An Algorithm for the Newton Resultant

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1 Introduction

Given a system of $n+1$ generic Laurent polynomials, for $i = 1, \ldots, n+1$,

$$f_i(\underline{x}) = \sum_{q \in \mathcal{A}_i} c_{iq}\, x^q; \qquad q = (q_1, \ldots, q_n); \qquad \underline{x}^q = x_1^{q_1} x_2^{q_2} \cdots x_n^{q_n}; \quad (1.1)$$

with (finite) support sets $\mathcal{A}_i \subset L$, where L is some affine lattice isomorphic to $\mathbb{Z}^n$; we consider the *Newton resultant* $R(f_1, f_2, \ldots, f_{n+1})$. This is the unique (up to sign) irreducible polynomial with coefficients in $\mathbb{Z}$ and monomials in the c_{iq} which determines whether or not system (1.1) has common roots in the *algebraic torus* $(\mathbb{C} - \{0\})^n$. The resultant depends only on the *Newton polytopes* $N_i := conv(\mathcal{A}_i) \subset \mathbb{R}^n$ of the sets $\mathcal{A}_i$. If the system could not have common roots in the torus for any choice of the c_{iq}, then the resultant is defined to equal 1, by convention. What we call the Newton resultant appears as the "sparse mixed resultant" in [CE], [PS], and the "$\mathcal{A}$–resultant" in [GKZ].

Our terminology emphasizes the dependence on the combinatorics of the Newton polytopes, and removes the misleading reference to sparcity in the sense of having *few* monomials. The algebraic torus is the natural setting for us, since we are interested in the properties of systems of polynomials which are invariant under symmetries of the affine lattice L. Translation by $q \in L$ corresponds to multiplication by x^q at the level of polynomials, and since x^q may have negative exponents, we should restrict to points none of whose coordinates are zero, *i.e.* the algebraic torus. We refer to roots in the algebraic torus as *toric roots*.

2 Basics about mixed volumes

The *Minkowski sum* $A \oplus B$ of polytopes $A, B \subset \mathbb{R}^n$ is their pointwise sum, $A \oplus B := \{u + v : u \in A, v \in B\}$. We shall consider the iterated Minkowski

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** Partially supported by NYI (NSF) CCR-9258533 sum $N := N_1 \oplus \ldots \oplus N_{n+1}$.

A basic combinatorial-geometric invariant of any n lattice polytopes $P_1, \ldots, P_n$ is their *mixed volume* $\mathcal{MV}(P_1, \ldots, P_n)$. It is defined as the coefficient of the monomial $\lambda_1 \lambda_2 \cdots \lambda_n$ in the polynomial $\mathrm{Vol}(\lambda_1 P_1 \oplus \lambda_2 P_2 \oplus \ldots \oplus \lambda_n P_n)$. Classic expositions on mixed volumes may be found in [BF], and [E].

The mixed volume is determined (and may be computed) using *mixed subdivisions* of the *Minkowskii sum* $P := P_1 \oplus \ldots \oplus P_n$. Mixed subdivisions arise by choosing (randomly) *lifting functionals* $\omega_i : \mathbb{R}^n \to \mathbb{R}$, and then considering "lifted polytopes" $\widehat{P}_i \subset \mathbb{R}^{n+1}$ = the graph of P_i under ω_i:

$$\widehat{P}_i := \{ (q, \omega_i(q)) : q \in P_i \}.$$

Let $\widehat{P} = \widehat{P}_1 \oplus \ldots \oplus \widehat{P}_n$ denote the Minkowski sum of the lifted polytopes. The *lower convex hull* $\widehat{\Delta}$ of $\widehat{P}$ is the collection of facets $\widehat{F}$ of $\widehat{P}$ whose inner normal has positive last component. Each such facet has the form $\widehat{F} = \widehat{F}_1 \oplus \ldots \oplus \widehat{F}_n$, where $\widehat{F}_i$ is a face of $\widehat{P}_i$. We say that $\widehat{F}$ is a *mixed facet* if $dim(\widehat{F}_i) = 1$ for $i = 1, \ldots, n$. More generally, any facet of $\widehat{\Delta}$ has a *type* $(d_1, \ldots, d_n)$, where $d_i = \dim(\widehat{F}_i)$. Facets of $\widehat{\Delta}$ may be found using linear programming.

