

The integrals in Gradshteyn and Ryzhik. Part 8: Combinations of powers, exponentials and logarithms.

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ABSTRACT. We describe some examples of integrals from the table of Gradshteyn and Ryzhik where the integrand is a combination of powers, exponentials and logarithms. The expressions for some of these integrals involve the Stirling numbers of the first kind.

1. Introduction

The uninitiated reader of the table of integrals by I. S. Gradshteyn and I. M. Ryzhik [4] will surely be puzzled by choice of integrands. In this note we provide an elementary proof of the evaluation **4.353.3**

$$(1.1) \quad \int_0^1 (ax + n + 1)x^n e^{ax} \ln x \, dx = e^a \sum_{k=0}^n (-1)^{k-1} \frac{n!}{(n-k)!a^{k+1}} + (-1)^n \frac{n!}{a^{n+1}}.$$

We also consider the integrals

$$(1.2) \quad q_n := \int_0^1 x^n e^{-x} \ln x \, dx$$

and the companion family

$$(1.3) \quad p_n := \int_0^1 x^n e^{-x} \, dx.$$

The integral q_n corresponds to the case $a = -1$ in (1.1). Section 3 provides closed-form expressions for p_n and q_n . Section 4 considers the generalization

$$(1.4) \quad P_n(a) = \int_0^1 x^n e^{-ax} \, dx \text{ and } Q_n(a) = \int_0^1 x^n e^{-ax} \ln x \, dx.$$

2000 *Mathematics Subject Classification*. Primary 33.

Key words and phrases. Powers and exp-log.

The authors wish to the partial support of NSF-CCLI 0633223.

The main result of this section is the closed-form expressions

$$(1.5) \quad P_n(a) := \int_0^1 x^n e^{-ax} dx = \frac{n!}{a^{n+1}} \left(1 - e^{-a} \sum_{k=0}^n \frac{a^k}{k!} \right),$$

and

$$Q_n(a) := \int_0^1 x^n e^{-ax} \ln x dx = \frac{n!}{a^{n+1}} \left[\sum_{k=1}^n \frac{1}{k} \left(1 - e^{-a} \sum_{j=0}^{k-1} \frac{a^j}{j!} \right) + aQ_0(a) \right],$$

where

$$(1.6) \quad Q_0(a) = \int_0^1 e^{-ax} \ln x dx = -\frac{1}{a} (\gamma + \ln a + \Gamma(0, a)),$$

and $\Gamma(0, a)$ is the incomplete gamma function defined by

$$(1.7) \quad \Gamma(a, x) := \int_x^\infty t^{a-1} e^{-t} dt.$$

2. The evaluation of 4.353.3

The identity

$$(2.1) \quad \frac{d}{dx} (x^{n+1} e^{ax}) = (ax + n + 1)x^n e^{ax}$$

and integration by parts yield

$$(2.2) \quad \int_0^1 (ax + n + 1)x^n e^{ax} \ln x dx = - \int_0^1 x^n e^{ax} dx.$$

This last integral appears as **3.351.1** in [4]. We have obtained a closed-form expression for it in [2]. A new proof is presented in Section 4.

A closed form expression for the right hand side of (2.2) is obtained from

$$(2.3) \quad \int_0^1 x^n e^{ax} dx = \left(\frac{d}{da} \right)^n \frac{e^a - 1}{a}.$$

The symbolic evaluation of (2.3) for small values of $n \in \mathbb{N}$ suggests the existence of a polynomial $P_n(a)$ such that

$$(2.4) \quad \int_0^1 x^n e^{ax} dx = \frac{(-1)^{n+1} n!}{a^{n+1}} + \frac{P_n(a)}{a^{n+1}} e^a.$$

The next lemma confirms the existence of this polynomial.

Lemma 2.1. The function $P_n(a)$ defined by

$$(2.5) \quad P_n(a) = a^{n+1} e^{-a} \left(\left(\frac{d}{da} \right)^n \frac{e^a - 1}{a} - \frac{(-1)^{n+1} n!}{a^{n+1}} \right)$$

is a polynomial of degree n .

