Computer Graphics: Visual Perception

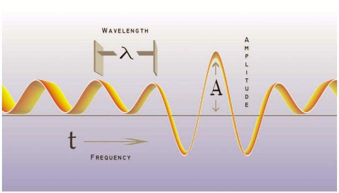
Bachelor in Informatics Engineering
Universidad Carlos III de Madrid
Computer Science Department

Academic Year 2017-2018

Source: LIRMM, Université Montpellier

Outline

The Nature of Light



Light

By the *wave-particle* theory, light has both a wave nature and a particle nature.

- Wave: light is an *electromagnetic radiation* defined by its wavelength and its amplitude.
- Particle: light is a beam of *photons* defined by its speed in the media and its energy.

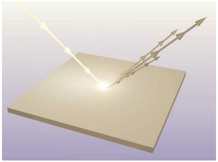
$$E = \frac{hc}{\lambda}$$ where h is the Planck's constant.

The Nature of Light

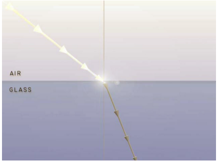
Properties

Light as it interacts with matter manifests itself in a great number of observable ways.

- *Reflection:* change in direction of a wave by bouncing on a surface.
- *Refraction:* change in direction of a wave by crossing a surface.
- *Interference:* composition of two interacting waves.
- *Diffraction:* bending of waves around small obstacles and spreading out of waves past small openings.
- *Scattering:* generalized reflection on non-uniform surfaces.
- *Dispersion:* generalized refraction on a wavelength-dependent refractive surface.



Reflection



Refraction

The Nature of Light

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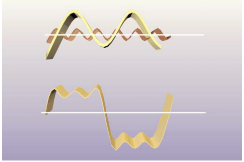
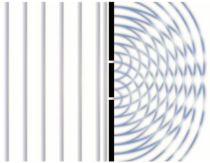


Interference



Diffraction

The Nature of Light

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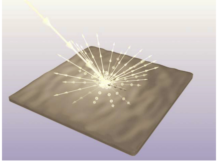
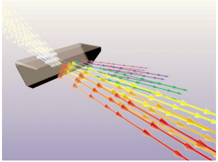


Scattering



Dispersion

Radiometry

Radiometry

Radiometry is the field that studies the measurement of electromagnetic radiation.

Measurements

Measurements are taken with respect to the unit hemisphere surrounding the center point of a surface. A *solid angle* refers to some small surface area on the hemisphere. A *steradian* (sr) is the solid angle of a cone that intercepts an area equal to the square of the sphere's radius. There are 2π steradians in a unit hemisphere.

Radiant Flux

The *radiant flux* Φ is the power emitted by the source, measured in *joules per second*, or *watts*.

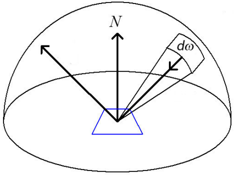
Irradiance

The *irradiance* E_r is the amount of radiant flux per unit area on the surface.

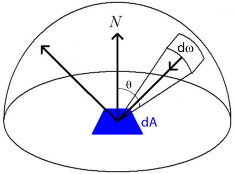
Radiance

Viewing the source as a narrow laser beam of $\partial\omega$ sr, the *radiance* is the amount of radiant flux of the source hitting a small surface of $\partial A \ \mathrm{m}^2$, with an angle θ:

$$L_r = \frac{\partial^2 \Phi}{\partial A \partial w cos\theta}$$



Steradian



Radiance

Emission of Light

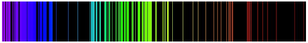
Emission Spectrum

When the electrons in the atom are excited, the additional energy pushes the electrons to higher energy orbits. When the electrons fall back down and leave the excited state, energy is re-emitted in the form of a photon. The wavelength of the photon is determined by the difference in energy between the two states.

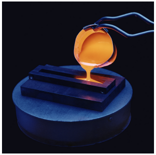
Types of Luminescence

Materials can emit light in various ways:

- *Incandescence:* the material emits light due to its temperature (ex: by being heated).
- *Electroluminescence:* the material emits light in response to an electric current passed through it.
- *Chemiluminescence:* the material emits light as a result of a chemical reaction.
- *Photoluminescence:* the material emits light in response to electromagnetic radiation (ex: fluorescence, phosphorescence).
- *Sonoluminescence:* the material emits lights as a result of sonic pressure.



