Real-time Data Acquisition in a Signals and Systems Course

Thad B. Welch[†], Ed Zivi[‡], Christopher Field[†], and Josette Rice[†]
[†]Electrical Engineering Department and [‡]Systems Engineering Department
U.S. Naval Academy, MD

Abstract

A sophomore or junior level course entitled *Signals and Systems* or *Linear Systems Theory* is contained within almost every electrical engineering program in the country. The United States Naval Academy offers a junior level *Signal and Systems* course that includes a significant amount of hands-on lab time. This course is taught in a 2-2-3 format. The availability of both PCs and DAQ software that allow for seamless introduction of real-world data into the MATLAB workspace has facilitated this process. This paper discusses some of the lab exercises that are used in this course. These lab experiments have allowed our students to see immediate applicability for the theory and skills that they are learning in class.

1. Introduction

A sophomore or junior level course entitled *Signals and Systems* or *Linear Systems Theory* is contained within almost every undergraduate electrical engineering (EE) program in the country. The majority of these courses are taught for three hours of academic credit. While variations routinely occur, most programs provide three hours of lecture per week. Homework, which regularly includes computer-based projects, is also assigned. In class demonstrations help to reinforce course topics, but few programs incorporate traditional lab time into their courses.

The United States Naval Academy (USNA) offers a junior level *Signal and Systems* course that includes a significant amount of hands-on lab time. This course is taught in a 2-2-3 format (two hours/week of lecture, two hours/week of lab, for three hours of academic credit. Due to the availability of both personal computers (PCs) and data acquisition (DAQ) software that allow for the seamless introduction of real-world data into the MATLAB workspace, it is now both possible and cost effective to incorporate hands-on labs into any course of this type.

2. Combining MATLAB with a *Signals and Systems* curriculum

A *Signals and Systems* course has traditionally consisted of a study of the mathematical tools and relationships necessary to relate the time and the transform domains. Stored real-world signals, computer-generated signals, and mathematical models of real signals and systems are available for computer-based homework and exercises. The use of PCs in the EE curriculum has clearly increased student interest in the *Signals and Systems* course material, in part because PCs have helped to move us beyond pure theory and into the real world. For example, homework or PC-based exercises can now use web delivered EKG data, music corrupted by noise, or sonar signals containing multipath returns.

All of the lab exercises that we have added to this course are possible with existing test equipment, however, this equipment is very expensive. Function generators, storage oscilloscopes that have fast Fourier transform (FFT) capabilities, audio spectrum analyzers, and network analyzers are all wonderful tools. However, to populate a lab with 8 to 10 student stations with this equipment could easily cost well over $100,000.00! Each school must decide what they can afford and the appropriate mix of hardware and software labs that are necessary to meet their program outcomes and goals.

When version 5.3 (release 11) of MATLAB and the beta version of the data acquisition (DAQ) toolbox were released in mid-1999 it became possible to add real-world data gathering and real-time data analysis labs to what had traditionally been a very theoretical course, at a very reasonable price. Version 5.3.1 (release 11.1) of MATLAB also released version 1.0 of the data acquisition (DAQ) toolbox in November of 1999 and further refined this software.

3. DAQ enabled exercises

A few examples of DAQ enabled exercises include: the relationships between the time and frequency domains with spectral estimation of voice and music signals, hardware system characterization in the time domain, and hardware system characterization in the frequency domain.

3.1 The relationships between the time and frequency domains

This exercise uses MATLAB in conjunction with the PC's sound card to create a real-time spectrum analyzer display. A traditional magnitude/amplitude versus frequency plot, averaged magnitude/amplitude versus frequency plot, and a waterfalling spectrogram are provided. Using this program, our students analyze the frequency content of a voice signal from a microphone and music from student provided CDs. Thus, the concept of harmonics is easily demonstrated and the graphics display can be stopped and saved to disk at anytime. Figure 1 provides an example of this program's display. This program can also be used to confirm the magnitude of the Fourier series coefficients associated with a periodic waveform. Since variable gains exist within the Windows system for sound card playback and record levels, care must be taken to calibrate the system prior to use. To perform this calibration, a function generator should be used to drive the sound card's line input with known signals.