PROOF. Let $D = \frac{d}{da}$. Then $D^{n+1} = D(D^n)$ produces the recurrence

$$(2.6) \quad P_{n+1}(a) = aP'_n(a) + (a - n - 1)P_n(a).$$

The initial condition $P_0(a) = 1$ and (2.6) show that P_n is a polynomial of degree n . \square

Theorem 2.2. The polynomial

$$(2.7) \quad Q_n(a) := (-1)^n P_n(-a)$$

has positive integer coefficients, written as

$$(2.8) \quad Q_n(a) = \sum_{k=0}^n b_{n,k} a^k.$$

These coefficients satisfy

$$(2.9) \quad \begin{aligned} b_{n+1,0} &= (n+1)b_{n,0} \\ b_{n+1,k} &= (n+1-k)b_{n,k} + b_{n,k-1}, \quad 1 \leq k \leq n \\ b_{n+1,n+1} &= b_{n,n}. \end{aligned}$$

Moreover, the polynomial $Q_n(a)$ is given by

$$(2.10) \quad Q_n(a) = n! \sum_{k=0}^n \frac{a^k}{k!}$$

PROOF. The recurrence (2.6) yields

$$(2.11) \quad Q_{n+1}(a) = -aQ'_n(a) + (a + n + 1)Q_n(a).$$

The recursion for the coefficients $b_{n,k}$ follows directly from here. Moreover, it is clear that $b_{n,n} = 1$ and $b_{n,0} = n!$. A little experimentation suggests that $b_{n,k} = n!/k!$, and this can be established from (2.9). \square

This proposition amounts to the evaluation of **3.351.1** in [4]:

$$(2.12) \quad \int_0^u x^n e^{ax} dx = \frac{(-1)^{n+1} n!}{a^{n+1}} + \frac{e^{au}}{a^{n+1}} \sum_{k=0}^n \frac{n!}{k!} (-1)^{n-k} u^k a^k.$$

The reader will find a proof of this formula in [2].

3. A new family of integrals

In this section we consider the family of integrals

$$(3.1) \quad q_n := \int_0^1 x^n e^{-x} \ln x dx,$$

and its companion

$$(3.2) \quad p_n := \int_0^1 x^n e^{-x} dx.$$

Lemma 3.1. The integrals p_n, q_n satisfy the recursion

$$(3.3) \quad p_{n+1} = (n+1)p_n - e^{-1}$$

$$(3.4) \quad q_{n+1} = (n+1)q_n + p_n$$

PROOF. Integrate by parts. □

The initial conditions are

$$(3.5) \quad p_0 = 1 - e^{-1} \text{ and } q_0 = \int_0^1 e^{-x} \ln x \, dx = \gamma - \text{Ei}(-1).$$

Here γ is Euler's constant defined by

$$(3.6) \quad \gamma := \lim_{n \rightarrow \infty} \sum_{k=1}^n \frac{1}{k} - \ln n$$

with integral representation

$$(3.7) \quad \gamma = \int_0^{\infty} e^{-x} \ln x \, dx$$

given as **4.331.1**. The reader will find in [3] a proof of this identity. The second term in (3.5) is converted into

$$(3.8) \quad \int_1^{\infty} e^{-x} \ln x \, dx = \int_1^{\infty} \frac{e^{-x}}{x} \, dx$$

and this last form is identified as $\text{Ei}(-1)$, where Ei is the exponential integral defined by

$$(3.9) \quad \text{Ei}(z) = - \int_{-z}^{\infty} \frac{e^{-x}}{x} \, dx.$$

In the current context, the value of $\text{Ei}(-1)$ will be simply one of the terms in the initial condition q_0 .