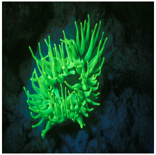
Emission spectrum of Iron



Incandescence

Electroluminescence

Chemiluminescence



Photoluminescence

Emission of Light (Incandescence)

Black Body

A *black body* is an idealized object that absorbs all electronic radiations when it is in a *cold state*, and emits a temperature-dependent spectrum of light when it its *heated*.

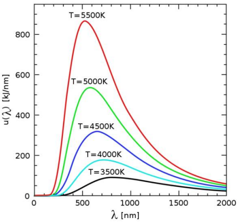
Wein's Law

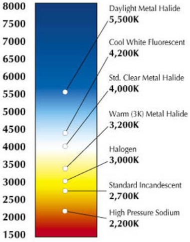
The wavelength of the peak of radiance of a black body decreases linearly as its temperature increases. *The hotter the object gets, the bluer the radiation it emits.*

$$\lambda_{\max} = \frac{b}{T} \text{ where } b = 2.898 \times 10^{-3} mK$$

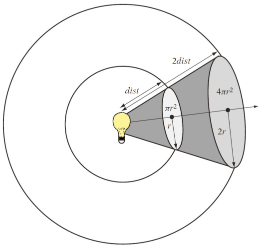
Color Temperature

The *color temperature* maps the wavelength of a black body's peak of radiance to its temperature in Kelvins.





Transmission of Light



Inverse-Square Law

The irradiance of light transmitted from a point source is inversely proportional to the square of the distance from the source.

$$E_{\text{dist}} \propto \frac{E_{\text{source}}}{\pi r^2}$$

Reflection of Light

Reflection

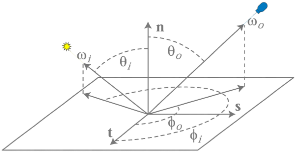
Reflection of light is a combination of *specular* reflection and *diffuse* reflection, which depend on the nature of the material (texture).

BRDF

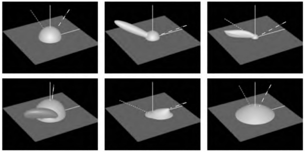
The bidirectional reflectance distribution function is a model that defines how the light is reflected at an opaque surface. It takes an incoming light direction ω_i, and outgoing direction ω_0, both defined with respect to the surface normal $\boldsymbol{n}$, and returns the ratio of reflected radiance exiting along ω_0 to the radiance incident on the surface from direction ω_i.

$$f(\boldsymbol{\omega_0}, \boldsymbol{\omega_i}) = \frac{L_r(\boldsymbol{\omega_0})}{L_r(\boldsymbol{\omega_i})(\boldsymbol{n} \cdot \boldsymbol{\omega_i})}$$

The specification of f is characterized by the type of material.



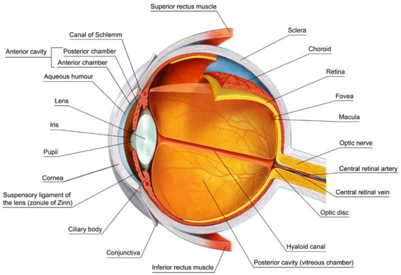
Model

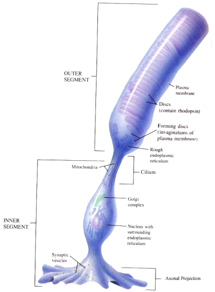


Simulations

Outline

The Eye

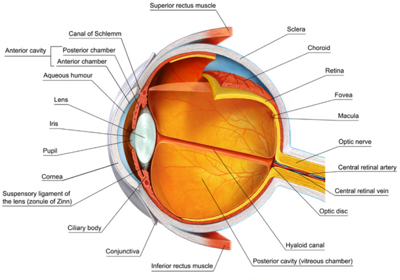


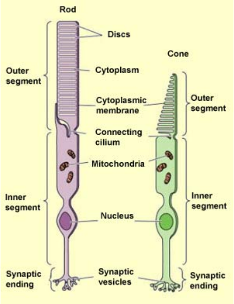


Phototransduction

Phototransduction is the process whereby the energy of photons is converted into electrical impulses by changing the membrane potential of *photoreceptors*.

