

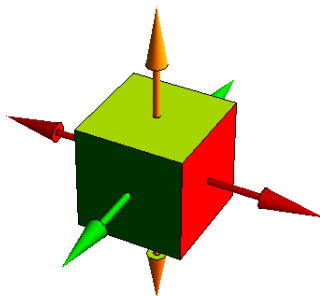
Lecture 24: Divergence theorem

There are three integral theorems in three dimensions. We have seen already the fundamental theorem of line integrals and Stokes theorem. Here is the divergence theorem, which completes the list of integral theorems in three dimensions:

Divergence Theorem. Let E be a solid with boundary surface S oriented so that the normal vector points outside. Let $\vec{F}$ be a vector field. Then

$$\iiint_E \operatorname{div}(\vec{F}) \, dV = \iint_S \vec{F} \cdot d\vec{S}.$$

To prove this, one can look at a small box $[x, x+dx] \times [y, y+dy] \times [z, z+dz]$. The flux of $\vec{F} = \langle P, Q, R \rangle$ through the faces perpendicular to the x -axis is $[\vec{F}(x+dx, y, z) \cdot \langle 1, 0, 0 \rangle + \vec{F}(x, y, z) \cdot \langle -1, 0, 0 \rangle] dydz = P(x+dx, y, z) - P(x, y, z) = P_x dx dy dz$. Similarly, the flux through the y -boundaries is $P_y dy dx dz$ and the flux through the two z -boundaries is $P_z dz dx dy$. The total flux through the faces of the cube is $(P_x + P_y + P_z) dx dy dz = \operatorname{div}(\vec{F}) dx dy dz$. A general solid can be approximated as a union of small cubes. The sum of the fluxes through all the cubes consists now of the flux through all faces without neighboring faces. and fluxes through adjacent sides cancel. The sum of all the fluxes of the cubes is the flux through the boundary of the union. The sum of all the $\operatorname{div}(\vec{F}) dx dy dz$ is a Riemann sum approximation for the integral $\iiint_G \operatorname{div}(\vec{F}) dx dy dz$. In the limit, where dx, dy, dz goes to zero, we obtain the divergence theorem.



The theorem explains what divergence means. If we average the divergence over a small cube is equal the flux of the field through the boundary of the cube. If this is positive, then more field exists the cube than entering the cube. There is field "generated" inside. The divergence measures the expansion of the field.

1 Let $\vec{F}(x, y, z) = \langle x, y, z \rangle$ and let S be sphere. The divergence of $\vec{F}$ is the constant function $\operatorname{div}(\vec{F}) = 3$ and $\iiint_G \operatorname{div}(\vec{F}) \, dV = 3 \cdot 4\pi/3 = 4\pi$. The flux through the boundary is $\iint_S \vec{r} \cdot \vec{r}_u \times \vec{r}_v \, dudv = \iint_S |\vec{r}(u, v)|^2 \sin(v) \, dudv = \int_0^\pi \int_0^{2\pi} \sin(v) \, dudv = 4\pi$ also. We see that the divergence theorem allows us to compute the area of the sphere from the volume of the enclosed ball or compute the volume from the surface area.

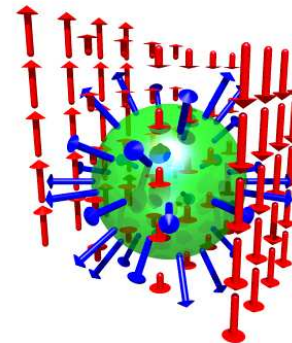
2 What is the flux of the vector field $\vec{F}(x, y, z) = \langle 2x, 3z^2 + y, \sin(x) \rangle$ through the solid $G = [0, 3] \times [0, 3] \times [0, 3] \setminus ([0, 3] \times [1, 2] \times [1, 2] \cup [1, 2] \times [0, 3] \times [1, 2] \cup [0, 3] \times [0, 3] \times [1, 2])$ which is a cube where three perpendicular cubic holes have been removed? **Solution:** Use the divergence theorem: $\operatorname{div}(\vec{F}) = 2$ and so $\iiint_G \operatorname{div}(\vec{F}) \, dV = 2 \iiint_G dV = 2\operatorname{Vol}(G) = 2(27 - 7) = 40$. Note that the flux integral here would be over a complicated surface over dozens of rectangular planar regions.

3 Find the flux of $\operatorname{curl}(\vec{F})$ through a torus if $\vec{F} = \langle yz^2, z + \sin(x) + y, \cos(x) \rangle$ and the torus has the parametrization

$$\vec{r}(\theta, \phi) = \langle (2 + \cos(\phi)) \cos(\theta), (2 + \cos(\phi)) \sin(\theta), \sin(\phi) \rangle.$$

Solution: The answer is 0 because the divergence of $\operatorname{curl}(\vec{F})$ is zero. By the divergence theorem, the flux is zero.