We determine first an explicit expression for p_n . The recursion (3.3) shows the existence of integers a_n, b_n such that

$$(3.10) \quad p_n = a_n + b_n e^{-1},$$

with $a_0 = 1, b_0 = -1$. From (3.3) we obtain

$$(3.11) \quad a_{n+1} + b_{n+1} e^{-1} = (n+1)a_n + [(n+1)b_n - 1] e^{-1}.$$

The irrationality of e produce the system

$$(3.12) \quad a_{n+1} = (n+1)a_n, \text{ with } a_0 = 1,$$

$$(3.13) \quad b_{n+1} = (n+1)b_n - 1, \text{ with } b_0 = -1.$$

The expression $a_n = n!$ follows directly from (3.12). To solve (3.13), define $B_n := b_n/n!$ and observe that

$$(3.14) \quad B_{n+1} = B_n - \frac{1}{(n+1)!},$$

that telescopes to

$$(3.15) \quad b_n = -n! \sum_{k=0}^n \frac{1}{k!}.$$

We have shown:

Proposition 3.2. The integral p_n in (3.2) is given by

$$(3.16) \quad p_n = \int_0^1 x^n e^{-x} dx = \frac{n!}{e} \left(e - \sum_{k=0}^n \frac{1}{k!} \right).$$

We now determine a similar closed-form for q_n . The recursion (3.4) shows the existence of integers c_n, d_n, f_n such that

$$(3.17) \quad q_n = c_n + d_n e^{-1} + f_n q_0.$$

In order to produce a system similar to (3.12,3.13) we will assume that the constants $1, e^{-1}$ and $q_0 = -(\gamma + \text{Ei}(-1))$ are linearly independent over \mathbb{Q} . Under this assumption (3.4) produces

$$(3.18) \quad c_{n+1} = (n+1)c_n + n!,$$

$$(3.19) \quad d_{n+1} = (n+1)c_n - n! \sum_{k=0}^n \frac{1}{k!},$$

$$(3.20) \quad f_{n+1} = (n+1)f_n,$$

with the initial conditions $c_0 = 0, d_0 = 0$ and $f_0 = 1$.

The expression $f_n = n!$ follows directly from (3.20). To solve (3.18) and (3.19) we employ the following result established in [1].

Lemma 3.3. Let a_n, b_n and r_n be sequences with $a_n, b_n \neq 0$. Assume that z_n satisfies

$$(3.21) \quad a_n z_n = b_n z_{n-1} + r_n, \quad n \geq 1$$

with initial condition z_0 . Then

$$(3.22) \quad z_n = \frac{b_1 b_2 \cdots b_n}{a_1 a_2 \cdots a_n} \left(z_0 + \sum_{k=1}^n \frac{a_1 a_2 \cdots a_{k-1} r_k}{b_1 b_2 \cdots b_k} \right).$$

We conclude that

$$(3.23) \quad c_n = n! \sum_{k=1}^n \frac{1}{k},$$

and

$$(3.24) \quad d_n = -n! \sum_{k=1}^n \frac{1}{k} \sum_{j=0}^{k-1} \frac{1}{j!}.$$

The expression for c_n shows that they coincide with the Stirling numbers of the first kind: $c_n = |s(n+1, 2)|$.

We have established

Proposition 3.4. The integral q_n in (3.1) is given by

$$(3.25) \quad q_n = \int_0^1 x^n e^{-x} \ln x \, dx = n! \left[\frac{1}{e} \sum_{k=1}^n \frac{1}{k} \left(e - \sum_{j=0}^{k-1} \frac{1}{j!} \right) + q_0 \right].$$

EXAMPLE 3.1. The expressions for p_n and q_n provide the evaluation of **4.351.1** in [4]

$$(3.26) \quad \int_0^1 (1-x)e^{-x} \ln x \, dx = \frac{1-e}{e},$$

by identifying the integral as $q_0 - q_1$. The recurrence (3.4) shows that

$$(3.27) \quad q_0 - q_1 = -p_0 = e^{-1} - 1,$$

as claimed.

EXAMPLE 3.2. The evaluation of **4.362.1** in [4]

$$(3.28) \quad \int_0^1 x e^x \ln(1-x) \, dx = \int_0^1 (1-t)e^{1-t} \ln t \, dt$$

is achieved by observing that this integral is $e(q_0 - q_1) = 1 - e$.