The Eye



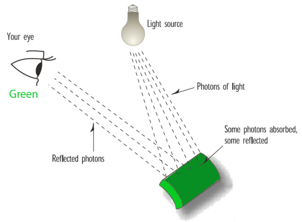


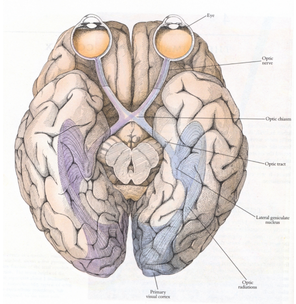
Retina

The retina contains two major types of light-sensitive photoreceptor cells used for vision:

- *rods:* in the peripheral retina, they are responsible for low-light (scotopic) monochrome vision;
- *cones:* in the fovea, they are responsible for bright-light (photopic) color vision.

Perception



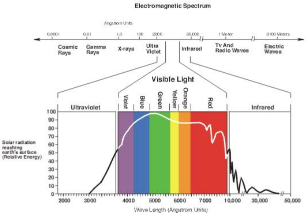


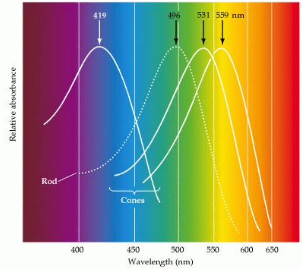
Color vision

Color vision is the capacity to distinguish objects based on the wavelengths of the light they reflect.

- An object (ex: can) absorbs all frequencies of visible light shining on it, except for a group of frequencies (ex: green) which are reflected.
- The *visual system* (eyes → visual cortex) derives color by comparing the responses to light from the several types of *cones* in the eye.

Perception





Trichomatic vision

Humans have three types of cones: short (blue region), medium (green region), and long (red region).

- The human visual system can perceive between 1 million and 7 millions colors.
- The peak response of human color receptors varies amongst individuals. Human are most sensitive to greens.

Photometry

Photometry

Photometry is the field that studies measurement of light, in terms of its *perceived brightness* to the human eye. The energy, flux and densities at each wavelength are *weighted* by by a luminosity function (visual sensitivity function) that models human brightness sensitivity.

Luminous Flux

Amount of light F being generated by the source, measured in *lumen*.

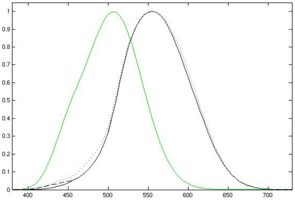
Illuminance

Amount of luminous flux E_v falling on a given area of surface, measured in *lux*.

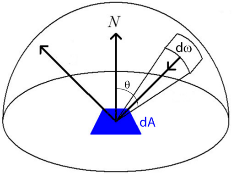
Luminance

Viewing the source as a narrow laser beam of $\partial\omega$ sr, the *luminance* is the amount of limunous flux of the source hitting a small surface of $\partial A\ \mathrm{m}^2$, with an angle θ:

$$L_v = \frac{\partial^2 F}{\partial A \partial w cos\theta}$$



Photopic (black) and scotopic (green) luminosity functions



Luminance

Outline

Colors

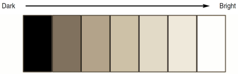
Hue
Monochromatic light as it is perceived.

Saturation
Amount of grey in a hue. It its the perception of hue's purity.

Value
Amount of lightness in a hue. It is the perception of hue's brightness.

Hue

Saturation



Value

Colors

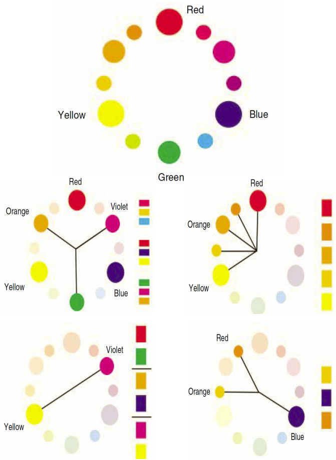
Color Wheel

Circle of color hues.

- Primary colors: fundamental hues that when added together create white light.
- Secondary colors: addition of two primary colors.
- Tertiary colors: addition of two secondary colors.

