Dimension problems

Coding the Matrix, 2015

`For auto-graded problems, edit the file Dimension_problems.py to include your solution.`

For the next two problems, use the Exchange Lemma iteratively to transform a set $S = \{\boldsymbol{w}_0, \boldsymbol{w}_1, \boldsymbol{w}_2\}$ into a set $B = \{\boldsymbol{v}_0, \boldsymbol{v}_1, \boldsymbol{v}_2\}$. In each step, one vector of B is injected, and one vector of S is ejected. Be careful to ensure that the ejection does not change the set of vectors spanned.

You might find the following table useful in keeping track of the iterations.

	S_i	A	$\boldsymbol{v}$ to inject	$\boldsymbol{w}$ to eject
i = 0	$\{\boldsymbol{w}_0, \boldsymbol{w}_1, \boldsymbol{w}_2\}$	$\emptyset$		
i = 1				
i = 2				
i = 3	$\{\boldsymbol{v}_0, \boldsymbol{v}_1, \boldsymbol{v}_2\}$	$\{\boldsymbol{v}_0, \boldsymbol{v}_1, \boldsymbol{v}_2\}$	-	

You are to specify the list of vectors comprising S_1 (after one iteration) and S_2 (after two iterations) in the process of transforming from $\{\boldsymbol{w}_0, \boldsymbol{w}_1, \boldsymbol{w}_2\}$ to $\{\boldsymbol{v}_0, \boldsymbol{v}_1, \boldsymbol{v}_2\}$.

✓ **Problem 1:** Vectors over $\mathbb{R}$:

$$\boldsymbol{w}_0 = [1,0,0] \qquad \boldsymbol{v}_0 = [1,2,3]$$
$$\boldsymbol{w}_1 = [0,1,0] \qquad \boldsymbol{v}_1 = [1,3,3]$$
$$\boldsymbol{w}_2 = [0,0,1] \qquad \boldsymbol{v}_2 = [0,3,3]$$

✓ **Problem 2:** Vectors over $GF(2)$:

$$\boldsymbol{w}_0 = [0, one, 0] \qquad \boldsymbol{v}_0 = [one, 0, one]$$
$$\boldsymbol{w}_1 = [0, 0, one] \qquad \boldsymbol{v}_1 = [one, 0, 0]$$
$$\boldsymbol{w}_2 = [one, one, one] \qquad \boldsymbol{v}_2 = [one, one, 0]$$

✓ **Problem 3:** In this problem, you will write a procedure to achieve the following goal:

- *input:* a list S of vectors, and a list B of linearly independent vectors such that Span S = Span B
- *output:* a list T of vectors that includes B and possibly some vectors of S such that
  - $|T| = |S|$, and
  - Span T = Span S

This is not useful in its own sake, and indeed there is a trivial implementation in which T is defined to consist of the vectors in B together with enough vectors of S to make $|T| = |S|$. The point of writing this procedure is to illustrate your understanding of the proof of the Morphing Lemma. The procedure should therefore mimic that proof: T should be obtained step by step from S by, in each iteration, injecting a vector of B and ejecting a vector of $S - B$ using the Exchange Lemma. The procedure must return the list of pairs (injected vector, ejected vector) used in morphing S into T.

The procedure is to be called `morph(S, B)`. The spec is as follows:

- *input:* a list S of distinct vectors, and a list B of linearly independent vectors all belonging to Span S and none belonging to S
- *output:* a k-element list $[(\boldsymbol{z}_1, \boldsymbol{w}_1), (\boldsymbol{z}_2, \boldsymbol{v}_2), \ldots, (\boldsymbol{z}_k, \boldsymbol{w}_k)]$ of pairs of vectors such that, for $i = 1, 2, \ldots, k,$

$$\text{Span } S = \text{Span } (S \cup \{\boldsymbol{z}_1, \boldsymbol{z}_2, \ldots, \boldsymbol{z}_i\} - \{\boldsymbol{w}_1, \boldsymbol{w}_2, \ldots, \boldsymbol{w}_i\})$$

  where $B = [\boldsymbol{z}_1, \boldsymbol{z}_2, \ldots, \boldsymbol{z}_k]$.

This procedure uses a loop. You can use the procedure `exchange(S, A, z)` or the procedure `vec2rep(veclist, u)` or the `solver` module.