4. A parametric family

In this section we consider the evaluation of

$$(4.1) \quad P_n(a) := \int_0^1 x^n e^{-ax} \, dx$$

$$(4.2) \quad Q_n(a) := \int_0^1 x^n e^{-ax} \ln x \, dx.$$

The integrals q_n considered in Section 3 corresponds to the special case: $q_n = Q_n(1)$.

We now establish a recursion for Q_n by differentiating (4.2).

Lemma 4.1. The integral $Q_n(a)$ satisfies the relation

$$(4.3) \quad Q_{n+1}(a) = -\frac{d}{da} Q_n(a).$$

To obtain a closed-form expression for $Q_n(a)$ we need to determine the initial condition

$$(4.4) \quad Q_0(a) = \int_0^1 e^{-ax} \ln x \, dx.$$

This is expressed in terms of the *incomplete gamma function* defined in **8.350.1** by

$$(4.5) \quad \Gamma(a, x) := \int_x^\infty t^{a-1} e^{-t} \, dt.$$

Observe that $\Gamma(a, 0) = \Gamma(a)$, the usual gamma function.

Lemma 4.2. The initial condition $Q_0(a)$ is given by

$$(4.6) \quad Q_0(a) = \int_0^1 e^{-ax} \ln x \, dx = -\frac{1}{a} (\gamma + \ln a + \Gamma(0, a)).$$

PROOF. The change of variables $t = ax$ yields

$$(4.7) \quad Q_0(a) = \frac{1}{a} \int_0^a e^{-t} \ln t \, dt - \frac{\ln a}{a} (1 - e^{-a}).$$

Then

$$(4.8) \quad \int_0^a e^{-t} \ln t \, dt = \int_0^\infty e^{-t} \ln t \, dt - \int_a^\infty e^{-t} \ln t \, dt.$$

The first integral is

$$(4.9) \quad \int_0^\infty e^{-t} \ln t \, dt = -\gamma,$$

that simply reflects the fact that $\gamma = -\Gamma'(1)$. Integrating by parts yields

$$(4.10) \quad \int_a^\infty e^{-t} \ln t \, dt = e^{-a} \ln a + \Gamma(0, a).$$

The formula for $Q_0(a)$ is established. \square

We now determine a closed-form expression for $P_n(a)$ and $Q_n(a)$ following the procedure employed in Section 3.

Lemma 4.3. The integrals P_n and $Q_n(a)$ satisfy the recursion

$$(4.11) \quad P_{n+1}(a) = \frac{1}{a} ((n+1)P_n(a) - e^{-a})$$

$$(4.12) \quad Q_{n+1}(a) = \frac{1}{a} ((n+1)Q_n(a) + P_n(a)).$$

The initial conditions are given by

$$(4.13) \quad P_0(a) = \frac{1}{a}(1 - e^{-a}), \text{ and } Q_0(a) = -\frac{1}{a}(\gamma + \Gamma(0, a) + \ln a).$$

PROOF. Integrate by parts. \square

We conclude that we can write

$$(4.14) \quad P_n(a) = A_n(a) - B_n(a)e^{-a},$$

and

$$(4.15) \quad Q_n(a) = C_n(a) - D_n(a)e^{-a} - E_n(a)(\gamma + \Gamma(0, a) + \ln a).$$

Lemma 4.4. The recursions (4.11) and (4.12) imply that

$$(4.16) \quad \begin{aligned} A_{n+1}(a) &= \frac{1}{a}(n+1)A_n(a), \\ B_{n+1}(a) &= \frac{1}{a}[(n+1)B_n(a) + 1], \\ C_{n+1}(a) &= \frac{1}{a}[(n+1)C_n(a) + A_n(a)], \\ D_{n+1}(a) &= \frac{1}{a}[(n+1)D_n(a) + B_n(a)], \\ E_{n+1}(a) &= \frac{1}{a}(n+1)E_n(a) \end{aligned}$$

with initial conditions

$$(4.17) \quad A_0(a) = B_0(a) = E_0(a) = \frac{1}{a} \text{ and } C_0(a) = D_0(a) = 0.$$

These recursion can now be solved as in Section 3 to produce a closed-form expression for the integrals $P_n(a)$ and $Q_n(a)$. We employ the notation

$$(4.18) \quad H_n = \sum_{k=1}^n \frac{1}{k}$$

for the harmonic numbers and

$$(4.19) \quad \text{Exp}_n(x) = \sum_{k=0}^n \frac{x^k}{k!}$$

for the partial sums of the exponential function.

