Algebraic Reduction of Feynman Diagrams to Scalar Integrals: a Mathematica implementation of LERG-I

Robin G. Stuart

Instituto de Física,
Universidad Nacional Autónoma de México,
Apartado Postal 20-364, 01000 México D. F.

Abstract

A Mathematica implementation of the program LERG-I is presented that performs the reduction of tensor integrals, encountered in one-loop Feynman diagram calculations, to scalar integrals. The program was originally coded in REDUCE and in that incarnation was applied to a number of problems of physical interest.

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^1On leave of absence from Randall Physics Laboratory, University of Michigan, Ann Arbor, MI 48190-1120, USA
NEW VERSION SUMMARY

Title of new version: LERG-I

Reference to original program: Comput. Phys. Commun. 48 (1988) 367, Comput. Phys. Commun. 56 (1990) 337.

Author of original program: R. G. Stuart

Licensing provisions: none

Computer: NeXT Workstation

Installation: Instituto de Física, UNAM, Mexico, D. F.

Operating System: Unix

Programming language used: Mathematica

No. of bits in a word: 32

No. of lines in distributed program, including test deck etc.: 1776

Nature of the physical problem:

Expressions obtained in the calculation of one-loop radiative corrections in particle physics are generally simplified by expressing them in terms of scalar integrals. LERG-I reduces the form factors, associated with the various possible Lorentz tensors, occurring in the problem, to scalar integrals.

Method of solution:

The program makes use of identities that, in the context of dimensional regularization, relate form factors to one and other in a hierarchical fashion. The end result is that all form factors are finally defined in terms of scalar integrals.

Reason(s) for the new version:

The wide availability and use of Mathematica for computer algebraic manipulation has made it a popular choice for programming applications in high energy physics.

Restrictions on the complexity of the problem:

Processes with up to four external particles can be treated. Machine storage is usually the only limitation.

Typical running time:

Depends heavily on the complexity of the problem. The examples provided as test runs took roughly 0.2 CPU s to execute.

References:

[1] Mathematica, S. Wolfram, Addison-Wesley (1988).
1 Introduction

The precision of experiments in high-energy physics has steadily improved over the past few years to the extent that it is has become rather commonplace for the inclusion of one-loop radiative corrections to be required to reliably compare theory with experiment. For simple cases, with just a few non-zero masses and momenta, this can be straightforwardly done by means of a hand calculation. For more complicated situations, it is convenient or necessary to use computer algebraic manipulation for its speed and reliability.

A variety of techniques have been devised for the calculation of one-loop integrals [1] – [8] and a number of packages implementing them have appeared [3, 5]. One of the earliest and most general was LERG–I [9, 10] that was written in REDUCE. In this paper a version of LERG–I that runs under Mathematica is presented.

In the calculation of one-loop radiative corrections, one encounters a large number of tensor integrals. It turns out [2, 9] that all such integrals can be reduced to expressions involving four distinct types of scalar integrals with coefficients that are rational functions of masses and momenta. The resulting expressions are unique and are, in most cases, relatively simple and compact because of the limited number of form factors involved.

Both REDUCE and Mathematica are capable of producing output that is suitable for use as FORTRAN code. The output of LERG–I may be written to a file for inclusion in a FORTRAN program. The numerical evaluation of the general two-, three- and most four-point scalar integrals is well under control and is implemented in a number of places [11]–[13]. Compact expressions are known for a large number of scalar integrals for particular sets of arguments and it is sometimes more convenient to use these than the general routines.

The method used by LERG–I for the reduction of scalar form factors to scalar integrals is basically that of Passarino and Veltman [2] but is implemented algebraically rather than numerically. Their method was extended in ref. [9] so that two-point form factors could be reduced to two-point and one-point scalar integrals thereby yielding algebraically unique expressions.

The method of Passarino and Veltman breaks down when certain kinematic determinants vanish. In ref. [9] it was also extended to cover a large class of cases in which the kinematic determinant vanishes. In that situation, three-point scalar integrals reduce to two-point scalar integrals and four-point scalar integrals reduce to three-point integrals. It can be shown [14] that when the kinematic determinant vanishes, the approach used by in refs [2, 11] is correct for three-point functions, provided at least one external momentum is time-like. Physically interesting one-loop Feynman diagrams can be constructed with external momenta either space-like or light-like. The regions where the method of refs [2, 11] is not applicable lie in the extreme limits of phase space so it is quite rare to encounter them. This limitation should be borne in mind when using both the REDUCE and Mathematica implementations of LERG–I.
A general method that is correct for any set of external momenta is known [15].