Suppose $\pi : \mathbb{R}^{n+1} \to \mathbb{R}^n$ projects to the first n coordinates, then $\Delta := \{ \pi(\widehat{F}) : \widehat{F} \in \widehat{\Delta} \}$ is a subdivision of P. Each cell C of Δ has the form $\pi(\widehat{F}) = F_1 \oplus \ldots \oplus F_n$ where $\pi(\widehat{F}_i) = F_i$ is a face of P_i. We assume that the weights ω are *sufficiently generic*, meaning that $\dim(C) = \dim(F_1) + \ldots + \dim(F_n)$, for every $C \in \Delta$. In this case Δ is called a *mixed subdivision* of P. The projection of mixed facets of $\widehat{\Delta}$ are *mixed cells* of Δ. The sum of the volumes of the mixed cells of any mixed subdivision Δ equals the mixed volume $\mathcal{MV}(P_1, \ldots, P_n)$. This is an integer which does not depend on the choice of subdivision. For details on mixed subdivisions and their relation to mixed volumes see [Bet].

Mixed cells are parallelotopes. If one considers them "half-open", then their volume equals their number of lattice points. We may determine a consistent sense of "half open" by fixing some random direction δ, and only counting lattice points lying on facets where δ is inward pointing, for instance.

In our application we have $n + 1$ polytopes. Their Minksowski sum also has a mixed decomposition obtained by means identical to the above, *i.e.* as the projection of the lower envelope of a lifted sum, with the difference that now *every* cell, even a mixed cell, is the sum of at least one vertex from one of the $n + 1$ inputs. Mixed cells in this setting are sums of n edges and one vertex, so that lattice points lying in mixed cells of a mixed decomposition of $N = N_1 \oplus \ldots \oplus N_{n+1}$ have associated to them a unique index which contributes the vertex. This index is crucial to the construction we are going to describe.

3 Basics about Newton Resultants

The mathematical foundations for the theory of Newton resultants can be found in [GKZ], [PS], and [CE], where it is shown that:

(1)

$$\deg_{f_j}(R) = MV(N_1, \ldots, \widehat{N_j}, \ldots, N_{n+1}).$$

(2)

$$R(\ldots, f_j \cdot f_j', \ldots) = R(\ldots, f_j, \ldots) \cdot R(\ldots, f_j', \ldots).$$

(3)

$$R(f_1, f_2, \ldots, f_{n+1}) = R' \cdot \prod_{\gamma} f_1(\gamma),$$

where the product in item (3) is over toric roots of $f_2 = \ldots = f_{n+1} = 0$, and R' is a product of lower dimensional resultants not involving f_1.

In [CE] an algorithm is proposed for computing the Newton resultant using analogues of Macaulay matrices. We shall describe an explicit implementation of this algorithm with complexity estimates. Maple code for the implementation is included in the Appendix.

The basic principle underlying the construction is simple: regard each equation $f_j(\underline{x}) = 0$ as a linear relation on the power-products $\underline{x}^q : q \in \mathcal{A}_j$:

$$f_i(\underline{x}) = (c_1, \ldots, c_n) \cdot (\underline{x}^{q_1}, \ldots, \underline{x}^{q_n}) = 0. \tag{3.1}$$

Any common solution $\underline{x}_0$ determines a null vector of this linear system by evaluation of the monomials x^q at x_0. However, one typically has more variables in $\cup_j \mathcal{A}_j$ than equations $(n+1)$. New equations can be generated by taking monomial multiples $\underline{x}^u f_j = 0$ of the old equations. This generates new power-products $\underline{x}^{u+q}$, and the game is to pick multiples which generate as few new power-products as possible, so that one eventually ends up with as many equations as variables. Suppose we write this linear system as $M \cdot (x^u) = 0$, where M has components c_{jq} as in (3.1).

The vanishing of the determinant of this linear system is a necessary condition for the existence of a common root. Therefore the resultant, which is irreducible ([PS]) must divide $\det(M)$. Multivariate factorization of the determinant, and extraction of the factor of appropriate degree (according to item (1) above) gives you the resultant.