Categories

- Triads colors: three hues that are equidistant from each other in the wheel
- Analogous colors: any combination of colors that have a common hue
- Complementary colors: hues opposite each other in the wheel
- Split complementary colors: three hues such as the addition of two of them is complementary to the third.

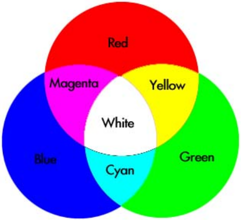


RGB Model

Model

Three *primary* colors: red, green and blue.
Mathematically, any color is represented by a vector in the simplex $[0, 1]^3$

$$\boldsymbol{c} = \begin{bmatrix} c_r \\ c_g \\ c_b \end{bmatrix}$$



Color Storage

The standard format uses 8 bits per color and 8 bits for alpha. It *doesn't* match human perception:

- wastes precision in some ranges: the difference is not noticable
- lacks precision in other ranges: certain colors are not covered

Color Operations

- Color addition:

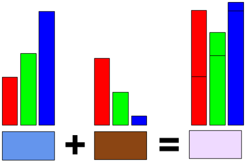
$$\boldsymbol{c} + \boldsymbol{d} = \begin{bmatrix} c_r + d_r \\ c_g + d_g \\ c_b + d_b \end{bmatrix}$$

- Color scaling:

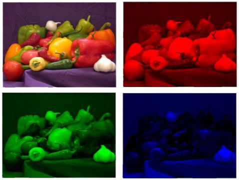
$$\alpha \boldsymbol{c} = \begin{bmatrix} \alpha c_r \\ \alpha c_g \\ \alpha c_b \end{bmatrix}$$

- Color filtering:

$$\boldsymbol{c}\boldsymbol{d} = \begin{bmatrix} c_r \, d_r \\ c_g \, d_g \\ c_b \, d_b \end{bmatrix}$$

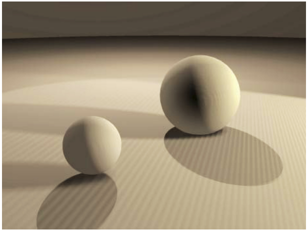


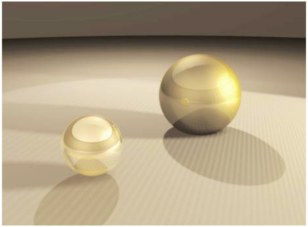
Addition



RGB Filtering

Materials





Diffuse vs Specular

- a *matte object* has a dull, rough surface. It is mostly a *diffuse receptor*: the luminance is independent of the view direction.
- a *shiny object* has a glossy and reflective surface. It is mostly a *specular receptor*, the luminance is dependent of the view direction.

Materials

Metal vs Nonmetal

- a *metal object* is a shiny object with its own specular color, and almost no diffuse light. The shininess varies among metals.
- a *nonmetal shiny object* has always a white specular color, and some of the diffuse component visible.

Materials

Opaque vs Transparent

A transparent object allows light to pass through itself while an opaque object blocks it

RGBA Model

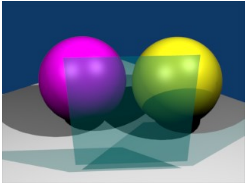
Each color vector has a forth dimension, *alpha*, which specifies the degree of opacity of an object.

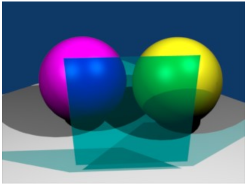
Rendering

Given an ordering of the objects which puts the opaque objects before the transparent objects, the final color of a vertex V is obtained by:

$$\boldsymbol{c}'_V = \alpha_V \boldsymbol{c}_V + (1 - \alpha_V)\boldsymbol{c}_O$$

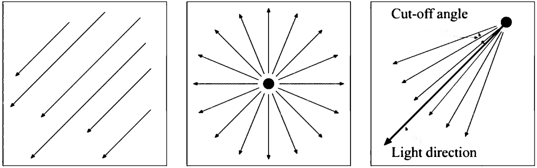
where '$\boldsymbol{c}_O$ is the opaque object before V in the scene.





Outline

Light Sources



Directional Light **Point Light** **Spot Light**

Definition

A light source is defined by:

- $\boldsymbol{L}$: a 3D unit vector called the *light direction*
- i_L: a scalar called the *light intensity*. It simulates the luminance.