The reduction method of ref. [9] could treat a wide range of problems with vanishing kinematic determinant but it too broke down for certain combinations of external momenta and internal masses. In ref. [10] the class of problems that could be successfully treated was further extended and a new REDUCE version of LERG–I was released (April, 1989). The present Mathematica version is essentially identical in structure and scope to the April ‘89 release[1]. The general reduction of tensor form factors to scalar integrals is now available [15] but has not yet been fully implemented.

Since its development, LERG–I has been applied to a number of problems [16] – [21] that would have been difficult or impossible to treat by a hand calculation. LERG–I possesses a number of desireable features that aid in such lengthy calculations. The fact that expressions are reduced to a unique form means that equality between expressions can be unambiguously tested. Thus stringent checks that constraints such as Ward identities are satisfied can be performed at an algebraic level giving confidence in the correctness of results. LERG–I is also set up so that it can perform certain internal self-consistency checks during a computation. Some of the form-factors that appear in intermediate steps can be calculated in two different ways. Comparing them constitutes a powerful test. This feature is, however, rather time-consuming and is not performed by default in the Mathematica implementation.

The ability to handle the reduction to scalar integrals for vanishing determinant is an important and useful feature. It often happens that one is performing a calculation that is a generalization of a simpler known result and one wishes to demonstrate that the former reduces to the latter in the appropriate limit. This can generate a vanishing kinematic determinant that would require intervention by hand, thus making the comparison more difficult and itself prone to error. Because LERG–I can handle most such cases automatically, these problems are usually avoided.

The methods employed by LERG–I have been exhaustively expounded in refs [2, 9, 10]. We, therefore, only briefly outline its general features in section 2. In section 3, the specifics of the Mathematica version of LERG–I are discussed and in section 4 the three examples that appeared in refs [9, 10] are retreated.

## 2 Mathematica implementation of LERG–I

The calculation of one-loop Feynman diagrams is expedited by writing the tensor integrals that appear in terms of a set of tensor form factors introduced in ref. [2]. For example, the two-point tensor integrals can be represented as follows,

\[ \int \frac{d^qd^p}{i\pi^2} \frac{q\mu q\nu}{[(q^2 + m_1^2)(q + p)^2 + m_2^2]} = \delta_{\mu\nu} B_{22}(p^2; m_1^2, m_2^2) + p_\mu p_\nu B_{21}(p^2; m_1^2, m_2^2). \]  

\( q \)

\( p \)

\( m_1 \)

\( m_2 \)

\( \delta_{\mu\nu} \)

\( B_{22} \)

\( B_{21} \)

(1)

\[1\]Note that the implementation of lists changed between REDUCE 3.2 and REDUCE 3.3. The April ‘89 release of LERG–I therefore comes in two versions depending on which version of REDUCE it is to be used with.
In eq. (1), $B_{22}$ is quadratically divergent and $B_{21}$ diverges logarithmically. It is assumed that the form factors are regularized using dimensional regularization and that terms proportional to $(n-4)^m$, with $m \geq 1$ are dropped. Here $n$ is the number of space-time dimensions.

The one-, two-, three- and four-point tensor form factors are denoted $A(m^2)$, $B_{ij}(p^2; m_1^2, m_2^2)$, $C_{ij}(p_1^2, p_2^2, m_1^2, m_2^2, m_3^2, m_4^2)$ and $D_{ij}(p_1^2, p_2^2, p_3^2, p_4^2, p_5^2, p_6^2; m_1^2, m_2^2, m_3^2, m_4^2)$ respectively, where the $p$'s are momenta, the $m$'s are masses and $i, j$ are integers. The corresponding two-, three- and four-point scalar integrals are denoted $B_0$, $C_0$ and $D_0$ with the same arguments as above. The two-point scalar integrals $B_0$ is defined by

$$B_0(p^2; m_1^2, m_2^2) = \int \frac{d^n q}{i \pi^2} \frac{1}{[q^2 + m_1^2][(q + p)^2 + m_2^2]}.$$  

(2)

A complete list of the form factors and their definitions can be found in the appendices of ref. [9].

