18.335 Midterm, Fall 2012

Problem 1: (25 points)

(a) Your friend Alyssa P. Hacker claims that the function $f(x) = \sin x$ can be computed accurately (small forward relative error) near $x = 0$, but not near $x = 2\pi$, despite the fact that the function is periodic in exact arithmetic. True or false? Why?

(b) Matlab provides a function `log1p(x)` that computes $\ln(1+x)$. What is the point of providing such a function, as opposed to just letting the user compute $\ln(1+x)$ herself? (Hint: not performance.) Outline a possible implementation of `log1p(x)` [rough pseudocode is fine].

(c) Matlab provides a function `gamma(x)` that computes the "Gamma" function $\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dt$, which is a generalization of factorials, since $\Gamma(n+1) = n!$. Matlab also provides a function `gammaln(x)` that computes $\ln[\Gamma(x)]$. What is the point of providing a separate `gammaln` function? (Hint: not performance.)

Problem 2: (5+10+10 points)

Recall that a floating-point implementation $\tilde{f}(x)$ of a function $f(x)$ (between two normed vector spaces) is said to be *backwards stable* if, for every x, there exists some $\tilde{x}$ such that $\tilde{f}(x) = f(\tilde{x})$ for $\|\tilde{x} - x\| = \|x\| O(\varepsilon_{\text{machine}})$. Consider how you would apply this definition to a function $f(x,y)$ of *two* arguments x and y. Two possibilities are:

- First: The most direct application of the original definition would be to define a single vector space on pairs $v = (x,y)$ in the obvious way $[(x_1,y_1) + (x_2,y_2) = (x_1 + x_2, y_1 + y_2)$ and $\alpha \cdot (x,y) = (\alpha x, \alpha y)]$, with some norm $\|(x,y)\|$ on pairs. Then $\tilde{f}$ is backwards stable if for every (x,y) there exist $(\tilde{x},\tilde{y})$ with $\tilde{f}(x,y) = f(\tilde{x},\tilde{y})$ and $\|(\tilde{x},\tilde{y}) - (x,y)\| = \|(x,y)\| O(\varepsilon_{\text{machine}})$.
- Second: Alternatively, we could say $\tilde{f}$ is backwards stable if for every x,y there exist $\tilde{x},\tilde{y}$ with $\tilde{f}(x,y) = f(\tilde{x},\tilde{y})$ and $\|\tilde{x} - x\| = \|x\| O(\varepsilon_{\text{machine}})$ *and* $\|\tilde{y} - y\| = \|y\| O(\varepsilon_{\text{machine}})$.

(a) Given norms $\|x\|$ and $\|y\|$ on x and y, give an example of a valid norm $\|(x,y)\|$ on the vector space of pairs (x,y).

(b) Does First $\Longrightarrow$ Second, or Second $\Longrightarrow$ First, or both, or neither? Why?

(c) In class, we proved that summation of n floating-point numbers, in some sequential order, is backwards stable. Suppose we sum $m+n$ floating point numbers $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$ by $\tilde{f}(x,y) = x_1 \oplus x_2 \oplus x_3 \oplus \cdots \oplus x_m \oplus y_1 \oplus y_2 \oplus \cdots \oplus y_n$, doing the floating-point additions ($\oplus$) sequentially from left to right. Is this backwards stable in the First sense? In the Second sense? (No complicated proof required, but give a brief justification if true and a counterexample if false.)

Problem 3: (25 points)

Say A is an $m \times m$ diagonalizable matrix with eigenvectors $x_1, x_2, \ldots, x_m$ (normalized to $\|x_k\|_2 = 1$ for convenience) and distinct-magnitude eigenvalues λ_k such that $|\lambda_1| > |\lambda_2| > \cdots > |\lambda_m|$. In class, we showed that n steps of the QR algorithm produce a matrix $A_n = Q^{(n)*} A Q^{(n)}$ where $Q^{(n)}$ is equivalent (in exact arithmetic) to QR factorizing $A^n = Q^{(n)} R^{(n)}$. This proof was general for all A. For the specific case of $A = A^*$ where the eigenvectors are orthonormal, we concluded that as $n \to \infty$ we obtain $Q^{(n)} \to$ eigenvectors $(x_1 \cdots x_m)$ and $A_n \to \Lambda = \operatorname{diag}(\lambda_1, \ldots, \lambda_m)$.

Show that if $A \neq A^*$ (so that the eigenvectors x_k are no longer in generally orthogonal), the QR algorithm approaches $A_n \to T$ and $Q^{(n)} \to Q$ where $T = Q^* A Q$ is the **Schur factorization** of A. (Hint: show that $q_k = Q^{(n)} e_k$, the k-th column of $Q^{(n)}$, is in the span $\langle x_1, x_2, \ldots, x_k \rangle$ as $n \to \infty$, by considering $v_k = A^n e_k$, the k-th column of A^n. Similar to class, think about the power method $A^n e_k$, and what Gram-Schmidt does to this.)