Here is an illustration of how the procedure is used.

```
>>> S = [list2vec(v) for v in [[2,4,0],[1,0,3],[0,4,4],[1,1,1]]]
>>> B = [list2vec(v) for v in [[1,0,0],[0,1,0],[0,0,1]]]
>>> for (z,w) in morph(S, B):
...   print("injecting ", z)
...   print("ejecting ", w)
...   print()
...
injecting
 0 1 2
------
 1 0 0
ejecting
 0 1 2
------
 2 4 0

injecting
 0 1 2
------
 0 1 0
ejecting
 0 1 2
------
 1 0 3

injecting
 0 1 2
------
 0 0 1
ejecting
 0 1 2
------
 0 4 4
```

Test your procedure with the above example. Your results need not exactly match the results above.

Problem 4: For each of the following matrices, (a) give a basis for the row space (b) give a basis for the column space, and (c) verify that the row rank equals the column rank. Justify your answers.

1. $\begin{bmatrix} 1 & 2 & 0 \\ 0 & 2 & 1 \end{bmatrix}$

2. $\begin{bmatrix} 1 & 4 & 0 & 0 \\ 0 & 2 & 2 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}$

3. $\begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}$

4. $\begin{bmatrix} 1 & 0 \\ 2 & 1 \\ 3 & 4 \end{bmatrix}$

Problem 5: Write and test a procedure `subset_basis(T)` with the following spec:

- *input:* a set T of vectors
- *output:* a set S consisting of vectors of T such that S is a basis for the span of T.

Your procedure should be based on either a version of the Grow algorithm or a version of the Shrink algorithm. Think about each one to see which is easier for you. You will need a loop or comprehension for this procedure. You can use as a subroutine any one of the following:

- the procedure `is_superfluous(S, v)` from `The_Basis_problems`, or
- the procedure `is_independent(S)` from `The_Basis_problems` or from the module `independence` we provide, or
- the procedure `solve(A,b)` from the `solver` module.

Disclaimer: The algorithm you are intended to use here is pedagogically motivated. It is intended to illustrate and illuminate our proof of the Subset-Basis Lemma. Ideas discussed later give rise to better algorithms for this computational problem.

Problem 6: Write and test a procedure `superset_basis(C, T)` with the following spec:

- *input:* a linearly independent set C of vectors, and a set T of vectors whose span contains all vectors in C.
- *output:* a linearly independent set S consisting of all vectors in C and some from T such that the span of S equals the span of T (i.e. S is a basis for the span of T).

Your procedure should be based on either a version of the Grow algorithm or a version of the Shrink algorithm. Think about each one to see which is easier for you. You will need a loop or comprehension for this procedure. You can use as a subroutine any one of the following:

- the procedure `is_superfluous(S, v)` from `The_Basis_problems`, or

- the procedure `is_independent(S)` from `The_Basis_problems`, or from the module `independence` we provide, or
- the procedure `solve(A,b)` from the `solver` module.

Disclaimer: The algorithm you are intended to use here is pedagogically motivated. It is intended to illustrate and illuminate our proof of the Superset-Basis Lemma. Ideas discussed later give rise to better algorithms for this computational problem.

Problem 7: In this problem you will again write an independence-testing procedure. Write and test a procedure `my_is_independent(L)` with the following spec:

- *input:* a list L of vectors
- *output:* `True` if the vectors form a linearly independent list.

Vectors are represented as instances of `Vec`. We have provided a module `independence` that provides a procedure `rank(L)`. You should use this procedure to write `my_is_independent(L)`. No loop or comprehension is needed. This is a very simple procedure.

Problem 8: Write and test a procedure `my_rank(L)` with the following spec:

- *input:* a list L of Vecs
- *output:* The rank of L

You can use the procedure `subset_basis(T)` from Problem 5, in which case no loop is needed. Alternatively, you can use the procedure `is_independent(L)` from the module `independence` we provide; in this case, the procedure requires a loop.

Un~~graded pro~~blem: Each of the following subproblems specifies two subspaces $\mathcal{U}$ and $\mathcal{V}$ of a vector space. For each subproblem, check whether $\mathcal{U} \cap \mathcal{V} = \{\mathbf{0}\}$.

