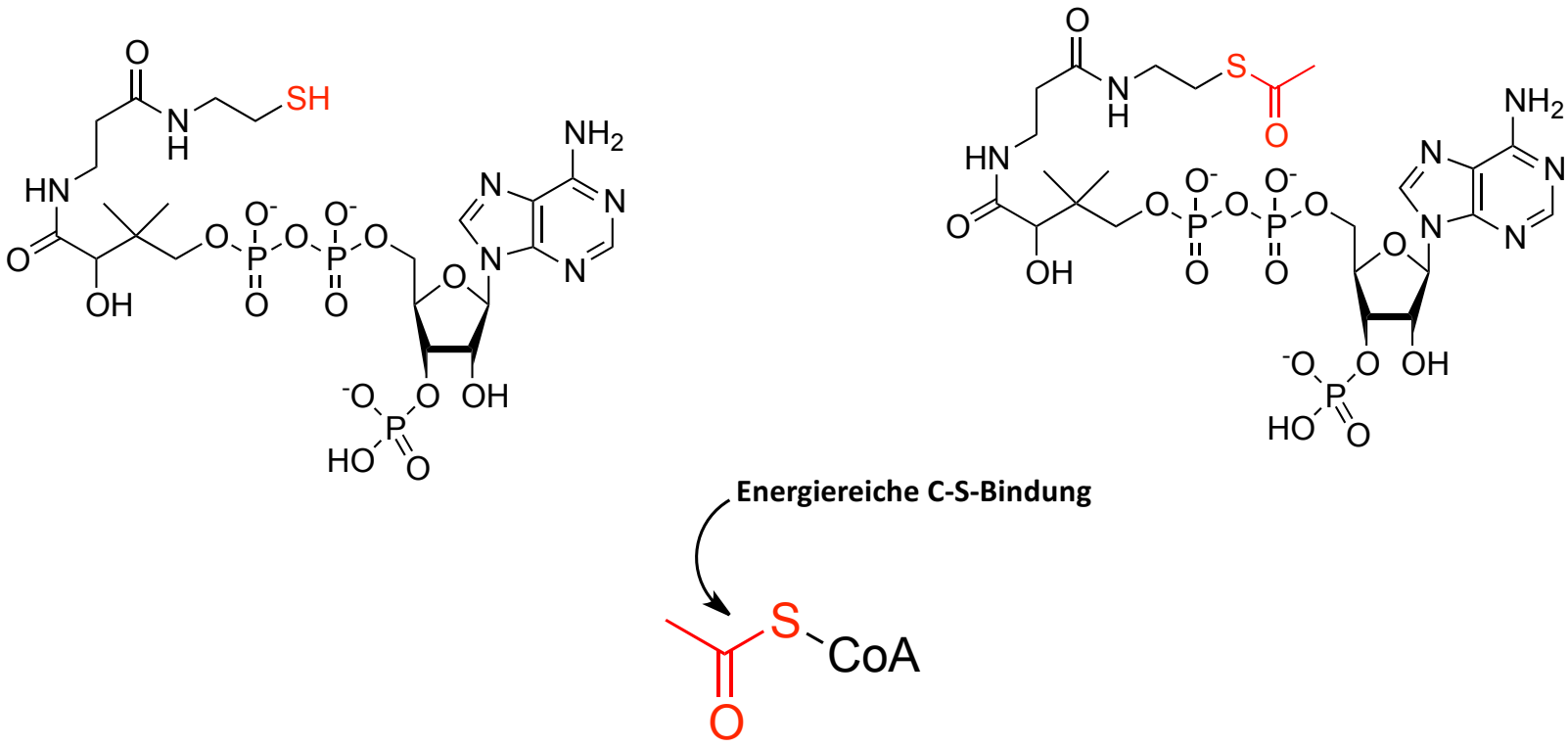


→ **Additions-Eliminations-Reaktion**

→ **Gleichgewichtsreaktion:** um Ester zu erhalten Überschuß an Alkohol verwenden und starke Säuren, entstehendes Wasser entfernen.

→ **Esterhydrolyse (= Umkehr der Veresterung):** Verseifung, im Alkalischen

Biologisch wichtige Carbonsäurederivate



Coenzym A mit einer Thiol (S-Alkohol)-Funktionalität → Bildung von energiereichen Thioester zB Acetyl-CoA

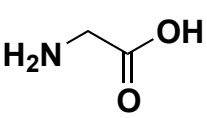
Acetyl-CoA: Aktivierte Essigsäure, wichtigstes Carbonsäurederivate im Stoffwechsel zB beteiligt in Auf- und Abbau von Fettsäuren, Alkoholstoffwechsel, Citratcyclus

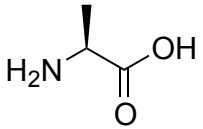
Exkurs: Aminosäuren – Peptide - Proteine

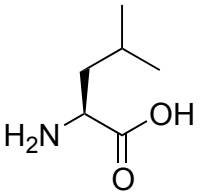
- **Eiweiße** oder **Proteine** (Polypeptide) sind hochmolekulare Naturstoffe aufgebaut aus 20 verschiedenen **Aminosäuren**.