By convention the light direction is pointing from the surface vertex toward the source of light.

Light Sources

Directional Lights

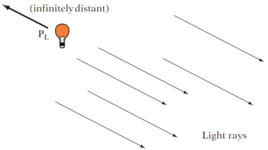
A *directional* light source, also called *infinite* light source, is one that radiates light in a single direction from infinitely far away. It is defined by a *point at infinity* $\boldsymbol{p}_L$ which simulates the origin.

- Light direction:

$$\boldsymbol{L} = \frac{\boldsymbol{p}_L - 0}{||\boldsymbol{p}_L - 0||}$$

- Light intensity:

$$i_L = 1$$



Light Sources

Point Light

A *point* light source, also called *local* light source, is one that radiates equally in every direction from a single point in space.
It is defined by its location point $\boldsymbol{p}_L$.

- Light direction: given a vertex point $\boldsymbol{p}_V$ on the surface,

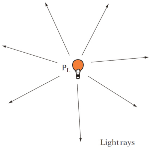
$$\boldsymbol{L} = \frac{\boldsymbol{p}_L - \boldsymbol{p}_V}{\|\boldsymbol{p}_L - \boldsymbol{p}_V\|}$$

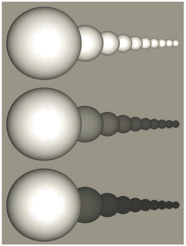
- Light intensity: inverse-square law attenuation

$$i_L = \frac{1}{k_c + k_l\, dist + k_q\, dist^2} \text{ where}$$

$$dist = \|\boldsymbol{p}_L - \boldsymbol{p}_V\|$$

The distance attenuation constants k_c, k_l, and k_q determine the shape of the attenuation curve





Constant, linear, and quadratic attenuation

Light Sources

Spotlight

A *spotlight* source is similar to a point light source but has a cone of radiation. It is defined by its location point $\boldsymbol{p}_L$, an axis $\boldsymbol{d}$, an half angle θ, and attenuation exponent s.

- Light direction: given a vertex point $\boldsymbol{p}_V$ on the surface,

$$\boldsymbol{L} = \frac{\boldsymbol{p}_L - \boldsymbol{p}_V}{\|\boldsymbol{p}_L - \boldsymbol{p}_V\|}$$

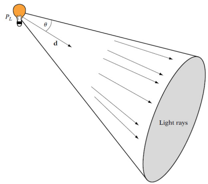
- Light intensity: inverse-square law attenuation

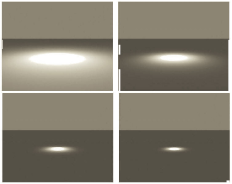
$$i_L = \frac{spot}{k_c + k_l\, dist + k_q\, dist^2} \quad \text{where}$$

$$dist = \|\boldsymbol{p}_L - \boldsymbol{p}_V\|$$

$$spot = \begin{cases} (-\boldsymbol{L}\cdot\boldsymbol{d})^s & \text{if } (-\boldsymbol{L}\cdot\boldsymbol{d}) \geq \cos\theta \\ 0 & \text{otherwise} \end{cases}$$

Illuminance reaches its maximum when $\boldsymbol{p}_L - \boldsymbol{p}_V$ and $\boldsymbol{d}$ are collinear, and falls off proportionally to the cosine of the angle between these vectors. The rate of decreasing is exponential in s.

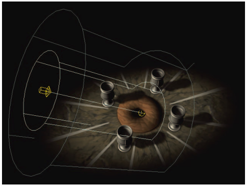




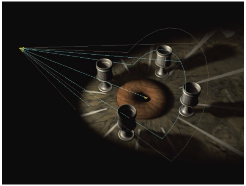
Attenuation for $s = 2, 10, 50, 100$

Light Sources

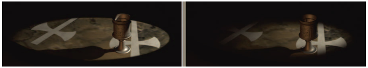
Point light



Direct light: spotlight with a radius instead of an angle

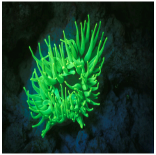


Spotlight



Different spotlights on textured surface

Categories of Light



Emissive

Emissive light is the light produced by the material itself. A typical approximation in realtime systems is to ignore the fact that this emissive light can illuminate other objects. The emissive color of a material is denoted $\boldsymbol{m}_e$.