The two-, three- and four-point scalar integrals have certain symmetry properties for their arguments. There are $n!$ ways of ordering the arguments of a given $n$-point scalar integrals corresponding to the $n!$ ways of ordering the denominators in the integrand. LERG-I automatically orders the arguments of scalar integrals in a unique canonical way. Thus scalar integrals that are actually equivalent, but initially differ in the ordering of their arguments, will be converted to a common form and combined. The canonical ordering of the arguments can be different between the REDUCE and Mathematica versions, because of differences in the internal ordering between the two systems, but the results will be equivalent. The functions

OrderedCQ[{p1^2,p2^2,p5^3,m1^2,m2^2,m3^2}]

and

OrderedDQ[{p1^2,p2^2,p3^2,p4^2,p5^2,p6^2,m1^2,m2^2,m3^2,m4^2}]

that return either True or False, are used to determine whether the arguments of three- and four-point functions are in canonical order.

In LERG-I, three- and four-point form factors with a particular set of arguments, must be initialized before use. Initializing three- or four-point form factors automatically initializes all ‘lower’ form-factors. Thus the statement

InitializeD3[p1^2,p2^2,p3^2,p4^2,p5^2,p6^2,m1^2,m2^2,m3^2,m4^2];

will assign a value to

D31[p1^2,p2^2,p3^2,p4^2,p5^2,p6^2,m1^2,m2^2,m3^2,m4^2],

corresponding to $D_{31}(p_1^2, p_2^2, p_3^2, p_4^2, p_5^2, p_6^2; m_1^2, m_2^2, m_3^2, m_4^2)$, as well as $D_{32}$, $D_{33}$ ... $D_{313}$ and $D_{2i}$, $D_{1i}$, $D_0$ with the same arguments. Also assigned values are all $C_{3i}$ and lower three-point form factors that are constructed from three of the four denominators in
the original four-point tensor integral. Thus, in the above example, three-point form
factors $C_{ij}(p_1^2, p_2^2, p_3^2, m_1^2, m_2^2, m_3^2)$, $C_{ij}(p_1^2, p_2^2, p_3^2; m_1^2, m_2^2, m_3^2)$, and $C_{ij}(p_2^2, p_3^2, p_4^2; m_2^2, m_3^2, m_4^2)$ are also assigned values.

In most situations, expressions turn out to be at most logarithmically divergent. Quadratic divergences do occur in individual Feynman diagrams but they cancel pairwise to yield overall logarithmically divergent quantities. In LERG-I quadratically divergences are isolated in the one-point scalar integral, $A(m^2)$. For expressions in which there is a pairwise cancellation between the $A$’s a substitution rule, CancelA, has been provided. A simple example of its use is

\begin{verbatim}
In[1]:= <<lergiii.m
In[2]:= A[m1^2] - A[m2^2] /. CancelA
Out[2]= -m1 + m2 - m1 B0[0, m1, m1] + m2 B0[0, m2, m2]
\end{verbatim}

Note that CancelA should only be applied to expressions for which it has been previously checked that there is a pairwise cancellation of $A$’s otherwise quadratic divergences that should have been present will be neglected.

The most convenient form for the output of final results is in terms of scalar integrals with coefficients that are rational functions of the squared masses and momenta. For this purpose LERG-I provides the function FactorScalarIntegrals[ expr ]. Expressions involving tensor form factors that actually evaluate to zero may not be identified as such unless FactorScalarIntegrals is applied.

In the solution of systems of linear equations, encountered in the reduction process, certain sets may be underconstrained. LERG-I employs the routine GeneralLinearSolve that takes the same input as the Mathematica function LinearSolve. It returns the general solution, that for underconstrained systems, may involve arbitrary constants that take the form arbitrary$nn$, where $nn$ is an integer. They will cancel in physically meaningful results and can therefore provide a useful check.

Many of the $C_{ij}$ and $D_{ij}$ form factors can be calculated in two distinct ways during the reduction process (see ref. [2], appendix E). That the two derivations yield the same algebraic result is a useful self consistency check. This feature is switched off by default but may be turn on for the three-point form factors by the statement

\begin{verbatim}
CConsistencyCheck = True
\end{verbatim}

and for the four-point form factors by

\begin{verbatim}
DConsistencyCheck = True
\end{verbatim}

If equality is not found then an error message is issued.
As stated earlier, the present implementation of LERG-I cannot handle the reduction to scalar integrals in all cases in which the kinematic determinant vanishes. LERG-I issues an error message if such a case is encountered.

The two-point tensor form factors, $B_{ij}(p^2; m_1^2, m_2^2)$, may be used without initialization. The form factor $B_0(0; 0, 0)$ is infrared divergent and should be absent in physically meaningful results. It may, however, occur in individual form factors in intermediate steps.