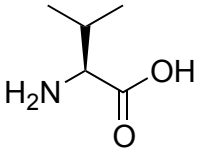
- **α-Aminosäuren:**

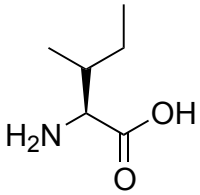
Neutrale Aminosäuren

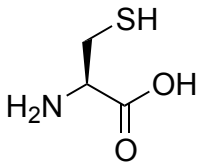

Glycin

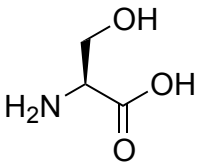

Alanin

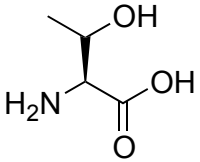

Leucin

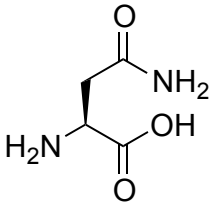

Valin

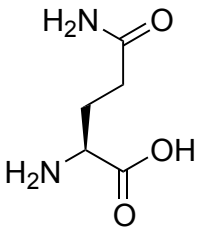

Isoleucin

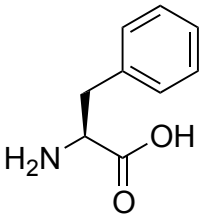

Cystein

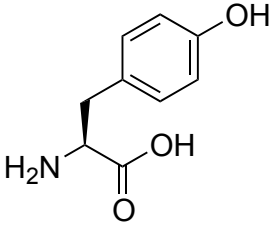

Serin

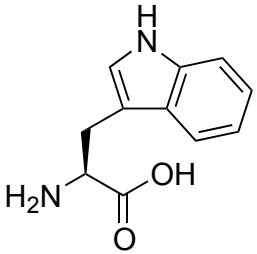

Threonin

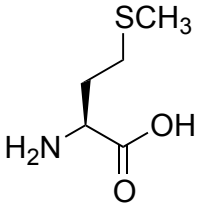

Asparagin

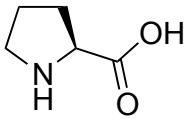

Glutamin


Phenylalanin

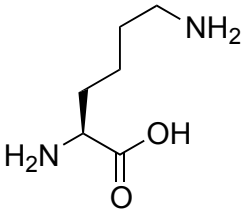

Thyrosin

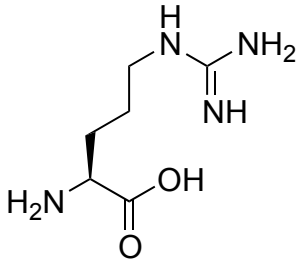

Tryptophan

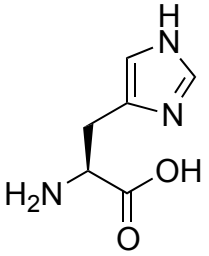

Methionin


Prolin

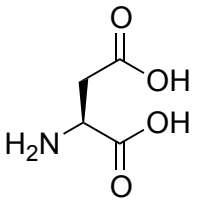
Basische Aminosäuren

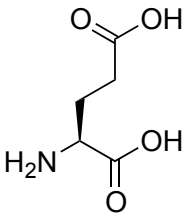

Lysin


Arginin

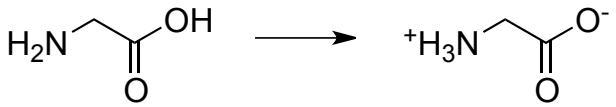

Histidin

Saure Aminosäuren


Asparaginsäure

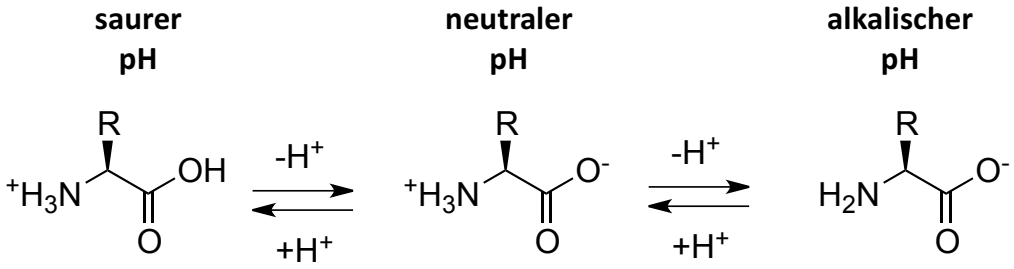

Glutaminsäure

Aminosäuren als Ampholyte

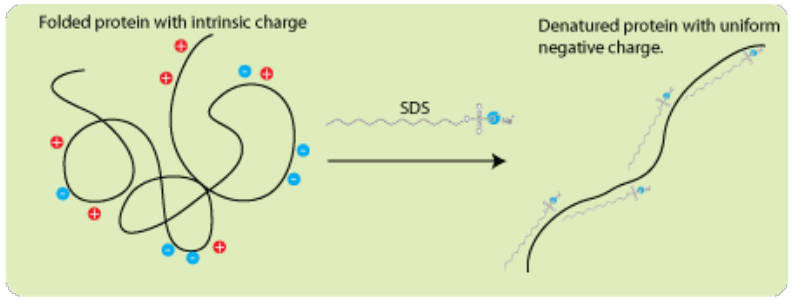


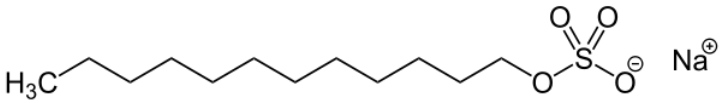
Intramolekulare Neutralisation → Bildung eines ZWITTERIONS

- **Säure- und Baseeigenschaften (ohne Berücksichtung der Seitenkette)**



Analytik von Proteinen

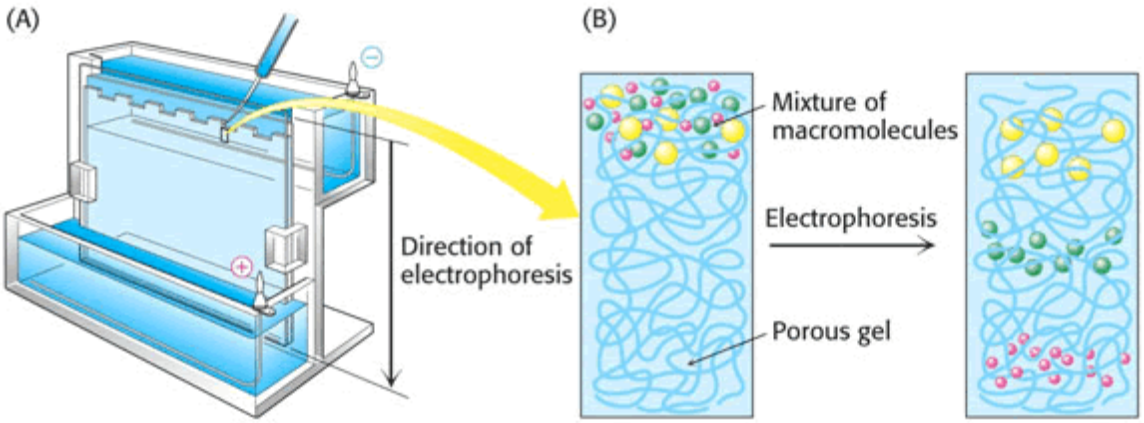


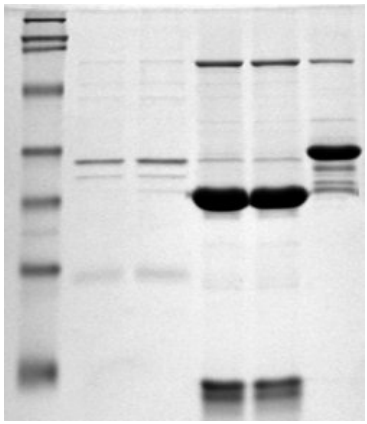


Sodium dodecylsulfate SDS

- Ladung eines nativen Proteins ist bestimmt durch pH-Wert und Seitenketten (basische, saure, usw.) → SDS gibt einheitliche negative Ladung.

- Protein wird in Gel NUR nach Größe aufgetrennt.