This is exactly the type of algorithm defined in [CE], where a matrix M is constructed whose columns are indexed by the monomials of the Minkowski sum $N = N_1 \oplus \ldots \oplus N_{n+1}$, and whose rows are indexed by monomial multiples of the f_j's: If $p \in C \subset N = N_1 \oplus \ldots \oplus N_{n+1}$, and $C = F_1 \oplus \ldots \oplus F_{n+1}$, and if i is the largest index for which F_i is a vertex – say q_j, corresponding to the j-th monomial $c_{ij}x^{q_j}$ of f_i – then let $RC(p) := (i,j)$. This is the so called "row content" of p. Define M by

$$M_{p,q} = \begin{cases} c_{ik}, & \text{if } q - p + q_{ij} = q_{ik} \text{ for some } k, \text{ where } (i,j) = RC(p) \\ 0, & \text{if } q - p + q_{ij} \in \mathcal{A}_i \end{cases}$$

We refer to [CE] for details of the proof that the matrix so constructed is square and has non-identically-vanishing determinant. We refer to this matrix M as a *Newton matrix* for the system (1.1).

Our objective here is to describe a concrete implementation of this algorithm. Optimally there would be exactly $\mathcal{MV}(f_1, \ldots, \widehat{f_j}, \ldots, f_n)$ rows indexed by multiples of f_j, so that the degree of the determinant $\det(M)$ would coincide with the degree predicted in item (1) above. Generally speaking, this will not happen. We can hope that by adding rows "greedily", *i.e.* only according as we need them to cover the monomials determined by columns of M which we have already occupied, then we might find a sub-determinant of M which is already good enough.

4 Description of the Algorithm

Input: A system of generic polynomials (1.1)

Output: A matrix M, whose determinant has the Newton resultant as a factor.

Parameters: n = dimension; m bounds $|\mathcal{A}_i|$; $\bar{m}$ bounds the number of extreme points of $N_i = conv(\mathcal{A}_i)$; h = the number points of the Minkowski sum $N = N_1 \oplus \ldots \oplus N_{n+1}$, which is $O(m^{n+1})$.

Step 1.

Compute the convex hulls $N_i = conv(\mathcal{A}_i)$ of the exponent vectors of the inputs (1.1). Assemble the vertices of N_i as the columns of a matrix,

$$A^{(i)} = \begin{bmatrix} q_{i11} & \cdots & q_{i1m} \\ \vdots & & \vdots \\ q_{in1} & \cdots & q_{inm} \end{bmatrix}.$$

We approximate the convex hull by sorting the given lattice points in a linear number of pseudo-random directions, and then run LP's to determine which of the remaining points are *not* hull vertices. Any such point p will be feasible for the LP with convexity constraints

$$\begin{aligned} \sum_{j \in C} \lambda_j v_j &= p, \\ \sum_{j \in C} \lambda_j &= 1, \\ \lambda_j \geq 0, \ \ j \in C. \end{aligned}$$

where C is the current set of candidate hull vertices.

Suppose we use k random directions. The combinatorial complexity of approximating the hull is $O(knm \log_2(m))$. The remaining LP's run in $O(md^{3.5})$ steps using interior point methods. The initial approximation appears as a heuristic improvement.

Step 2.

Compute a collection of pseudo-random vectors which will be used to lift the points of each polytope, $L = [L_1, \ldots, L_{n+1}]$. The cost here is $O(n^2)$.

Step 3.

Set up LP equations defining the lower envelope of the Minkowski sum of the lifted points as follows. A general point of of N_i has the form

$$v^{(i)} = A^{(i)} \cdot [\lambda_{i1}, \ldots, \lambda_{im}]^T,$$

where the λ_i satisfy a convexity constraint

$$\lambda_i = \lambda_{i1} + \ldots + \lambda_{im} = 1.$$

A general point of $N = N_1 \oplus \ldots \oplus N_{n+1}$ has the form

$$v = v^{(1)} + \ldots + v^{(n+1)}.$$

The objective function is determined by the random lifting vectors. The lower envelope $\widehat{\Delta}$ consists of those points $\widehat{v} = (v, v_{n+1})$ whose height v_{n+1} over the point $v \in N$ is minimal. Therefore, the objective function is defined to be

$$B = L_1 \cdot v^{(1)} + \ldots + L_{n+1} \cdot v^{(n+1)}.$$

The cost here is $O(n\bar{m}^2)$.

Step 4

Compute the Minkowski sum N, and the center of gravity g of N; g is used as an initial monomial for the construction of M. Then $enqueue(V, g)$, *i.e.* enqueue g on the work queue V.

The cost here is $O(h)$.

Step 5.

Loop:

If V is empty then *break* (goto 7).

Set $v_0 := dequeue(V)$.