Theorem 4.5. Let $a \in \mathbb{R}$ and $n \in \mathbb{N}$. Then

$$(4.20) \quad P_n(a) := \int_0^1 x^n e^{-ax} dx = \frac{n!}{a^{n+1}} [1 - e^{-a} \text{Exp}_n(a)],$$

and

$$Q_n(a) := \int_0^1 x^n e^{-ax} \ln x dx = \frac{n!}{a^{n+1}} \left[H_n - G(a) - e^{-a} \sum_{k=1}^n \frac{1}{k} \text{Exp}_{k-1}(a) \right],$$

where $G(a) = -aQ_0(a) = \gamma + \Gamma(0, a) + \ln a$.

These expressions provide the evaluations of two integrals in [4].

EXAMPLE 4.1. Formula 4.351.2 states that

$$(4.21) \quad \int_0^1 e^{-ax} (-ax^2 + 2x) \ln x dx = \frac{1}{a^2} [-1 + (1+a)e^{-a}].$$

In order to verify this, observe that the stated integral is

$$(4.22) \quad -a \int_0^1 x^2 e^{-ax} \ln x dx + 2 \int_0^1 x e^{-ax} \ln x dx = -aQ_2(a) + 2Q_1(a).$$

The expressions in Theorem 4.5 now complete the evaluation.

EXAMPLE 4.2. Formula **4.353.3** in [4] gives the value of

$$(4.23) \quad I_n(a) := \int_0^1 (-ax + n + 1)x^n e^{-ax} \ln x \, dx.$$

Observe that

$$(4.24) \quad I_n(a) = -aQ_{n+1}(a) + (n + 1)Q_n(a),$$

and using the recursion (4.12) we conclude that $I_n(a) = -P_n(a)$. The expression in Theorem 4.5 is precisely what appears in [4].

We conclude with the evaluation of a series shown to us by Tewodros Amdeberhan. Expand the exponential term in (4.21) and integrate term by term to obtain

$$(4.25) \quad \sum_{k=0}^{\infty} \frac{(-a)^k}{k!(n+1+k)^2} = \frac{n!}{a^{n+1}} \left(-\psi(n+1) + \ln a + \Gamma(0, a) + e^{-a} \sum_{k=0}^n \frac{1}{k} \text{Exp}_{k-1}(a) \right).$$

Here

$$(4.26) \quad \psi(x) = \frac{\Gamma'(x)}{\Gamma(x)}$$

is the *digamma* function defined in **8.360.1** of [4]. the identity

$$(4.27) \quad \psi(n+1) = H_n - \gamma,$$

that is a direct consequence of the functional equation $\Gamma(x+1) = x\Gamma(x)$ and $\Gamma'(1) = -\gamma$, was used to transform (4.25).

The identity (4.25) can be used to provide multiple expressions for the incomplete gamma function, such as

$$(4.28) \quad \int_a^{\infty} \frac{e^{-x}}{x} \, dx = \sum_{k=0}^{\infty} \frac{(-1)^k a^{n+1+k}}{n! k! (n+1+k)^2} + \psi(n+1) - \ln a - e^{-a} \sum_{k=1}^n \frac{\text{Exp}_{k-1}(a)}{k},$$

and the special case for $n = 0$:

$$(4.29) \quad \int_a^{\infty} \frac{e^{-x}}{x} \, dx = -\gamma - \ln a + \sum_{k=0}^{\infty} \frac{(-1)^k a^{k+1}}{(k+1)!(k+1)}.$$

These issues will be explored in a future publication.

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Received 3 06 2007, revised 13 06 2007

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