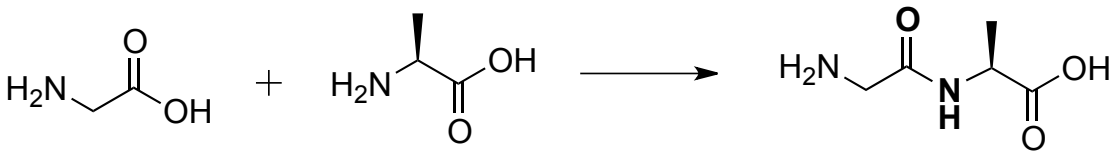




Die Peptidbindung

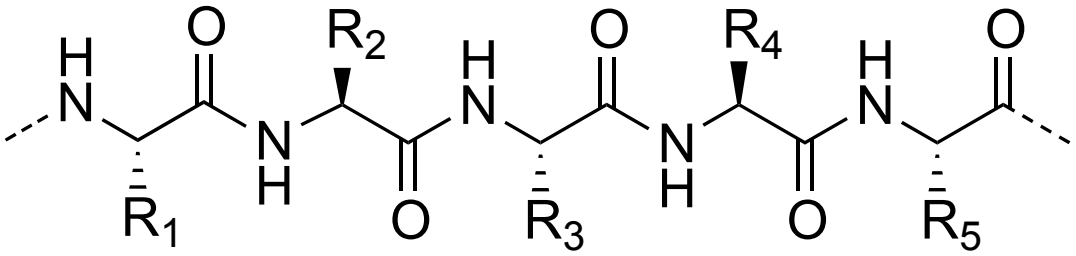
- Mehrere Aminosäuren werden am Ribosom unter Bildung einer Peptidbindung (Carbonsäureamid-Funktionalität) miteinander verknüpft.

- **Beispiel:**



Glycin **Alanin** **Glycyl-Alanin**
ein Dipeptid

N-terminale AS

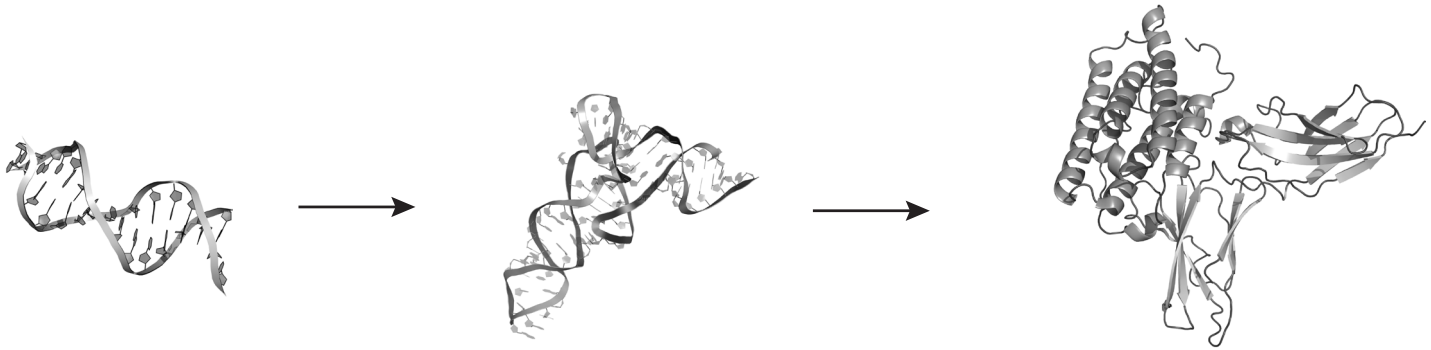


C-terminale AS

- **Reihenfolge der Aminosäuren** in einem Peptid wird als die **Sequenz** (**Primärstruktur**) bezeichnet.

Proteine – wichtige Moleküle in der Biochemie

- Zentrales Dogma der Molekularbiologie



Genomische DNA
2‘-Deoxyadenosin
2‘-Deoxycytidin
2‘-Deoxyguanosin
Thymidin

Ribosomale, Transfer und Boten- RNA
Adenosin
Cytidin
Guanosin
Uridin

Proteine
20
Aminosäuren

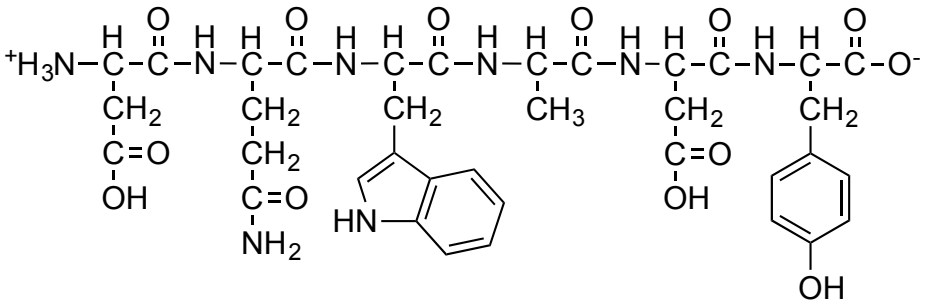
Aufbau und Struktur von Proteinen

1. Primärstruktur = Abfolge der Aminosäuren

H_2N = N-Terminus
COOH = C-Terminus

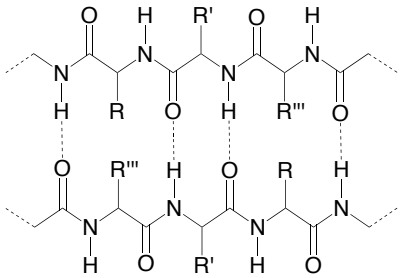
H_2N-Asp-Gln-Trp-Ala-Asp-Tyr-COOH

N-terminale AS

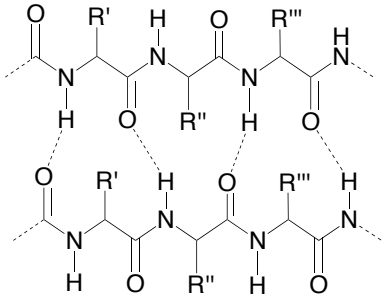


C-terminale AS

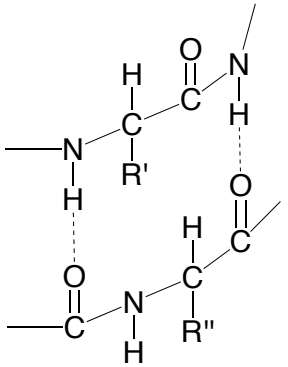
2. Sekundärstruktur = Ausbildung von Sekundärstrukturelementen: α- Helix, β-Faltblatt