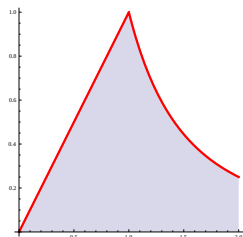
4 Similarly as Green's theorem allowed to calculate the area of a region by passing along the boundary, the volume of a region can be computed as a flux integral: Take for example the vector field $\vec{F}(x, y, z) = \langle x, 0, 0 \rangle$ which has divergence 1. The flux of this vector field through the boundary of a solid region is equal to the volume of the solid: $\iint_{\partial G} \langle x, 0, 0 \rangle \cdot d\vec{S} = \operatorname{Vol}(G)$.



5 How heavy are we, at distance r from the center of the earth?

Solution: The law of gravity can be formulated as $\operatorname{div}(\vec{F}) = 4\pi\rho$, where ρ is the mass density. We assume that the earth is a ball of radius R . By rotational symmetry, the

gravitational force is normal to the surface: $\vec{F}(\vec{x}) = \vec{F}(r)\vec{x}/||\vec{x}||$. The flux of $\vec{F}$ through a ball of radius r is $\int_{S_r} \vec{F}(x) \cdot d\vec{S} = 4\pi r^2 \vec{F}(r)$. By the **divergence theorem**, this is $4\pi M_r = 4\pi \int \int_{B_r} \rho(x) dV$, where M_r is the mass of the material inside S_r . We have $(4\pi)^2 \rho r^3/3 = 4\pi r^2 \vec{F}(r)$ for $r < R$ and $(4\pi)^2 \rho R^3/3 = 4\pi r^2 \vec{F}(r)$ for $r \geq R$. Inside the earth, the gravitational force $\vec{F}(r) = 4\pi \rho r/3$. Outside the earth, it satisfies $\vec{F}(r) = M/r^2$ with $M = 4\pi R^3 \rho/3$.



We are now at the end of the course. Lets have an overview over the integral theorems and give an other typical example in each case.

The fundamental theorem for line integrals, Green's theorem, Stokes theorem and divergence theorem are all incarnation of **one single theorem** $\int_A dF = \int_{\delta A} F$, where dF is a **exterior derivative** of F and where δA is the **boundary** of A . They all generalize the fundamental theorem of calculus.

Fundamental theorem of line integrals: If C is a curve with boundary $\{A, B\}$ and f is a function, then

$$\int_C \nabla f \cdot d\vec{r} = f(B) - f(A)$$

Remarks.

- 1) For closed curves, the line integral $\int_C \nabla f \cdot d\vec{r}$ is zero.
- 2) Gradient fields are **path independent**: if $\vec{F} = \nabla f$, then the line integral between two points P and Q does not depend on the path connecting the two points.
- 3) The theorem holds in any dimension. In one dimension, it reduces to the **fundamental theorem of calculus** $\int_a^b f'(x) dx = f(b) - f(a)$
- 4) The theorem justifies the name **conservative** for gradient vector fields.
- 5) The term "potential" was coined by George Green who lived from 1783-1841.

Example. Let $f(x, y, z) = x^2 + y^4 + z$. Find the line integral of the vector field $\vec{F}(x, y, z) = \nabla f(x, y, z)$ along the path $\vec{r}(t) = \langle \cos(5t), \sin(2t), t^2 \rangle$ from $t = 0$ to $t = 2\pi$.

Solution. $\vec{r}(0) = \langle 1, 0, 0 \rangle$ and $\vec{r}(2\pi) = \langle 1, 0, 4\pi^2 \rangle$ and $f(\vec{r}(0)) = 1$ and $f(\vec{r}(2\pi)) = 1 + 4\pi^2$. The fundamental theorem of line integral gives $\int_C \nabla f \cdot d\vec{r} = f(\vec{r}(2\pi)) - f(\vec{r}(0)) = 4\pi^2$.

Green's theorem. If R is a region with boundary C and $\vec{F}$ is a vector field, then

$$\int \int_R \text{curl}(\vec{F}) \, dx dy = \int_C \vec{F} \cdot d\vec{r}.$$

Remarks.

- 1) Greens theorem allows to switch from double integrals to one dimensional integrals.
- 2) The curve is oriented in such a way that the region is to the left.
- 3) The boundary of the curve can consist of piecewise smooth pieces.
- 4) If $C : t \mapsto \vec{r}(t) = \langle x(t), y(t) \rangle$, the line integral is $\int_a^b \langle P(x(t), y(t)), Q(x(t), y(t)) \rangle \cdot \langle x'(t), y'(t) \rangle dt$.
- 5) Green's theorem was found by George Green (1793-1841) in 1827 and by Mikhail Ostrogradski (1801-1862).
- 6) If $\text{curl}(\vec{F}) = 0$ in a simply connected region, then the line integral along a closed curve is zero. If two curves connect two points then the line integral along those curves agrees.
- 7) Taking $\vec{F}(x, y) = \langle -y, 0 \rangle$ or $\vec{F}(x, y) = \langle 0, x \rangle$ gives **area formulas**.