Check which polytope points contribute to the optimum sum for v_0. This is done by running the LP:

$$\begin{aligned} v &= v_0, \\ \lambda_i &= 1, \quad 1 \leq i \leq n+1 \\ \lambda_{ij} &\geq 0 \\ &\min(B) \end{aligned}$$

The vertices appearing in the representation of v as a sum points from the N_j can be read off from the coefficients which equal 1 in the representation $v = v_0$. The cost here is $O((mn)^{3.5})$ since there are mn variables λ_{ij}.

Step 6.

Compute the next row of the Newton matrix M:

step 6.1 Find the largest index i of a vertex q_{ij} contributing to the representation of v_0 from step 5.

step 6.2 Compute the displaced lattice vector $v' := v - q_{ij}$.

step 6.3 Compute the product $x^{v'} \cdot f_i$, placing the indeterminate coefficients in the appropriate columns of M.

step 6.4 For each column j of M hit by a monomial from step 6.3, if the lattice point w_j labeling column j is not already processed or enqueued, then $enqueue(V, w_j)$.

step 6.5 GOTO 5 (Loop)

The cost here is linear in n and m.

Step 7. Compute $\det(M)$.

The cost here is $O(h^{\alpha+1+\epsilon}\log_2(h))$, using Berkowitz's algorithm [B], where α is the current best exponent for matrix multiplication, and $\epsilon > 0$.

The overall cost is dominated by the cost of the determinant. Apart from this, the dominant component of the worst case complexity comes from the LP's occuring in the loop at step 5. The loop may execute as many as h times, with each loop costing as much as $O((mn)^{3.5})$ steps for the LP.