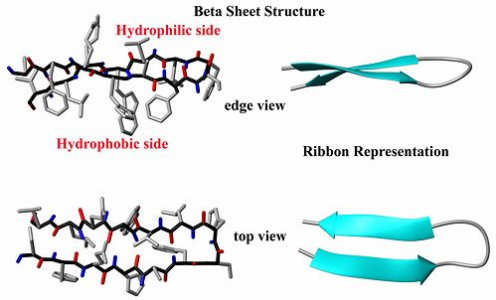
Antiparalleles β-Faltblatt

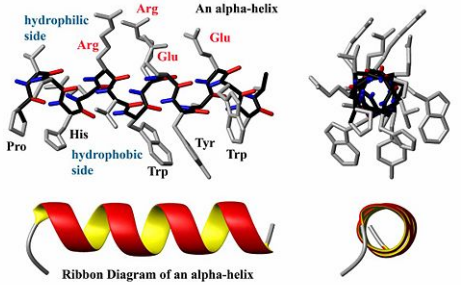


Paralleles β-Faltblatt



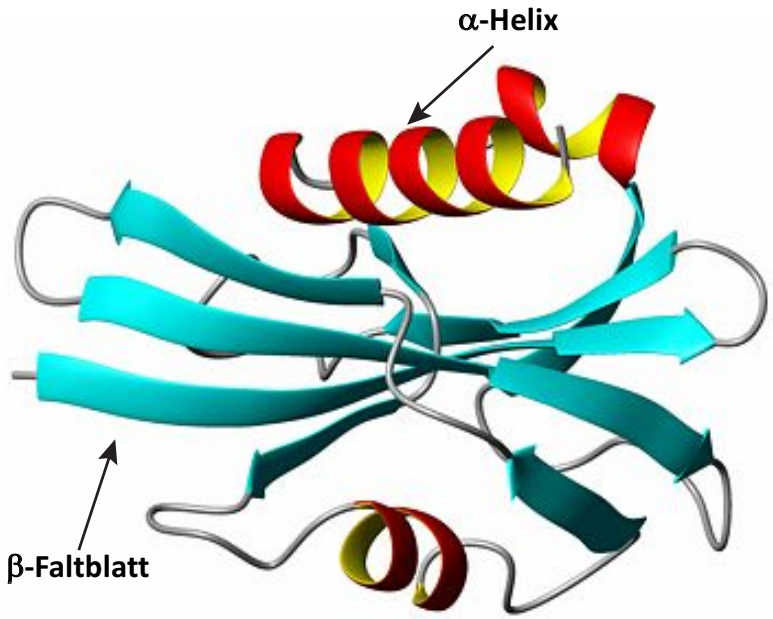
α-Helix



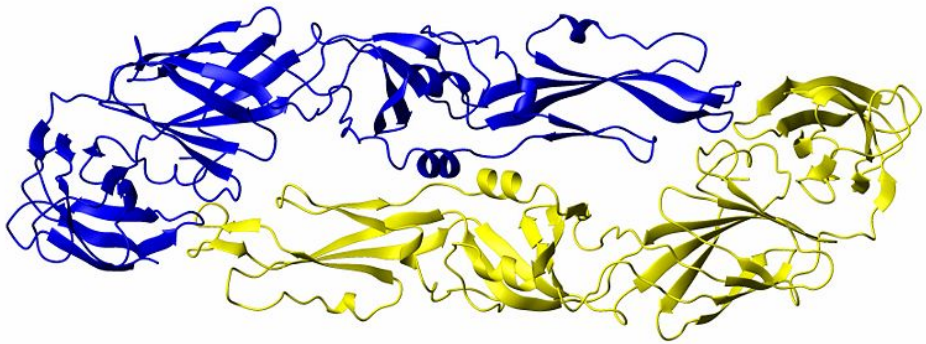


Aufbau und Struktur von Proteinen

3. Tertiärstruktur = räumliche Anordnung von Sekundärstrukturelementen → Motive und Domänen



3. Quartärstruktur = räumliche Anordnung von Tertiärstrukturelmenten zueinander zB Protein-Protein-Komplex



4.10. Heterocyclen

Heterocyclen

▪ Heterocyclische Verbindungen **enthalten außer C-Atomen ein oder mehrere Heteroatome** (z.B. N, S, O) als Ringglieder. Man unterscheidet **heteroaliphatische** und **heteroaromatische** Verbindungen.

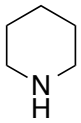
▪ **Heteroaliphaten**

Heterocyclische mit 5 oder mehr Ringatomen, die gesättigt sind oder isolierte Doppelbindungen enthalten, verhalten sich chemisch wie die analogen acyclischen Verbindungen. Kleinere Ringsysteme sind wegen der höheren Ringspannung reaktiver als größere.

▪ **Heteroaromaten**

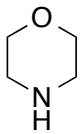
Bei cyclischer Konjugation und 4n + 2 π Elektronen in cyclischen Systemen mit Heteroatom-Ringgliedern spricht man von Heteroaromaten. Im Vergleich zu den reinen Kohlenstoff-Aromaten (z.B. Benzol) sind die aromatischen Eigenschaften allerdings schwächer ausgeprägt.

Beispiele



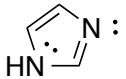
Piperidin
(pK_B = 6.2)

Pyrrolidin
(pK_B = 3)



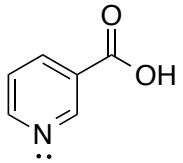
Morpholin

Pyrrol
(aromatisch)



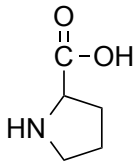
Imidazol
(aromatisch)

Furan
(aromatisch)

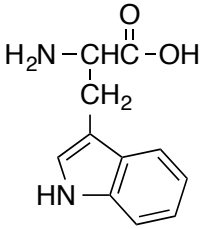


Nicotinsäure
(aromatisch)

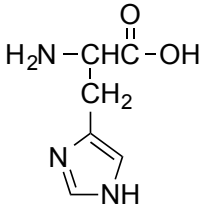
Aminosäuren



Prolin

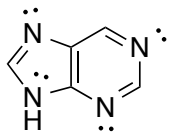


Tryptophan
(aromatisch)



Histidin
(aromatisch)

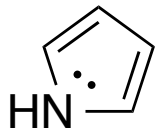
DNA und RNA Nucleobasen Grundgerüste



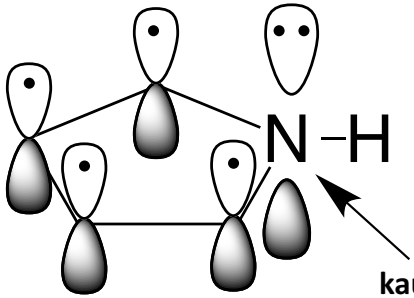
Purin
(aromatisch: Guanin und Adenin)

Pyrimidin
(aromatisch: Uracil/Thymin und Cytosin)

Fünfgliedrige Stickstoff-Heteroaromaten

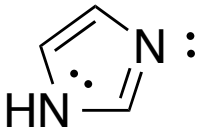


Pyrrol
(aromatisch)

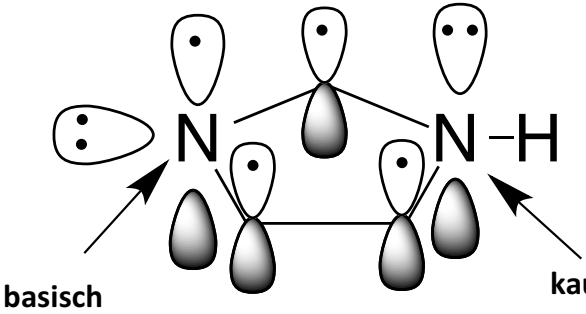


6 π-Elektronen
Das freie Eletronenpaar am Stickstoff ist TEIL des π-Systems-
→ verringerte Basizität.