Example. Find the line integral of the vector field $\vec{F}(x, y) = \langle x^4 + \sin(x) + y, x + y^3 \rangle$ along the path $\vec{r}(t) = \langle \cos(t), 5 \sin(t) + \log(1 + \sin(t)) \rangle$, where t runs from $t = 0$ to $t = \pi$.

Solution. $\text{curl}(\vec{F}) = 0$ implies that the line integral depends only on the end points $(0, 1)$, $(0, -1)$ of the path. Take the simpler path $\vec{r}(t) = \langle -t, 0 \rangle$, $-1 \leq t \leq 1$, which has velocity $\vec{r}'(t) = \langle -1, 0 \rangle$. The line integral is $\int_{-1}^1 \langle t^4 - \sin(t), -t \rangle \cdot \langle -1, 0 \rangle dt = -t^5/5|_{-1}^1 = -2/5$.

Remark We could also find a potential $f(x, y) = x^5/5 - \cos(x) + xy + y^5/4$. It has the property that $\text{grad}(f) = F$. Again, we get $f(0, -1) - f(0, 1) = -1/5 - 1/5 = -2/5$.

Stokes theorem. If S is a surface with boundary C and $\vec{F}$ is a vector field, then

$$\int \int_S \text{curl}(\vec{F}) \cdot d\vec{S} = \int_C \vec{F} \cdot d\vec{r}.$$

Remarks.

- 1) Stokes theorem allows to derive Greens theorem: if $\vec{F}$ is z -independent and the surface S is contained in the xy -plane, one obtains the result of Green.
- 2) The orientation of C is such that if you walk along C and have your head in the direction of the normal vector $\vec{r}_u \times \vec{r}_v$, then the surface is to your left.
- 3) Stokes theorem was found by André Ampère (1775-1836) in 1825 and rediscovered by George Stokes (1819-1903).
- 4) The flux of the curl of a vector field does not depend on the surface S , only on the boundary of S .
- 5) The flux of the curl through a closed surface like the sphere is zero: the boundary of such a surface is empty.

Example. Compute the line integral of $\vec{F}(x, y, z) = \langle x^3 + xy, y, z \rangle$ along the polygonal path C connecting the points $(0, 0, 0)$, $(2, 0, 0)$, $(2, 1, 0)$, $(0, 1, 0)$.

Solution. The path C bounds a surface $S : \vec{r}(u, v) = \langle u, v, 0 \rangle$ parameterized by $R = [0, 2] \times [0, 1]$. By Stokes theorem, the line integral is equal to the flux of $\text{curl}(\vec{F})(x, y, z) = \langle 0, 0, -x \rangle$ through S . The normal vector of S is $\vec{r}_u \times \vec{r}_v = \langle 1, 0, 0 \rangle \times \langle 0, 1, 0 \rangle = \langle 0, 0, 1 \rangle$ so that $\int \int_S \text{curl}(\vec{F}) \cdot d\vec{S} = \int_0^2 \int_0^1 \langle 0, 0, -u \rangle \cdot \langle 0, 0, 1 \rangle \, du dv = \int_0^2 \int_0^1 -u \, du dv = -2$.

Divergence theorem: If S is the boundary of a region E in space and $\vec{F}$ is a vector field, then

$$\iiint_B \operatorname{div}(\vec{F}) \, dV = \iint_S \vec{F} \cdot d\vec{S}.$$

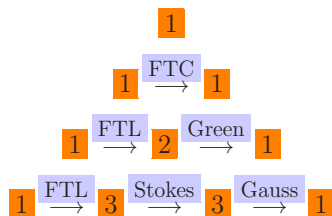
Remarks.

- 1) The divergence theorem is also called **Gauss theorem**.
- 2) It can be helpful to determine the flux of vector fields through surfaces.
- 3) It was discovered in 1764 by Joseph Louis Lagrange (1736-1813), later it was rediscovered by Carl Friedrich Gauss (1777-1855) and by George Green.
- 4) For divergence free vector fields $\vec{F}$, the flux through a closed surface is zero. Such fields $\vec{F}$ are also called **incompressible** or **source free**.

Example. Compute the flux of the vector field $\vec{F}(x, y, z) = \langle -x, y, z^2 \rangle$ through the boundary S of the rectangular box $[0, 3] \times [-1, 2] \times [1, 2]$.

