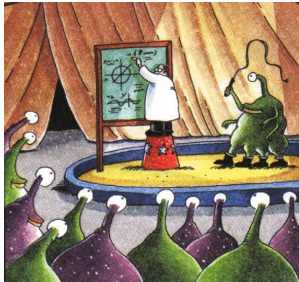# Week 08, Lecture 1 (REVISED)
Techniques of Integration

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Assignments, etc

► **Problem Set 6** is open, and will be covered in tutorials this well. Deadline is 5pm next Monday (10 November).

► **Problem Set 7** opens alter this week.

► The finally weekly assignment, will open next week.

► Reminder: The second **class test** takes place November 18.

This morning, I think we will think about…

See also Section **5.5** (Substitution) of **Calculus** by Strang & Herman:
math.libretexts.org/Bookshelves/Calculus/Calculus_(OpenStax) Maybe also
Section **7.1** (Integration by Parts).

Substitution

Suppose we want to evaluate an integral of the form

$$\int e^{x^3 + x^2}(3x^2 + 2x)\, \mathrm{d}x.$$

At first, this looks tricky: there is nothing like this in our table of integrals.

However, there is something a little unusual about it: it features both the function $x^3 + x^2$, and its derivative $3x^2 + 2x$.

It turns out that such problems are quite common (at least in textbooks and on exams!). Moreover, there is a handy technique called **substitution** for evaluating them. In this case:

Substitution

Method of substitution

When integrating an *integrand* of the form $\int f\big(g(x)\big)g'(x)dx$, set $u = g(x)$, and then use that

$$\int f\big(g(x)\big)\, g'(x)\, \mathrm{d}x = \int f(u)\, \mathrm{d}u\,.$$

Equivalently: $\int f(u)\, \dfrac{du}{\mathrm{d}x}\mathrm{d}x = \int f(u)\, \mathrm{d}u$. (For a proof of why this works, see Section 5.5 of the textbook).

After this substitution, our task is reduced to evaluating $\int f(u)\, \mathrm{d}u$ which, we hope, is easier.

Substitution

Example

Evaluate the integral $\int 3x^2 \sin(x^3)\,dx$.

Notice that $3x^2$ is the derivative of x^3.

Let's try integration by substition with $u = x^3$.

If $u = x^3$, then $\frac{du}{dx} = 3x^2$, so

$$du = \frac{du}{dx}\,dx = 3x^2\,dx\,.$$

Thus,

$$\int \sin(x^3)3x^2\,dx = \int \sin(u)\,du$$
$$= -\cos(u) + C$$
$$= -\cos(x^3) + C\,.$$

Substitution

Example

Evaluate $\int 2x\sqrt{1+x^2}\,dx$.

Notice that $2x$ is the derivative of $1 + x^2$.
Let's try integration by substition with $u = 1 + x^2$:

Substitution

Example

Evaluate $\int \cos(4x - 7)\, dx$.

Idea: think of this as $\dfrac{1}{4} \int \cos(4x - 7) 4\, dx$.

Substitution

Example

Show that $\displaystyle\int \sin^3(x)\,\cos(x)\,\mathrm{d}x = \frac{1}{4}\sin^4(x) + C$.

Substitution can be used with **definite integrals**. However, this may requires a change to the limits of integration.

Substitution with Definite Integrals

Let $u = g(x)$, with g' continuous on $[a, b]$, and f continuous over the range of $u = g(x)$. Then,

$$\int_{x=a}^{x=b} f\big(g(x)\big)g'(x)dx = \int_{u=g(a)}^{u=g(b)} f(u)\, du.$$

This allows us to apply the FTC2, without having to invert the substitution.

Example

Evaluate $I = \displaystyle\int_0^1 x^2(1 + 2x^3)^2 dx$

Example

Evaluate $I = \displaystyle\int_{-1}^{0} x e^{x^2}\, dx$

Rational functions

> **Recall: Rational Functions**
>
> A *rational function* is a function of the form $f(x) = \frac{p(x)}{q(x)}$, where $p(x)$ and $q(x)$ are polynomials.

Before trying to find an antiderivative of a rational function $f(x) = \dfrac{p(x)}{q(x)}$:

Step 1: If $\deg(p(x)) \geqslant \deg(q(x))$, divide $p(x)$ by $q(x)$.

Step 2: Check if integration by substitution might work.

Step 3: Factorise the denominator as far as possible.

Step 4: Write the rational function as sum of **partial fractions** to simplify.

Example

Evaluate the integral
$$\int \frac{x}{x^2 + 1} \, dx \, .$$

In this can we can use substitution.