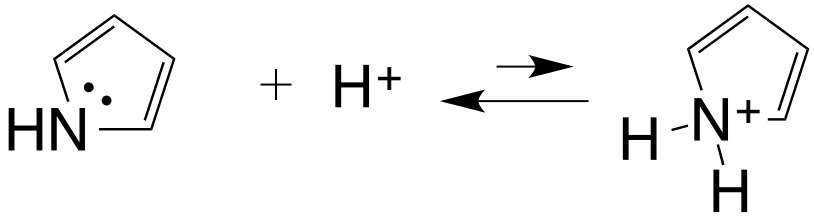
basisch



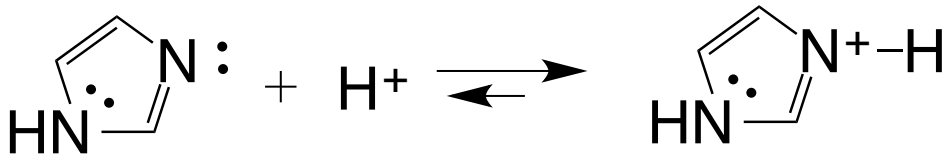
Imidazol
(aromatisch)



6 π-Elektronen
Das freie Eletronenpaar am 2. Stickstoff ist nicht TEIL des π-System. → basisch.

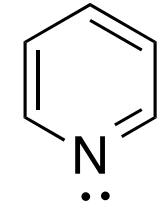


Pyrrol→ **kaum basisch**
(aromatisch)

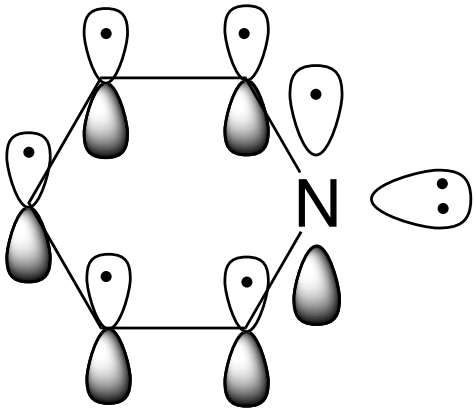


Imidazol → **BASE**
(aromatisch)

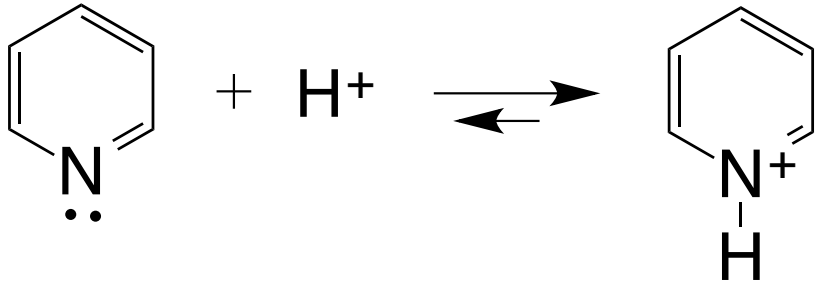
Sechsgliedrige Stickstoff-Heteroaromaten



Pyridin
(aromatisch)



6 π-Elektronen
Das freie Eletronenpaar am Stickstoff ist nicht TEIL des π-System. → basisch; $pK_B = 8.7$



4.11. Nukleotide und Nukleinsäuren

Nukleotide und Nukleinsäuren

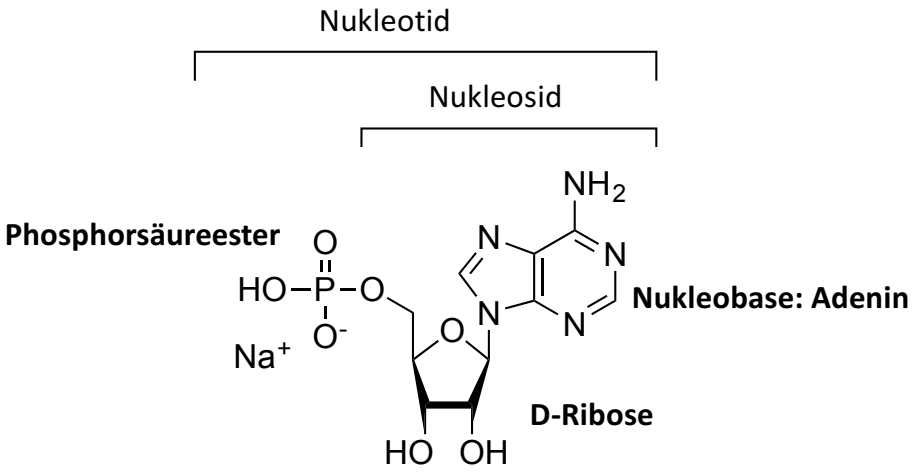
- Nukleotide = Bausteine der Nukleinsäuren
- **3 Bestandteile:** Organische Base (Nukleobase), Monosaccharid und Phosphorsäure

→ **Nukleobase:** N-haltige Heterocyclen mit aromatischen Ringsystem

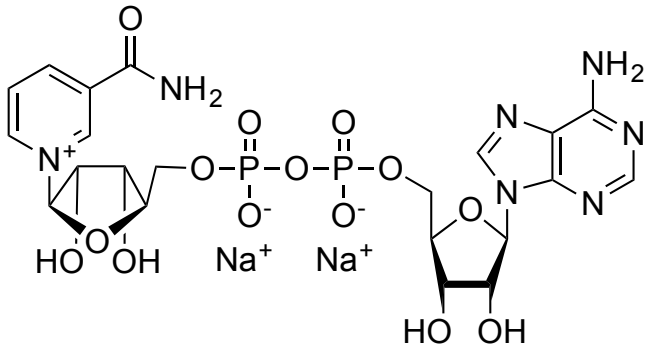
→ **Monosaccharid**: D-Ribose oder D-Desoxyribose

Nukleobase + Monosaccharid = Nukleosid

Nukleobase + Monosaccharid + Phosphorsäure = Nukleotid



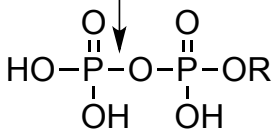
Natriumsalz des Adenosinmonophosphates



Nicotinamid-adenin-dinucleotid (NAD^+):
Cofaktor in biochemischen Redox-Prozessen