5 Appendix A

Maple code for the Newton matrix algorithm. (Warning: there are forward references.)

```
with(linalg):
with(simplex):

#################################################################
# verts -- calculates array of exponents of monomials in poly
#################################################################
verts := proc(poly, vars)

local d, n, vert;

    d := nops(vars);
    n := nops(poly);
    vert := array(1..d, 1..n);
    for i to n do
        term := op(i, poly);
        for j to d do
            vert[j, i] := degree(term, vars[j])
            od
        od;
    vert
end: # verts


#################################################################
# randlin -- random linear functionals
#################################################################

randlin := proc(d)
```

```
local i,j,l,die;

    die := rand(1..1000);
    l := array(1..d);
    for i to d do
        l[i] := array(1..d-1);
        for j to d-1 do l[i][j] := die() od
    od;
    l
end: # randlin


########################################################################
# randvect -- random displacement vector of length n
########################################################################

randvect := proc(n)
local rproc;

    rproc := rand(1..1000);
    r := array(1..n);
    for i to n do r[i] := convert(rproc()/10000, float) od;
    r
end: # randvect


########################################################################
# make_eqns -- sets up LP for lower envelope
########################################################################

make_eqns := proc(A, l, d)
# A = array of matrices, each contains vertices as columns.
# l = random linear functional
# d = length of A = dimension - 1;
#
# Constructs the following input equations for LP package:
#   objective       = \sum_i l_i(\sum_j \lambda_{i,j} A_{i,j}),
#   vertex eqns lhs = \sum_{ij} \lambda_{ij} A_{ij},
#   conv. constr.   = \sum \lambda_{i,j} = 1;
# where
#   l_i            = random linear functional,
#   \lambda_{i,j} = LP variables,

local C, cd, conveq, convsum, i, ipoly, j;
local lambda, nverts, objective, vertlhs;

    objective := 0; # objective function
    vertlhs := vector(d-1, 0); # lhs vertex equations
    conveq := {}; # convexity constraints
    nverts := dotp(vector(d,1), map(coldim, A));# tot. no. vert.

    for i to d do
        ipoly := A[i];
        convsum := 0;
        cd := coldim(ipoly);
        lambda := array(1..cd); # array for new variables

        for j to cd do
            lambda[j] := `lam`.i.`x`.j;
            convsum := convsum + lambda[j];
        od;

        conveq := conveq union {convsum = 1};
        C := multiply(ipoly, lambda);
        vertlhs := add(vertlhs, C);
        objective := objective + multiply(transpose(l[i]), C);
    od;
    [objective, conveq, vertlhs, nverts]
end: # make_eqns


################################################################
# cog -- computes center of gravity
################################################################

cog := proc(ipoly, d)
# ipoly = array of exponent columns.

local cd, i, v;

    cd := coldim(ipoly);
    v := multiply(ipoly, convert(vector(cd, 1), matrix));
    scalarmul(v, 1/cd)
end: # cog

################################################################
# Table of digit to num conversions
################################################################

chars := 0:
chars['0'] := 0:
chars['1'] := 1:
chars['2'] := 2:
chars['3'] := 3:
chars['4'] := 4:
chars['5'] := 5:
```

```
chars['6'] := 6:
chars['7'] := 7:
chars['8'] := 8:
chars['9'] := 9:


#################################################################
# recode -- converts string 'lamMxN' into vector [M, N]
#################################################################

recode := proc(z)
# converts string 'lamMxN' into vector [M, N]
local i, L, M, N, s, state;

    L := length(z);
    M := 0;
    N := 0;
    state := 1;
    for i from 4 to L do
        s := substring(z,i..i);
        if s = 'x' then state := 2 fi;
        if state = 1 then M := 10*M + chars[s]
        elif state = 2 then state := 3
        elif state = 3 then N := 10*N + chars[s] fi
    od;
    [M, N]
end:


#################################################################
# opt_verts -- checks which polytope points contribute
#              to optimum sum for vert.
```

```
#################################################################

opt_verts := proc(edata, vert, d)
# edata = equations from make_eqns(),
# vert  = vertex in Minkowski sum,
# d     = dimension + 1.

local assigns, conveq, eps, eqns, ivert, j, nverts, objective,
    optverts, verteq, vertlhs;

   # Pick apart input from make_eqns()
     objective := op(1, edata);# objective function
     conveq := op(2, edata); # convexity constraints
     vertlhs := op(3, edata); # vertex eqns left hand sides
     nverts := op(4, edata); # total number of input vertices

   # Run LP to find optimal sum (on lower envelope) for vert
    eps := 1.0 * 10^(-6);
    eqns := conveq;
    for j to d-1 do
        eqns := eqns union {vertlhs[j] = vert[j,1]} od;
    assigns := minimize(objective, eqns, NONNEGATIVE);

   # find vertices appearing in the representation
    optverts := {};
    for a in assigns do
        if (abs(rhs(a)-1.0) < eps) then
            optverts := optverts union {recode(lhs(a))};
        fi
    od;
    optverts
end: # opt_verts
```

```
#################################################################
# compute_rows -- greedy algorithm for rows of Newton matrix
#################################################################

compute_rows := proc(A, B, edata, v, delta, d)
#  A     = array of arrays ((d-1) X num vert.), input vert.
#  B     = array of arrays like A   plus  interior points
#  edata = eqn.'s defining lower hull for simplex package
#  v     = vertex in the Minkowski sum of the inputs A[i]
#  delta = random small displacement vector
#  d     = dimension + 1

local cols, guide, i, imax, ipoly, jmax, overts, rows, vt1, vt2;

    rows := {};
    guide := {};
    cols := {eval(v)};
    while not (eval(v) = {}) do  # i.e. cont. while v is defined
        print(v);
        rows := rows union {eval(v)};
        # lower hull vertices:
        overts := opt_verts(edata, add(v,delta), d);
        imax := 0;
        jmax := 0;
        for vt1 in overts do       # find index of last polytope
            if vt1[1] > imax then  # ..contrib. vert. to opt. sum
                imax := vt1[1];
                jmax := vt1[2]
            fi
        od;
        guide := guide union {[eval(v),imax,jmax]};
        vt2 := add(v, col(A[imax], jmax), 1, -1);
        ipoly := B[imax];
        for i to coldim(ipoly) do           # find exp. in
            vt1 := add(vt2, col(ipoly, i)); # ..mult. of B[imax]
            if not vmem(vt1, cols) then
                cols := cols union {eval(vt1)} fi
        od;
        v := {}; # undefine v, and then check
        for vt1 in cols do # ..if any new rows are needed
            if not vmem(vt1, rows) then v := eval(vt1); break fi
        od
    od;
    guide
end: # compute rows


##################################################################
# newtonres -- computes Newton resultant matrix
##################################################################

newtonres := proc(A, B)
# A, B = array of arrays, ((d-1) X no. vert.), cols are vert.
# A    = vertices only,
# B    = all exponents in Newton polytopes

local d, delta, edata, i, ip, ipoly;
local ivert, j, k, M, msize, v, vt1, vt2;

    d := rowdim(convert(A,matrix));  # no. polytopes = dim. - 1
    delta := randvect(d-1);          # rand. displacement vector
    l := randlin(d);       # rand. linear functional
```

```
print(‘Computing data common to all vertex equations‘);
edata := make_eqns(A, 1, d);     # [obj, conveq, vertlhs]

print(‘greedy search for row indices‘);
v := cog(A[1], d);       # start at the ctr. grav.
for i from 2 to d do       # ..of Minkowski sum
    v := add(v, cog(A[i], d)) od;
v := map(round, v);
guide := compute_rows(A, B, edata, v, delta, d);

print(‘constructing the matrix‘);
msize := nops(guide);
guide := convert(guide, list);
M := array(1..msize, 1..msize);

for i to msize do
    ivert := guide[i];
    ip := ivert[2];
    vt1 := add(ivert[1], col(A[ip], ivert[3]), 1, -1);
    ipoly := B[ip];
    for j to msize do
        vt2 := add(guide[j][1], vt1, 1, -1);
        M[i, j] := 0;
        for k to coldim(ipoly) do
            if equal(vt2, submatrix(ipoly, 1..d-1, [k])) then
                M[i, j] := ‘C‘.ip.‘x‘.k
            fi
        od
    od
od;
M
```

```
end: # mixed


#################################################################
# randhull -- approx. convex hull, sorting in random directions
#################################################################

randhull := proc(v,limit)
# v     = input vector of vertices
# limit = number of random directions to sort by

local d, i, j, k, max, maxindex, min, minindex, n, newc, rv, t;
local processed, unprocessed, vertlhs, conveq, convsum, lambda;
local work, work1, possible, sub, temp;

    d := rowdim(v); # v = input vector of vertices, d = dim.
    n := coldim(v); # n = numbers of vertices

    processed := {};
    unprocessed := {};
    for i to n do unprocessed := unprocessed union {i} od;

    for i to limit do
        rv := randmatrix(1,d);
        rv := scalarmul(rv, 1/norm(rv));

        minindex := 1;
        maxindex := 1;
        min := multiply(rv, col(v, 1));
        min := min[1];
        max := eval(min);
    for j from 2 to n do
        t := multiply(rv, col(v, j));
        t := t[1];
        if t < min then
            minindex := j;
            min := t
        elif t > max then
            maxindex := j;
            max := t
        fi
    od;

    processed := processed union {minindex, maxindex};
    unprocessed := unprocessed minus {minindex, maxindex}

od; # ends random iterations

# Now use LP to check other vertices
lambda := matrix(1, n);
for i to n do lambda[1, i] := `lam`.i od;
work1 := unprocessed;
possible := processed;
work := {};

while (work minus work1 <> {}) or (work1 minus work <> {}) do
    work := work1;

    for i in work do
        temp := possible minus {i};
        sub := convert(temp, list);
        vertlhs := vector(d, 0); # vertex equation lhs
        conveq := {}; # convexity constraint
```

```
            convsum := 0;
            for j in temp do
                convsum := convsum + lambda[1, j]
            od;
            conveq := conveq union {convsum = 1};
            vertlhs := multiply(submatrix(v, 1..d, sub),
                     transpose(submatrix(lambda, 1..1, sub)));
            for j to d do
              conveq := conveq union {vertlhs[j, 1] = v[j, i]}
            od;
            if feasible(conveq, NONNEGATIVE) then
                print(col(v,i),'interior');
                work1 := work1 minus {i};
                possible := possible minus {i}
            else
                possible := possible union {i}
            fi
        od
    od;

    possible;
end: # randhull


################################################################
# dotp -- dot product of vectors
################################################################

dotp := proc(x, y)
    multiply(transpose(x), y)
end: # dotp
```

```
##################################################################
# norm -- computes the 2 norm of a vector (as 1Xn matrix)
##################################################################
norm := proc(x)

local i,r;

    r := x[1,1]^2;
    for i from 2 to coldim(x) do r := r + x[1,i]^2 od;
    convert(sqrt(r), float)
end: # norm


##################################################################
# vmem -- checks if el lies in (set or list) vset, using equal
##################################################################

vmem := proc(el, vset)
local found, el2;

    found := false;
    for el2 in vset do
        if equal(el, el2) then found := true; break fi od;
    found
end: # vmem


##################################################################
# set2array -- convert set of row vectors to array of col vectors
##################################################################
```

```
set2array := proc(s)

    n := nops(s);
    d := nops(convert(op(1, s), list));
    transpose(array(1..n, 1..d, convert(s, list)));
end: # set2array
```

---

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