Categories of Light

Ambient

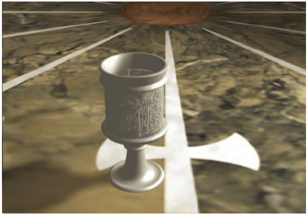
Ambient light captures all indirect lights in the scene. It is specified by:

- i_L: the light source intensity
- $\boldsymbol{l}_A$: the light's ambient color
- $\boldsymbol{m}_A$: the surface ambient color

The overall ambient term for a given vertex is:

$$\boldsymbol{c}_A = i_L \boldsymbol{l}_A \boldsymbol{m}_A$$

Spotlight + Black Ambient



Spotlight + Gray Ambient

Categories of Light

Diffuse

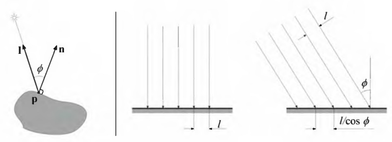
Diffuse lighting treats the surface as a pure matte object, which have the property that their luminance is independent of view direction. It is specified by:

- $\boldsymbol{L}$: the light source direction
- i_L: the light source intensity
- $\boldsymbol{l}_D$: the light's diffuse color
- $\boldsymbol{n}$: the surface normal
- $\boldsymbol{m}_D$: the surface diffuse color

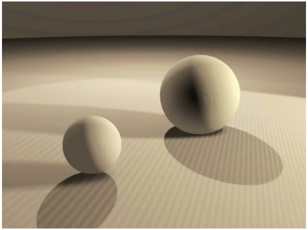
The overall diffuse term for a given vertex is given by the Lambert's law:

$$\boldsymbol{c}_D = i_L \max(0, \boldsymbol{L} \cdot \boldsymbol{n}) \boldsymbol{l}_D \boldsymbol{m}_D$$

The alpha component of the diffuse material color define the alpha value of the vertex.



Effect of $\boldsymbol{L} \cdot \boldsymbol{n}$



Diffuse reflector

Categories of Light

Specular

Specular lighting treats the surface as a pure shiny object, which reflects the light from a given direction $\boldsymbol{L}$ out along a single direction $\boldsymbol{r}$. It is specified by:

- $\boldsymbol{v}$: the viewer's direction
- $\boldsymbol{L}$: the light source direction
- i_L: the light source intensity
- $\boldsymbol{l}_S$: the light's specular color
- $\boldsymbol{n}$: the surface normal
- $\boldsymbol{m}_S$: the surface specular color
- m_{shine}: the shininess factor

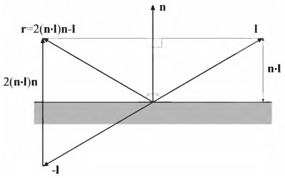
The reflection vector is given by:

$$\boldsymbol{r} = 2(\boldsymbol{L} \cdot \boldsymbol{n})(\boldsymbol{n} - \boldsymbol{L})$$

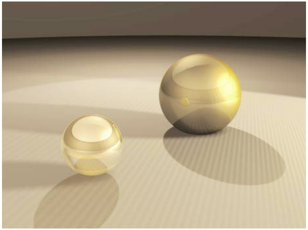
The specular term for a given vertex is given by:

$$\boldsymbol{c}_S = \begin{cases} i_L \boldsymbol{l}_S \boldsymbol{m}_S \max\left(0, (\boldsymbol{r} \cdot \boldsymbol{v})^{m_{\text{shine}}}\right) & \text{if } \boldsymbol{L} \cdot \boldsymbol{n} > 0 \\ \boldsymbol{0} & \text{otherwise} \end{cases}$$

The alpha component of the specular material color is ignored.



Reflection Vector



Specular reflector

Computer Graphics

Visual Perception: Lighting

$$
\begin{aligned}
\boldsymbol{c}_V &= \text{Emissive} + \text{SceneAmbient} + \sum_{\boldsymbol{L}}^{lights} (\text{ambient} + \text{diffuse} + \text{specular}) \\
&= \boldsymbol{m}_e + \boldsymbol{m}_a \boldsymbol{s}_a + \sum_{\boldsymbol{L}}^{lights} (\boldsymbol{c}_A + \boldsymbol{c}_D + \boldsymbol{c}_S)
\end{aligned}
$$