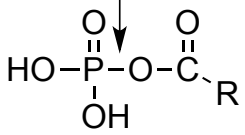
Exkurs: Energiespeicherung in Phosphorsäureverbindungen

Energiereiche Bindung



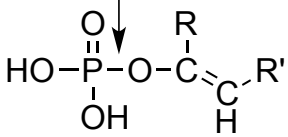
Pyrophosphat

Energiereiche Bindung



Gemischtes Anhydrid

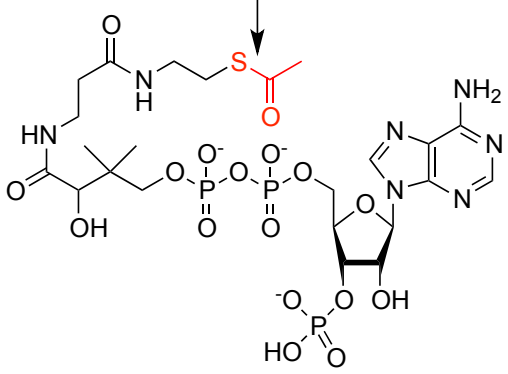
Energiereiche Bindung

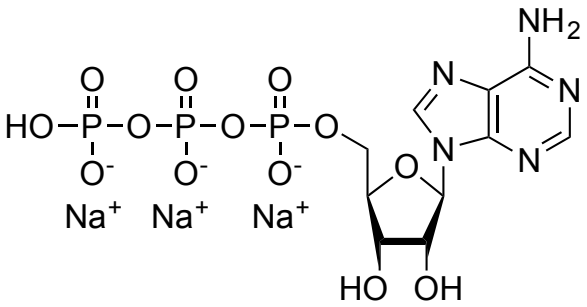


Enolphosphat

Vergleiche früher: **Acetyl-Coenzym A**

Energiereiche Bindung



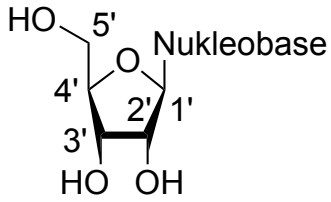


ATP – Adenosintriphosphat: Treibstoff für Zelle

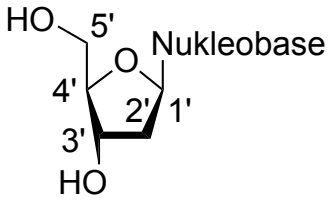
Nukleotide in Nukleinsäuren

- In den Nukleinsäuren liegen Nukleotide in Form von Phosphorsäurediestereinheiten vor.

- **D-Ribose** Zuckereinheit in Ribonukleinsäure (**RNA**), **D-Desoxyribose** Zuckereinheit in Desoxyribonukleinsäre (**DNA**)

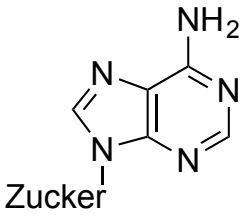


D-Ribose

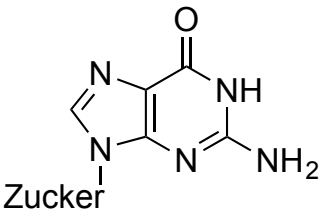


D-2‘-Desoxyribose

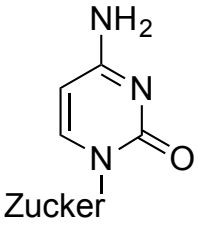
- **Nukleobasen:**



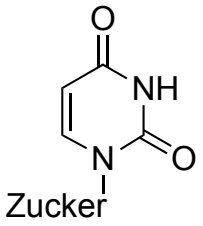
Adenin (RNA und DNA)



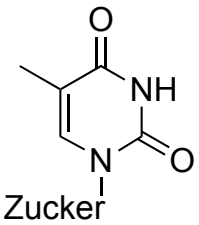
Guanin (RNA und DNA)



Cytosin (RNA und DNA)



Uracil (RNA)

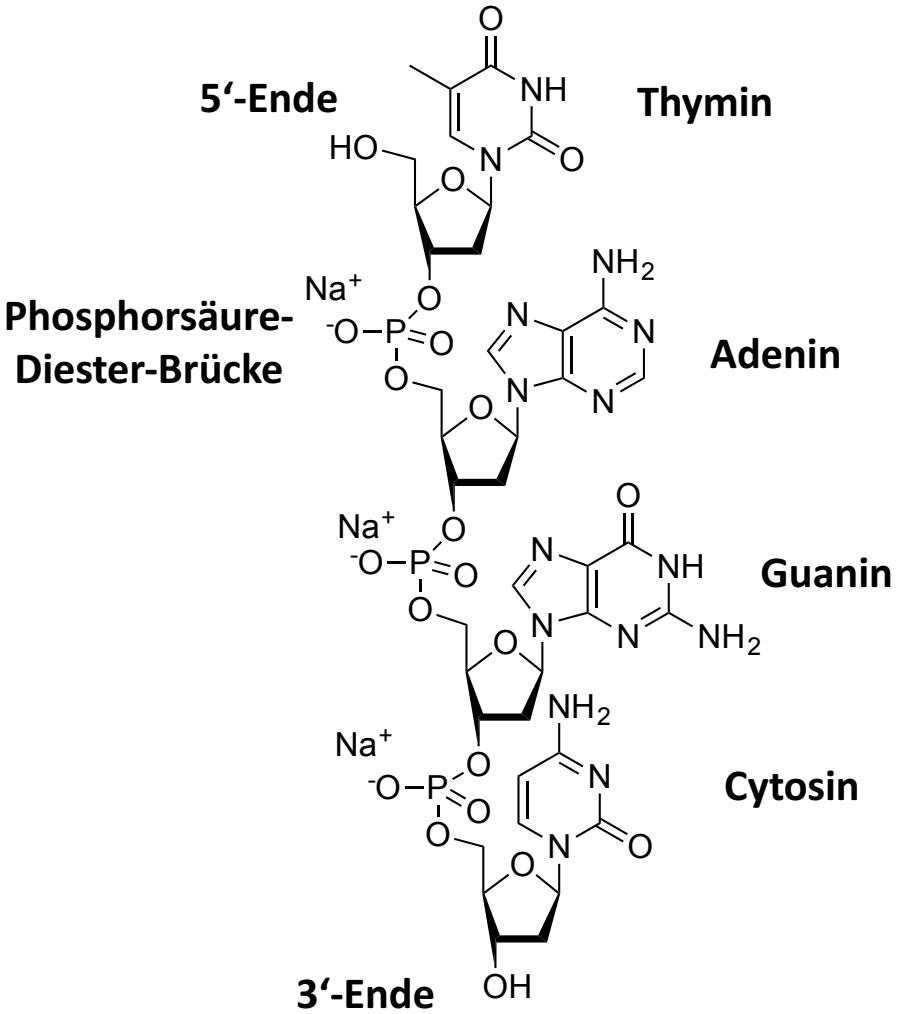


Thymin (DNA)