The function $DB0[p^2, m1^2, m2^2]$ returns the derivative of $B_0(p^2; m_1^2, m_2^2)$ with respect to $p^2$ for the given arguments. The derivatives of expressions involving $B_0$ may be obtained, in the usual way by means of the operator $D$. As the derivative does not exist at threshold, calling $DB0$ with arguments that satisfy $p^2 = -(m_1 + m_2)^2$ generates an error. Derivatives with respect to the mass arguments of $B_0$ are not available in the present implementation.

### 3 Examples and Test-Run Output

In this section the examples that appeared in refs [9, 10] are presented in a form suitable for reduction by the Mathematica version of LERG-I. To run the examples the file lergiii.m should be placed where it can be found by Mathematica.

Upon entering Mathematica one types

```
<<example1.m
```

The package Lergi will be loaded automatically and processing will proceed. The final result in all examples is assigned to the variable Result. Its value may be viewed by simply typing its name. The simplest way of obtaining a hardcopy of the output is by invoking Mathematica with a command like

```
math < example1.m > example1.out
```

The test run outputs that appear at the end of this paper were produced in this way. The first line in each program is there for formatting purposes as are the continuation characters ‘\’. They may be dropped if desired.

### 3.1 Example 1

Example 1 in ref. [9] was supposed to give an expression for the form factor that occurs in the $W-W$ box diagram in the process $e^+e^- \rightarrow \mu^+\mu^-$. The input was incorrect however. The arguments of the four-point form factors were given as $D_{ij}(0, 0, 0, 0, -s, -t; M_W^2, 0, M_W^2, 0)$ but should have been $D_{ij}(0, 0, 0, 0, -s, -u; M_W^2, 0, M_W^2, 0)$ where $s, t$ and $u$ are the usual Mandelstam variables. The final result needs an overall minus sign. The input error has been corrected here so that the output is not directly comparable with that of ref. [9]. The relation $s + t + u = 0$ has also been used.

A program for making the reduction for this process is
AppendTo[ $Echo, "stdout" ]; Off[ General::spell1 ]; <<lergiIII.m
(* Initialize D2 and lower form factors *)
InitializeD2[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ]
(* The following statements save us from *)
(* typing lots of arguments later *)
DF0 = D0[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
DF11 = D11[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
DF12 = D12[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
DF13 = D13[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
DF25 = D25[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
DF26 = D26[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
DF27 = D27[ 0,0,0,0,-s,-u, MW^2,0,MW^2,0 ];
(* The integral in the W box diagram is as follows *)
Result = FactorScalarIntegrals[
  u/2 * ( DF25 - DF26 + DF11 - DF12 + DF13 + DF0 ) + DF27
]
The value assigned to the variable Result is
\[
\frac{1}{27} \left( B_0(-s; M_W^2, M_W^2) - B_0(-u; 0, 0) \right) + \frac{t^2 + u^2 - 2sM_W^2}{2t^2} C_0(0, -s, 0; 0, M_W^2, M_W^2) + \frac{u(u - t + 2M_W^2)}{2t^2} C_0(-u, 0, 0; 0, M_W^2) + \frac{u(u^2 + t^2) - 2M_W^4(s - u) + 4M_W^2u^2}{4t^2} D_0(-u, 0, -s, 0; 0, 0, 0, 0, M_W^2, M_W^2)
\]

3.2 Example 2
In this example the Z-\(\gamma\) box diagram for the process \(e^+e^- \rightarrow V\) where \(V\) is the toponium resonance. Recent experimental evidence for the top quark around 174 GeV \[22\] essentially rules out the existence of toponium as a viable system. This example is nevertheless illustrative of situations in which kinematic determinants vanish. The Mathematica version of the program that appeared in \[9\] is given below.
AppendTo[ $Echo, "stdout" ]; Off[ General::spell1 ]; <<lergiIII.m
3.3 Example 3

This example gives the Mathematica version of the program that appeared in ref. [10] to calculate the box-diagram contribution to the flavour-changing neutral current process $b \rightarrow s \nu \bar{\nu}$. It could not be handled by the original version of LERG-I. Note that the expressions for some of the form factors generated by the initialization will contain arbitrary constants introduced by the function GeneralLinearSolve. These will cancel out in most physical results. The form factors $D_{27}$ turn out not to contain arbitrary constants.