Solution. By Gauss theorem, the flux is equal to the triple integral of $\operatorname{div}(F) = 2z$ over the box: $\int_0^3 \int_{-1}^2 \int_1^2 2z \, dx dy dz = (3-0)(2-(-1))(4-1) = 27$.

How do these theorems fit together? In n -dimensions, there are n theorems. We have here seen the situation in dimension $n=2$ and $n=3$, but one could continue. The fundamental theorem of line integrals generalizes directly to higher dimensions. Also the divergence theorem generalizes directly since an n -dimensional integral in n dimensions. The generalization of curl and flux is more subtle, since in 4 dimensions already, the curl of a vector field is a 6 dimensional object. It is a $n(n-1)/2$ dimensional object in general.



In one dimensions, there is one derivative $f(x) \rightarrow f'(x)$ from scalar to scalar functions. It corresponds to the entry 1 – 1 in the Pascal triangle. The next entry 1 – 2 – 1 corresponds to differentiation in two dimensions, where we have the gradient $f \rightarrow \nabla f$ mapping a scalar function to a vector field with 2 components as well as the curl, $F \rightarrow \operatorname{curl}(F)$ which corresponds to the transition 2 – 1. The situation in three dimensions is captured by the entry 1 – 3 – 3 – 1 in the Pascal triangle. The first derivative 1 – 3 is the gradient. The second derivative 3 – 3 is the curl and the third derivative 3 – 1 is the divergence. In $n = 4$ dimensions, we would have to look at 1 – 4 – 6 – 4 – 1. The first derivative 1 – 4 is still the gradient. Then we have a first curl, which maps a vector field with 4 components into an object with 6 components. Then there is a second curl, which maps an object with 6 components back to a vector field, we would have to look at 1 – 4 – 6 – 4 – 1. When setting up calculus in dimension n , one talks about **differential forms** instead of scalar fields or vector fields. Functions are 0 forms or n -forms. Vector fields can be described by 1 or $n-1$ forms. The general formalism defines a derivative d called **exterior derivative** on differential forms as well as integration of such k forms on k dimensional objects. There is a **boundary operation** δ which maps a k -dimensional object into a $k-1$ dimensional object. This boundary operation is dual to differentiation. They both satisfy the same relation $dd(F) = 0$ and $\delta\delta G = 0$. Differentiation and integration are linked by the general Stokes theorem:

$$\int_{\delta G} F = \int_G dF$$

which becomes a single theorem called **fundamental theorem of multivariable calculus**. The theorem becomes much simpler in quantum calculus, where geometric objects and differential forms are on the same footing. It turns out that the theorem becomes then

$$\langle \delta G, F \rangle = \langle G, dF \rangle$$

which you might see in linear algebra in the form $\langle A^T v, w \rangle = \langle v, Aw \rangle$, where A is a matrix and $\langle v, w \rangle$ is the dot product. If we deal with "smooth" functions and fields that we have to pay a prize and consider in turn "singular" objects like points or curves and surfaces. These are idealized objects which have zero diameter, radius or thickness. Nature likes simplicity and elegance¹: and has chosen quantum mathematics to be more fundamental but it manifests only in the very small. While it is well understood mathematically, it will take a while until this formalism will enter calculus courses.

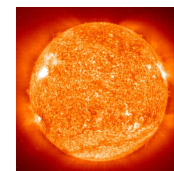
Homework

- 1 Compute using the divergence theorem the flux of the vector field $\vec{F}(x, y, z) = \langle 3y, xy, 2yz \rangle$ through the unit cube $[0, 1] \times [0, 1] \times [0, 1]$.
- 2 Find the flux of the vector field $\vec{F}(x, y, z) = \langle xy, yz, zx \rangle$ through the solid cylinder $x^2 + y^2 \leq 1$, $0 \leq z \leq 1$.
- 3 Use the divergence theorem to calculate the flux of $\vec{F}(x, y, z) = \langle x^3, y^3, z^3 \rangle$ through the sphere $S : x^2 + y^2 + z^2 = 1$ where the sphere is oriented so that the normal vector points outwards.

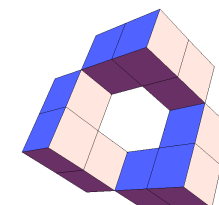
Assume the vector field

$$\vec{F}(x, y, z) = \langle 5x^3 + 12xy^2, y^3 + e^y \sin(z), 5z^3 + e^y \cos(z) \rangle$$

- 4 is the magnetic field of the **sun** whose surface is a sphere of radius 3 oriented with the outward orientation. Compute the magnetic flux $\iint_S \vec{F} \cdot d\vec{S}$.



- 5 Find $\int_S \vec{F} \cdot d\vec{S}$, where $\vec{F}(x, y, z) = \langle x, y, z \rangle$ and S is the boundary of the solid built with 9 unit cubes shown in the picture.



¹Leibniz: 1646-1716