Computers in Engineering COMP 208

Linear Algebra
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Representing Vectors

- A vector is a sequence of numbers (the components of the vector)
- If there are n numbers, the vector is said to be of dimension n
- To represent a vector in C, we use an array of size n, indexed from 0 to n-1
- In Fortran we use an array indexed from 1 to n

Vector Operations

- Scaling
  - Multiply each element by a given scalar factor
- Adding and Subtracting
  - Given two vectors of the same dimension add the components to get a new vector of the same dimension

Vector Operations (cont)

- Dot Product
  - Sum the Products of Vector Components
- Vector Norm
  - Length of the Vector, Square-root of the sum of squares of Components

Dot Product

```
#include <math.h>

double vector_dot(double v1[], double v2[],
                  int size){
  int i;
  double dot = 0.0;
  for(i = 0; i < size; i++)
    dot += v1[i] * v2[i];
  return dot;
}

double vector_norm(double v[], int size)(
  return sqrt(vector_dot(v, v, size)
}
```


Read a Vector

```
void fscan_vector(FILE * in, double v[], int size){
  int i;

  for(i = 0; i < size; i++) {
    fscanf(in, "%lf", &v[i]);
  }
}

void scan_vector(double v[], int size){
  fscan_vector(stdin, v, size);
}
```

Output a Vector

```
void fprint_vector(FILE * out, double v[], int size){
  int i;

  fprintf(out, "{");
  for(i = 0; i < size - 1; i++)
    fprintf(out, "%g, ", v[i]);
  fprintf(out, "%g}\n", v[i]);

  return;
}

void print_vector(double v[], int size)
{
  fprint_vector(stdout, v, size);

  return;
}
```

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Possible Confusion

```
for(i = 0; i < size - 1; i++)
  fprintf(out, "%g, ", v[i]);
fprintf(out, "%g}\n", v[i]);
```

- Does Indentation Always Dictates Meaning?

```
for(i = 0; i < size - 1; i++)
  fprintf(out, "%g, ", v[i]);
  fprintf(out, "%g}\n", v[i]);

for(i = 0; i < size - 1; i++)
fprintf(out, "%g, ", v[i]);
fprintf(out, "%g}\n", v[i]);
```

- Same Results

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Output a Vector

```
void fprint_vector(FILE * out, double v[], int size){
  int i;

  fprintf(out, "{");
  for(i = 0; i < size - 1; i++) {
    fprintf(out, "%g, ", v[i]);
  }
  fprintf(out, "%g}\n", v[i]);

  return;
}

void print_vector(double v[], int size)
{
  fprint_vector(stdout, v, size);
  return;
}
```

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Representing Matrices

A matrix with m rows and n columns can be represented as a two dimensional array in C (or Fortran).

In C the declaration could be

```
double voltage[m][n];
```

The first dimension is the number of rows and the second the number of columns

A specific value in row i, column j is referenced as `voltage[i][j]`

Initialization

We can initialize a matrix (or any array) when it is declared:

```
int val[3][4] = {{8,16,9,24},
                 {3,7,19,25},
                 {42,2,4,12}};
```


Row Major Ordering

What happens if we write

```
int val[3][4] =
  {{8,16,9,24,3,7,19,25,42,2,4,12}};
```

We begin filling in values starting with `v[0][0]` and continue.

If the array is stored in row major order, this has the same effect as the previous example

Implementing Row Major Order

- We can simulate a matrix using a one dimensional array by taking the two indices and finding the position in row major order.
- We have to know how many columns there are, that is the number of elements in each row.

```
int in2d(int row, int col, int n){
  return col + row * n;
}
```


Simulating Matrices in One Dimension

- In the previous example we showed how to simulate a matrix by a one dimensional vector.
- This may be done in some applications to make highly computational intensive programs more efficient
- We could also simulate a matrix with a one dimensional array that stores the values in column major order
- Imagine adding one to every element?
- Used with other Data Structures as well

Input of Matrix

```
void fscan_matrix(FILE * in, double **m,
                  int h, int w){
  int i, j;

  for(i = 0; i < h; ++i)
    for(j = 0; j < w; ++j)
      fscanf(in, "%lf", &m[i][j]);

  return;
}

void scan_matrix(double **m, int h, int w){
  fscan_matrix(stdin, m, h, w);
  return;
}
```