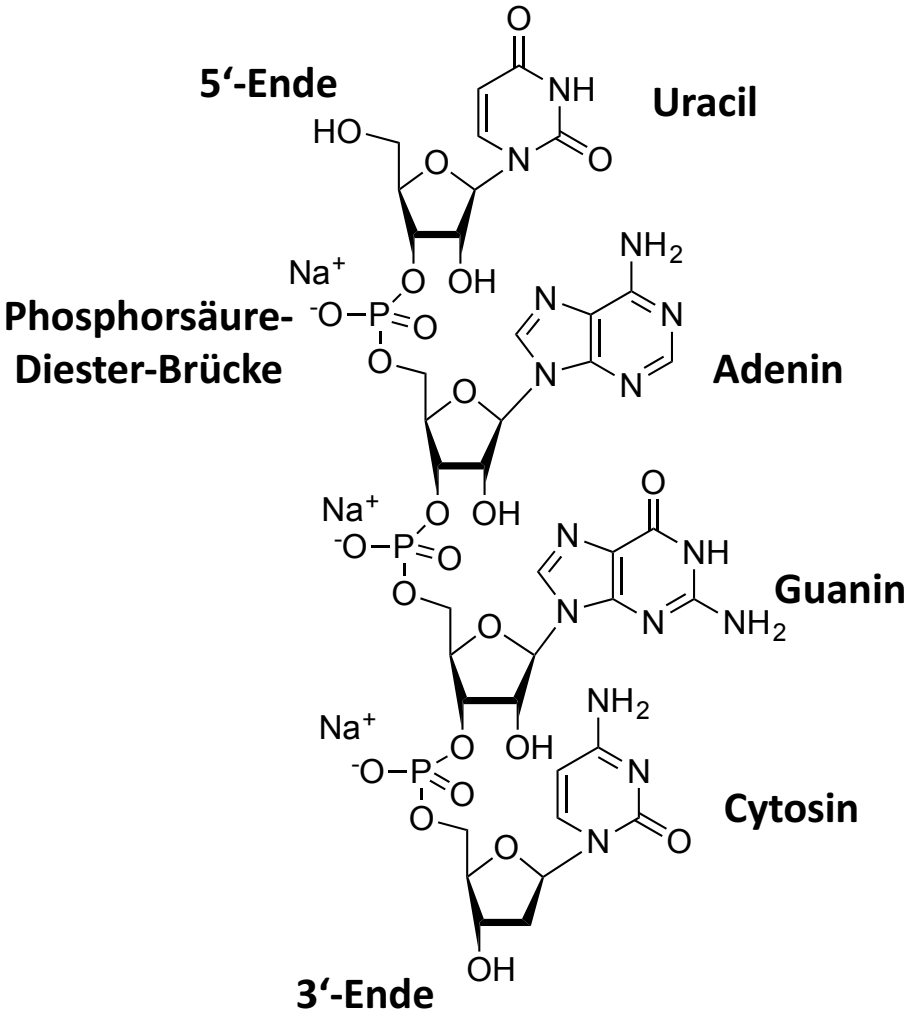
PURIN

PYRIMIDIN

Nukleinsäuren

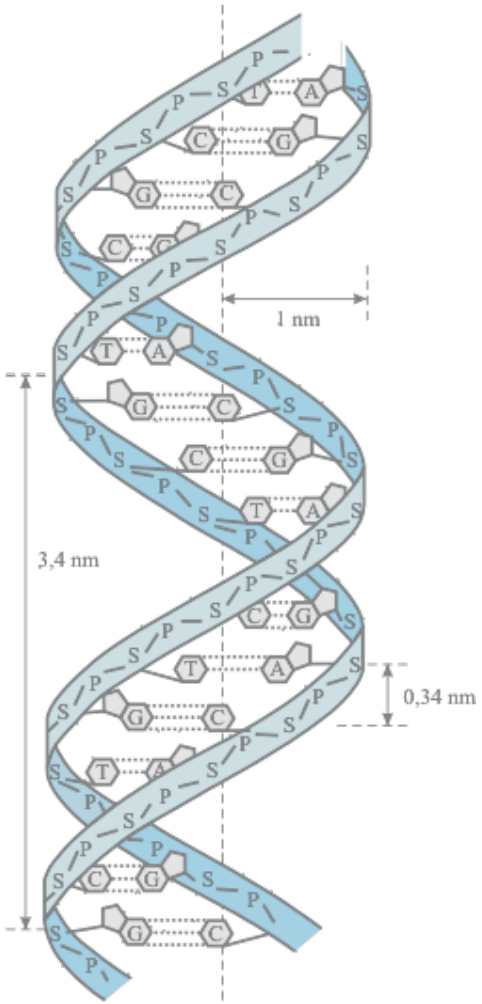


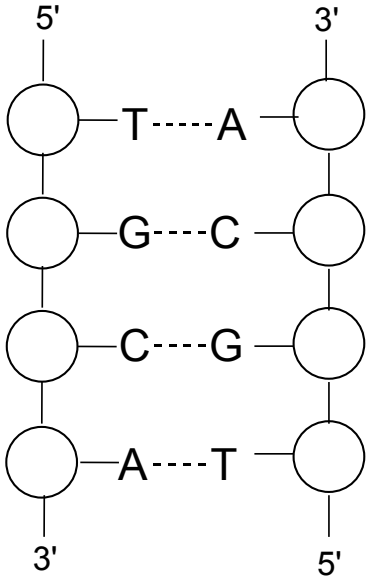
DNA



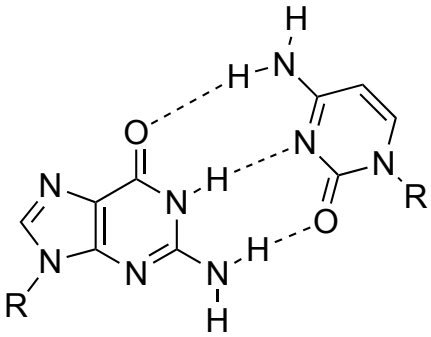
RNA

Aufbau der DNA

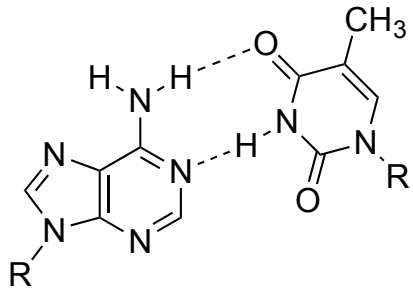




Antiparallele Duplexanordnung