Example

Evaluate the integral

$$\int \frac{3x + 4}{x^2 + 7x + 12}\, dx\, .$$

In this case, we must factorise the denominator, and express the integrand as **partial fractions**. Factorise:
$x^2 + 7x + 12 = (x + 4)(x + 3)$.
Express as Partial Fractions:

$$\frac{3x + 4}{x^2 + 7x + 12} = \frac{A}{x + 4} + \frac{B}{x + 3}$$

With a little work, we can find that $A = 8$ and $B = -5$. Therefore,

$$\frac{3x + 4}{x^2 + 7x + 12} = \frac{8}{x + 4} - \frac{5}{x + 3}\, .$$

We can now express the integral as

$$\int \frac{3x+4}{x^2+7x+12}\, dx = \int \left(\frac{8}{x+4} - \frac{5}{x+3} \right) dx$$

$$= \underbrace{\int \frac{8}{x+4}\, dx}_{\mathrm{I}_1} - \underbrace{\int \frac{5}{x+3}\, dx}_{\mathrm{I}_2}\,.$$

First, we evaluate I_1.

$$\mathrm{I}_1 = \int \frac{8}{x+4}\, dx = 8 \int \frac{1}{x+4}\, dx\,.$$

If we let $u = x+4$, then $du = dx$ and, hence,

$$\mathrm{I}_1 = 8 \int \frac{1}{x+4}\, dx = 8 \int \frac{1}{u}\, du = 8 \ln|u| + C_1 = 8 \ln|x+4| + C_1\,.$$

Similarly, we find that: $\mathrm{I}_2 = \int \frac{5}{x+3}\, dx = 5 \ln|x+3| + C_2.$

To conclude:

$$\int \frac{3x+4}{x^2+7x+12}\, dx = \int \left(\frac{8}{x+4} - \frac{5}{x+3} \right) dx$$

$$= \int \frac{8}{x+4}\, dx - \int \frac{5}{x+3}\, dx$$

$$= I_1 - I_2$$

$$= (8 \ln|x+4| + C_1) - (5 \ln|x+3| + C_2)$$

$$= 8 \ln|x+4| - 5 \ln|x+3| + C.$$

We use **substitution** when integrating the product of two functions, $f(x)g'(x)$, where $f(x) = f\big(g(x)\big)$, which is a very specialised situation.

Integration by parts is also applied when we are integrating the **product** of a function and a derivative $f(x) = u(x)v'(x)$, but with no other constraint.

Integration by Parts (IBP) is, by some distance, the most important technique for integration, in both theory and practice.

Integration by Parts

If u and v are differentiable functions in the variable x, then

$$\int u(x)\,dv = u(x)v(x) - \int v(x)\,du\,.$$

It can also be written as $\quad \displaystyle\int uv'\,dx = uv - \int vu'\,dx\,.$

The link between the two formulations is given by

$$dv = v'\,dx \quad \text{and} \quad du = u'\,dx\,.$$

The Product Rule for differentiation is

$$\frac{d}{dx}(uv) = \frac{du}{dx}v + u\frac{dv}{dx}.$$

We can use this rule to develop another integration technique after a little rearrangement. From the above we have

$$u\frac{dv}{dx} = \frac{d}{dx}(uv) - \frac{du}{dx}v$$

and integrating both sides gives

$$\int u\frac{dv}{dx}dx = uv - \int v\frac{du}{dx}dx.$$

Example

Evaluate $I = \int x\cos(x)\,dx$

We'll take $u = x$ and $dv = \cos(x)dx$.

One of the challenges of Integration by Parts is knowing how to choose *u* and *dv*. When integrating $\boxed{\int x\cos(x)\,dx}$ we choose $u = x$, because its derivative, $u' = 1$ is simpler.

Suppose we had made the bad choice of

$$u(x) = \cos(x), \qquad\qquad dv = x\,dx,$$

then we'd get:

More generally, given choices for u and dv, we proceed as follows:

1. Some functions are easy to differentiate (and maybe not so easy to integrate), and so make a good choice for u. Important examples include **logarithms** and **inverse trigonometric** functions.

2. Some functions (such as polynomials) have simple(r) derivatives, so are also a good choice for u.

3. Trigonometric and exponential functions don't simplify if differentiated, but can be integrated. So they can be a good choice for dv.

Example (of choosing *u*

Evaluate $I = \int \dfrac{\ln(x)}{x^2}\, dx$.

Example

Evaluate $I = \int \ln(x)\, dx$.

Since $\int \ln(x)\, dx$ can be written as $\int \left(\ln(x)\right)(1)\, dx$, we use integration by parts, with $u = \ln(x)$ and $dv = dx$.

Sometimes, we have to apply Integration by Parts more than once.

Example

Evaluate $I = \int x^2 e^x \, dx$.

It is good to check any new rule/method for a simple example we already know the answer to. Now that we know about repeated application, we can do that:

Example

We know that $\mathrm{I} = \int x^2 dx = (1/3)x^3$. We can also use IbP.

Take $u(x) = x$ and $dv = xdx$:

Exercises

Exer 8.1.1

Evaluate the follow integrals

1. $\int \sin(\ln x) \dfrac{1}{x}\, \mathrm{d}x$.

2. $\int x^2(x^3+5)^9\, \mathrm{d}x$

3. $\int \dfrac{\sin(x)}{\cos^3(x)}\, dx$

Exer 8.1.2

Evaluate $\displaystyle\int_0^1 x^2(x^3+5)^9\, \mathrm{d}x$

Exercises

Exer 8.1.3

Evaluate the follow integrals

1. $\int xe^{2x}\,dx$.

2. $\int x^2\cos(x)\,dx$.

Exer 8.1.4

Evaluate $\int_1^e \ln(x^2)\,dx$.