**, What about [][]?

- Why can't we use [][] in our function arguments:

```
void fscan_matrix(FILE * in, double m[][],
                  int h, int w)
```

- C needs to know the length of the second dimension!
- Need to use a double pointer if we want to allow for completely dynamic matrices

How do we allocate a dynamic matrix?

```
double ** make_matrix(int h, int w) {
    int i;
    double **array2 = (double **)malloc(h * sizeof(double *));
    if (array2) {
        array2[0] = (double *)malloc(h * w * sizeof(double));
        if(array2[0]) {
            for(i = 1; i < h; i++)
                array2[i] = array2[0] + i * w;

            return array2;
        } else {
            free(array2);
        }
    }

    return NULL;
}
```


Matrix Output

```
void fprint_matrix(FILE * out, double **m, int h, int w){
  int i, j;
  fprintf(out, "{\n");
  for(i = 0; i < h - 1; ++i) {
    fprintf(out, "  {");
    for(j = 0; j < w - 1; ++j)
      fprintf(out, "%g, ", m[i][j]);
    fprintf(out, "%g},\n", m[i][j]]);
  }
  fprintf(out, "  {");
  for(j = 0; j < w - 1; ++j)
    fprintf(out, "%g, ", m[i][j]);
  fprintf(out, "%g}\n}\n", m[i][j]);
  return;
}

void print_matrix(double **m, int h, int w){
  fprint_matrix(stdout, m, h, w);
  return;
}
```

Matrix Transposition

- A common operation is to compute the transpose of a matrix
- We could do this in place and overwrite the contents of the matrix
- In the following algorithm, we compute a new matrix containing the transposed matrix

Matrix Transposition

```
double ** matrix_transpose(double ** m1, int h, int w){
  int i, j;

  double ** mr = make_matrix(w, h);

  if (mr) {
    for(i = 0; i < h; ++i)
      for(j = 0; j < w; ++j)
        mr[j][i] = m1[i][j];

    return mr;
  } else {
    return NULL;
  }
}
```


Example

```
int main() {
  //double m[4][3] = { {0, 1, 2}, {2, 3, 4}, {5, 6, 7}, {9, 1, 0}};
  int h = 2, w = 3;
  double ** m = make_matrix(h, w);
  scan_matrix(m, h, w);

  print_matrix(m, h, w);

  double ** mt = matrix_transpose(m, h, w);

  if (mt) {
    print_matrix(mt, w, h);

    free_matrix(mt);
  }
  free_matrix(m);

  return 0;
}
```

Matrix Multiplication

- Matrix multiplication is a fundamental operation that occurs in many applications
- Given two matrices A, a matrix with h1 rows and w1 columns and B a matrix with w1 rows and h2 columns, we can compute their product matrix C
- Note that the number of columns of A must equal the number of rows of B

Matrix Multiplication

- The element c[i][j] is computed as the dot product of the ith row of A and the jth column of B
- The overall algorithm computes has two nested loops that vary i and j, computing each dot product
- The computation of the dot product is done in another loop nested inside those two

Matrix Multiplication

```
double ** matrix_mult(double **m1, double **m2,
                      int hm1, int wm1, int wm2){
  int i, j, k;
  double sum;

  double ** mr = make_matrix(hm1, wm2);

  if (mr) {
     for(i = 0; i < hm1; ++i) {
        for(j = 0; j < wm2; ++j) {
          sum = 0;
          for(k = 0; k < wm1; ++k) {
                sum += m1[i][k] * m2[k][j];
          }

          mr[i][j] = sum;
        }
     }
  }
  return mr;
}
```

Solving Linear Systems

- One of the most widespread applications of computers is the solving of systems of linear equations
- These systems arise in numerous application areas
- There is a large body of literature and research on how to solve these systems efficiently and accurately
- We examine two simple approaches

An Easy Example

If the system of equations is triangular, we can solve it by a process called back substitution:

```
w - 1.5x +  y + 2.5z = 1.5
        x + 0y -    z = -1
              y +   0z = -2
                     z = 7
```


Matrix Representation

- We can represent this system of equations using an upper triangular matrix, A and a vector b. The equations can be written Ax=b, where x is a vector of length 4 representing the values of (w,x,y,z)

Matrix Representation

```
A = 1 -1.5   1 2.5  b = (1.5
    0    1   0  -1         -1
    0    0   1   0         -2
    0    0   0   1          7)
```


Back Substitution

First solve for z and then substitute in the previous equation to solve for y.