AppendTo[$Echo, "stdout" ];
<<lergiiii.m

(* Initialize required form factors *)

InitializeD2[0,0,0,0,0,0, MW^2, MI^2, MW^2 ]

Box = D27[0,0,0,0,0,0, MW^2, MI^2, MW^2 ]

}
(* This is the contribution of the box diagram to the effective Lagrangian, b→s nu nu-bar *)

Result = FactorScalarIntegrals[ Box /. MI -> Sqrt[ X ] * MW ]

4 Acknowledgements

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Example 1

Mathematica 2.1 for NeXT
Copyright 1988–92 Wolfram Research, Inc.
-- NeXT graphics initialized --

In[1]:=
In[2]:= <<lergiii.m

In[3]:= InitializeD2[0,0,0,0,-s,-u, MW^2,0,MW^2,0]

In[4]:=
In[5]:= DF0 = D0[0,0,0,0,-s,-u, MW^2,0,MW^2,0];
In[6]:= DF11 = D11[0,0,0,0,-s,-u, MW^2,0,MW^2,0];
In[7]:= DF12 = D12[0,0,0,0,-s,-u, MW^2,0,MW^2,0];
In[8]:= DF13 = D13[0,0,0,0,-s,-u, MW^2,0,MW^2,0];
In[9]:= DF25 = D25[0,0,0,0,-s,-u, MW^2,0,MW^2,0];
In[10]:= DF26 = D26[0,0,0,0,-s,-u, MW^2,0,MW^2,0];
In[11]:= DF27 = D27[0,0,0,0,-s,-u, MW^2,0,MW^2,0];

In[12]:= Result = FactorScalarIntegrals[u/2 *( DF25 - DF26 + DF11 - DF12 + DF13 + DF0 ) + DF27]

\[ \frac{2}{12} \frac{2}{2} \]
\[ -B0[-s, MW, MW] \]
\[ B0[-u, 0, 0] \]

Out[12]= \[\frac{2}{12}\] + \[\frac{2}{2}\] + 

12
\[
\frac{2(s + u)}{2(s + u)} - \frac{(-2MWs + s^2 + 2su + 2u)}{2(s + u)} \text{C0}[0, -s, 0, 0, MW, MW] \\
\frac{2}{2(s + u)} \\
\frac{2}{2(s + u)} \text{C0}[-u, 0, 0, 0, MW] \\
\frac{2}{2(s + u)} \\
\frac{(((-2MWs + 2MWu + s^2 + 4MWu + 2su + 2u))}{2(s + u)} \text{C0}[-u, 0, -s, 0, 0, MW, MW]) / (4(s + u)) \\
\text{In[13]}:=
\]
Example 2

Mathematica 2.1 for NeXT
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-- NeXT graphics initialized --

In[1]:=
In[2]:= <<lergiii.m

In[3]:= InitializeD2[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ]

In[4]:= DF0 = D0[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[5]:= DF12 = D12[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[6]:= DF13 = D13[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[7]:= DF22 = D22[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[8]:= DF23 = D23[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[9]:= DF24 = D24[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[10]:= DF25 = D25[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[11]:= DF27 = D27[ 0,MV^2/4,-MV^2/4,-MV^2,-MV^2/4,0, 0,0,MV^2/4,MZ^2 ];

In[12]:= Result = FactorScalarIntegrals[
MV^2/2*DF22 - MV^2/2*DF23 - MV^2*DF24 - MV^2*DF25 + 6*DF27 -
MV^2/2*DF12 - MV^2/2*DF13
]
Out[12]= \[\frac{2}{MV (MV - MZ)} - \frac{2}{MV - MZ}\] 

> \[\frac{2}{BO[-MV, 0, MZ]} + \frac{2}{BO[-MV, 0, MZ]}\] 

> \[\frac{2}{MV - MZ} + \frac{2}{MV}\] 

> \[\frac{2}{(MV - MZ) C0[-MV, 0, 0, 0, MZ]}\] 

In[13]=
Example 3

Mathematica 2.1 for NeXT
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-- NeXT graphics initialized --

In[1]:=
In[2]:= <<lergiii.m
In[3]:= InitializeD2[0,0,0,0,0,0,0, MW^2, MI^2, MW^2]
In[4]:= InitializeD2[0,0,0,0,0,0,0, MW^2, 0, MW^2]
In[5]:= Box = D27[0,0,0,0,0,0,0, MW^2, MI^2, MW^2] -
    D27[0,0,0,0,0,0,0, MW^2, 0, MW^2];
In[6]:= Result = FactorScalarIntegrals[Box /. MI -> Sqrt[X] * MW]

Out[6]= \[\frac{-X^2}{2 MW (-1 + X)} + \frac{X^2 B[0, MW, MW]}{4 MW (-1 + X)} - \frac{2^2 B[0, MW, MW, MW]}{4 MW (-1 + X)}\]

In[7]:=