1. Subspaces of $GF(2)^4$: let $\mathcal{U} =$ Span $\{1010, 0010\}$ and let $\mathcal{V} =$ Span $\{0101, 0001\}$.
2. Subspaces of $\mathbb{R}^3$: let $\mathcal{U} =$ Span $\{[1,2,3],[1,2,0]\}$ and let $\mathcal{V} =$ Span $\{[2,1,3],[2,1,3]\}$.
3. Subspaces of $\mathbb{R}^4$: let $\mathcal{U} =$ Span $\{[2,0,8,0],[1,1,4,0]\}$ and let $\mathcal{V} =$ Span $\{[2,1,1,1],[0,1,1,1]\}$

Problem 9: Write and test a procedure `direct_sum_decompose(U_basis, V_basis, w)` with the following spec:

- *input:* A list U_basis containing a basis for a vector space $\mathcal{U}$, a list V_basis containing a basis for a vector space $\mathcal{V}$, and a vector $\boldsymbol{w}$ that belongs to the direct sum $\mathcal{U} \oplus \mathcal{V}$
- *output:* a pair $(\boldsymbol{u}, \boldsymbol{v})$ such that $\boldsymbol{w} = \boldsymbol{u} + \boldsymbol{v}$ and $\boldsymbol{u}$ belongs to $\mathcal{U}$ and $\boldsymbol{v}$ belongs to $\mathcal{V}$.

All vectors are represented as instances of `Vec`. Your procedure should use the fact that a basis of $\mathcal{U}$ joined with a basis of $\mathcal{V}$ is a basis for $\mathcal{U} \oplus \mathcal{V}$. It should use the *solver* module or the procedure `vec2rep(veclist, u)` from `The_Basis_problems`.

Problem 10: Write and test a procedure `is_invertible(M)` with the following spec:

- *input:* an instance `M` of `Mat`
- *output:* $True$ if `M` is an invertible matrix, $False$ otherwise.

Your procedure should not use any loops or comprehensions. It can use procedures from the `matutil` module and from the `independence` module.

Problem 11: Write a procedure `find_matrix_inverse(A)` with the following spec:

- *input:* an invertible matrix A over $GF(2)$ (represented as a `Mat`)
- *output:* the inverse of A (also represented as a `Mat`)

Note that the input and output matrices are over $GF(2)$.

Your procedure should use as a subroutine the `solve` procedure of the `solver` module. Since we are using $GF(2)$, you need not worry about rounding errors. Your procedure should be based on the following result:

> Suppose A and B are square matrices such that AB is the identity matrix. Then A and B are inverses of each other.

In particular, your procedure should try to find a square matrix B such that AB is an identity matrix:

$$\begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix}\begin{bmatrix} & & \\ & B & \\ & & \end{bmatrix} = \begin{bmatrix} 1 & & \\ & \ddots & \\ & & 1 \end{bmatrix}$$

To do this, consider B and the identity matrix as consisting of columns.

$$\begin{bmatrix} & & \\ & A & \\ & & \end{bmatrix}\left[\begin{array}{c|c|c} \boldsymbol{b}_1 & \cdots & \boldsymbol{b}_n \end{array}\right] = \left[\begin{array}{c|c|c} 1 & & \\ & \cdots & \\ & & 1 \end{array}\right]$$

Using the matrix-vector definition of matrix-matrix multiplication, you can interpret this matrix-matrix equation as a collection of n matrix-vector equations: one for $\boldsymbol{b}_1$, ..., one for $\boldsymbol{b}_n$. By solving these equations, you can thus obtain the columns of B.

Remember: If A is an $R \times C$ matrix then AB must be an $R \times R$ matrix so the inverse B must be a $C \times R$ matrix.

Problem 12: You will write a procedure for finding the inverse of an upper-triangular matrix.
`find_triangular_matrix_inverse(A)`

- *input:* an instance M of `Mat` representing an upper triangular matrix with nonzero diagonal elements.

  You can assume that the row-label set and column-label set are of the form $\{0, 1, 2 \ldots, n-1\}$.

- *output:* a Mat representing the inverse of M

This procedure should use `triangular_solve` which is defined in the module `triangular`. It can also use the procedures in `matutil`, but that's all.