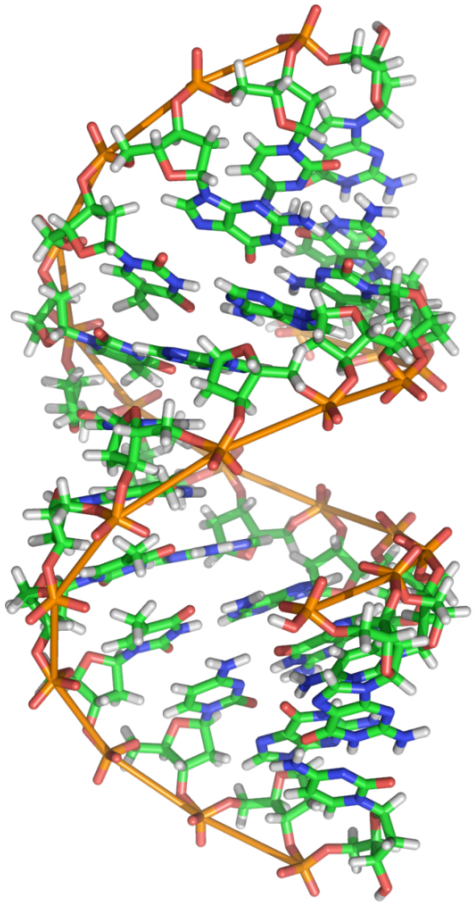


G-C Basenpaar
3 Wasserstoffbrücken

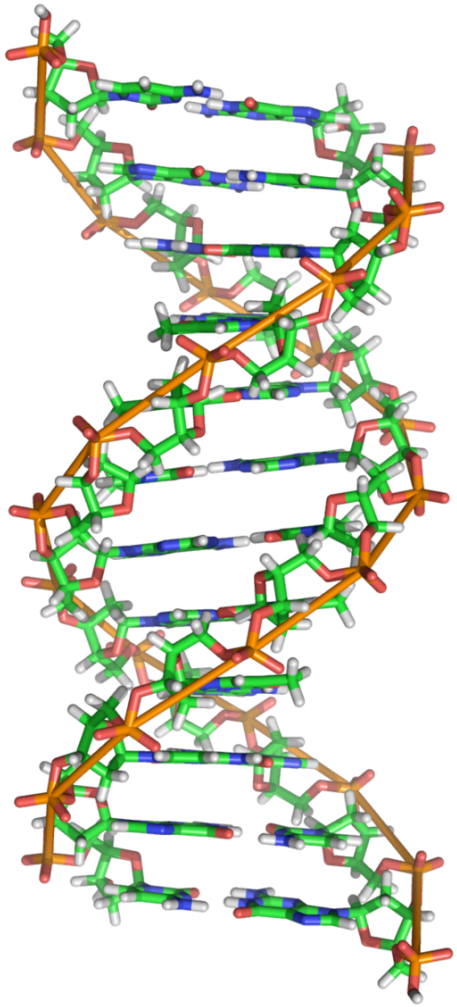


A-T Basenpaar
2 Wasserstoffbrücken

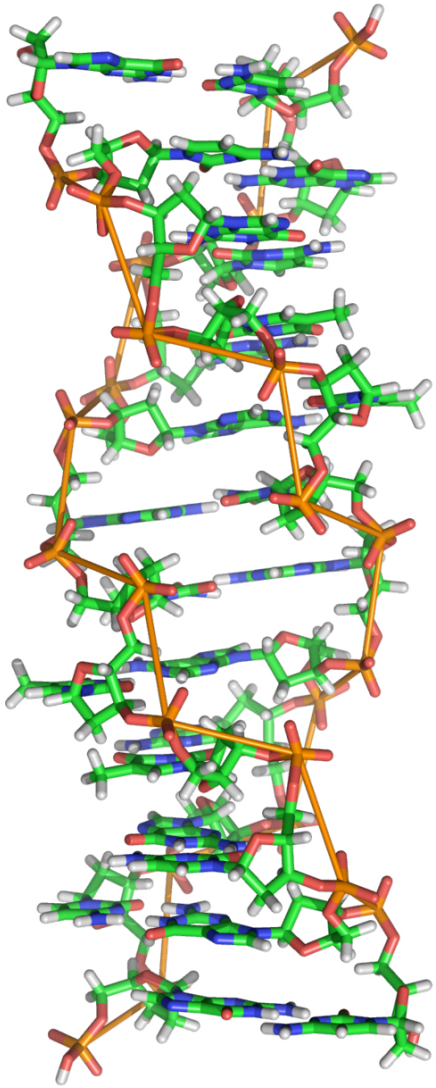
3D-Struktur der DNA

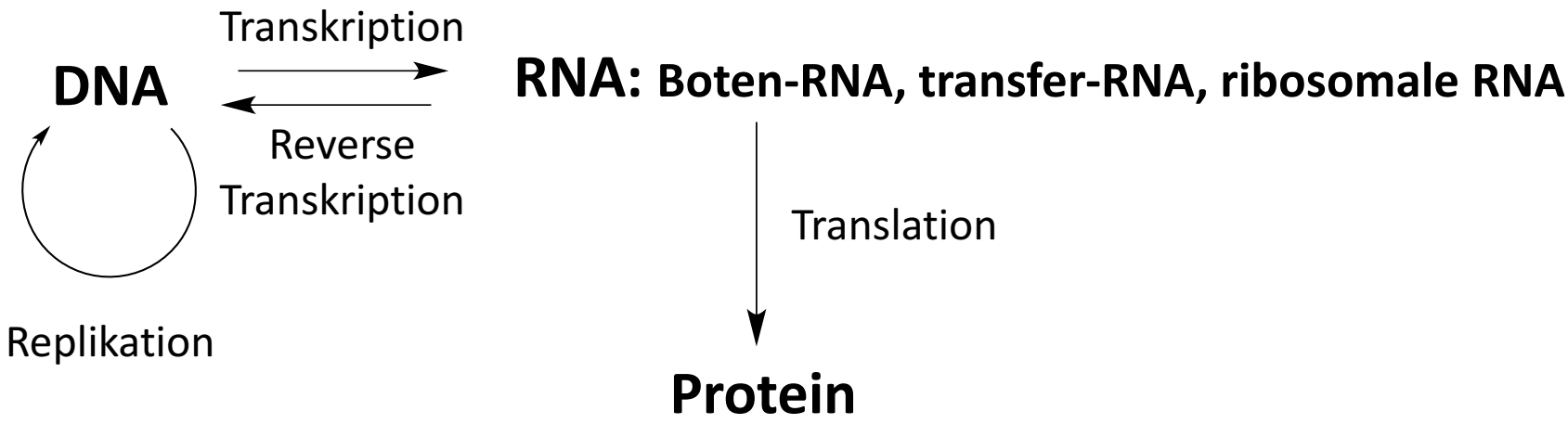


A-DNA



B-DNA



Z-DNA

Fluss der biologischen Information