Continue until all of the variables have been solved.

```
z = 7
y = -2 - 0*7 = -2
x = -1 - 0*-2 + 7 = 6
w = 1.5 + 1.5*6 - (-2) - 2.5*7 = -5
```


Gaussian Elimination

- The Gaussian elimination algorithm attempts to transform a system of linear equations into a triangular system
- As we have seen by example, a triangular system is easy to solve by back substitution
- We transform the system by eliminating one variable at each step

A Linear System Example

Consider the system of equations:

```
2w - 3x + 2y + 5z = 3
 w -  x +  y + 2z = 1
3w + 2x + 2y +  z = 0
 w +  x - 3y -  z = 0
```


A Linear System Example

Again we can write this in the form Ax=b where A is a 4x4 matrix, x is a 1x4 vector and b is a 1x4 vector:

```
A:                 b:
2 -3  2  5          3
1 -1  1  2          1
3  2  2  1          0
1  1  3 -1          0
```


Gaussian Elimination Example

We first eliminate the first entry in the second row, by multiplying the first row by 1.0/2.0 and subtracting the rows.

We do the same to the second entry in b.

```
A:                 b:
2 -3  2  5          3
0 .5  0 -.5        -.5
3  2  2  1          0
1  1  3 -1          0
```

Gaussian Elimination Example

Repeat this process for each row

A: b:

2	-3	2	5	3
0	.5	0	- .5	-.5
0	6.5	-1	-6.5	-4.5
0	2.5	-4	-3.5	-1.5

Gaussian Elimination Example

Now eliminate the second non-zero entries in the second column below the diagonal in the same way

A: b:

2	-3	2	5	3
0	.5	0	-.5	-.5
0	0	-1	0	2
0	0	-4	-1	1

Gaussian Elimination Example

Do the same for the third column. Notice that it is not necessary to continue with the last column

A: b:

2	-3	2	5	3
0	.5	0	-.5	-.5
0	0	-1	0	2
0	0	0	-1	-7

Gaussian Elimination

```
void genp(double **m, double v[], int h, int w){
  int row, next_row, col;
  double factor;

  for(row = 0; row < (h - 1); ++row) {
    for(next_row = row + 1; next_row < h; ++next_row) {
      factor = m[next_row][row] / m[row][row];

      for(col = 0; col < w; ++col)
        m[next_row][col] -= factor * m[row][col];

      v[next_row] -= factor * v[row];
    }
  }
}
```


Problems with Gaussian Elimination

- If there is a zero on the diagonal that of the row we are processing, there will be an attempt to divide by zero, causing an error
- Even if there isn't a zero, dividing by a small number causes large roundoff errors and inaccurate results.
- These problems can be reduced by pivoting
- We rearrange the rows at each step so that the largest possible value is the next one we chose to eliminate

Gaussian Elimination with Partial Privoting

```
void gepp(double **m, double v[], int h, int w){
  int row, next_row, col, max_row;
  double tmp, factor;

  for(row = 0; row < (h - 1); ++row) {

    // Find row with largest pivot.

    // Swap rows.

    // Rest like Gaussian Elimination without Pivoting.

  }
}
```

Finding a Pivot

```
max_row = row;
for(next_row = row + 1; next_row < h; ++next_row)
  if(m[next_row][row] > m[max_row][row])
        max_row = next_row;
```


Swapping Two Rows

```
if(max_row != row) {
  for(col = 0; col < w; ++col) {
    tmp = m[row][col];
    m[row][col] = m[max_row][col];
    m[max_row][col] = tmp;
    }
  tmp = v[row];
  v[row] = v[max_row];
  v[max_row] = tmp;
}
```


Back Substitution

- Once we have an upper triangular matrix, we can solve the system of equations by back substitution
- We first solve for the last variable and use the solution to solve for the second last and so on.

Back Substitution

```
void back_substitute(double **m, double v[],
                     int h, int w){
  int row, next_row;

  for(row = h - 1; row >= 0; --row) {
    v[row] /= m[row][row];
    m[row][row] = 1;
    for(next_row = row - 1; next_row >= 0; --next_row)
   {
      v[next_row] -= v[row] * m[next_row][row];
      m[next_row][row] = 0;
    }
  }
}
```