3.2 Hardware system characterization in the time domain

This exercise deals with determining the impulse response of a system, then calculating the frequency response of this system numerically. The impulse response of a system, as its name implies, is the output of a system when an impulse is applied to the input. The Fourier transform of the impulse response, is numerically computed using MATLAB's fast Fourier transform providing the system frequency response. Unfortunately, perfect impulses are impossible to generate and therefore, must be approximated.

In this lab the impulse response of a small audio speaker is determined. The basic idea is to mechanically excite the speaker cone and measure the resulting voice coil voltage. MATLAB, in conjunction with the PC's sound card, provides all required DAQ, numerical analysis, and display capabilities. Since an ideal mechanical excitation impulse cannot be generated, we approximated an impulse with a small object dropped on a quiescent speaker cone. Figure 2 shows the speaker's response to a pen drop while Figure 3 shows the speaker's response to a pen's cap. From Figure 2 and 3 it is clear that the system does not interact with the dropped object in an instantaneous fashion. For Figure 2, the pen stays in contact with the speaker cone for approximately 13 milliseconds (ms). For Figure 3, the pen cap stays in contact with the speaker cone for approximately 3 milliseconds (ms). During this contact time, the system is composed of both the speaker and the pen. The speaker's free response begins only after the pen or pen cap separates from the speaker cone. If the system's response is measured *after* contact with the dropped object has ended, the initial combined transient can be removed *prior* to taking the numeric Fourier transform of the impulse response. In this case, the actual excitation is replaced by a nonzero initial condition that can be approximated by an impulse. Figure 4 shows the result of this process with, an overlay of actual acoustic frequency response.

Inspection of Figure 4 indicates that removing the initial combined response provides accurate low frequency response characteristics. The initial resonant peak near 400 hertz is associated with the speaker's natural frequency, a dominant pole pair. Although, the system's response below this resonant peak is reasonably accurately modeled, the higher frequency response of both sides of the second resonant peak in not accurately modeled. Once again, the tools developed in the *Signals and Systems* course can be used to understand the divergence between ideal and real world measurements.

Due to the time domain truncation of data, the frequency response is attenuated at high frequencies. Essentially, the impulse approximation has been low pass filtered during the combined speaker/pen transient. We have now used the concepts and tools developed in the *Signals and Systems* course refine the data and understand fundamental limitations. Further attempts to mechanically excite the system resulted in very little improvement in the accuracy of the higher frequency response estimation. Therefore, an acoustic impulse was generated by striking our hands together in a single clap. Figure 5 shows the result of this process with an overlay of the actual acoustic frequency response.

An electrical equivalent to the procedure described above would be to excite an RC lowpass filter with an electrical impulse. This, however, cannot be done. Systems theory would suggest we measure the step response of the filter and then take the derivative of the output. This exercise was done as a hardware demonstration for the class.

3.3 Hardware system characterization in the frequency domain

An alternative frequency response measurement procedure would be to excite the RC lowpass filter with white noise or a frequency modulated (FM) slide. The filter's input and output would then be simultaneously sampled and the complex transfer extracted using a cross-spectrum and input power spectrum measurement. This can be accomplished using the MATLAB `tfe` command.

The DAQ toolbox can use the PC's sound card to simultaneously sample the filter's input and output, and generate the noise or FM slide signal. Figure 6 shows the simultaneously sampled filter input and output. Figure 7 shows the measured magnitude and phase response for an RC lowpass filter with a cutoff frequency of 10,000 rad/sec. The difference between the measured frequency response and the expected response is due to the loading effects that the PC's sound card has on the lowpass filter.

4. Conclusions

These and other lab exercises or demonstrations have allowed our students to see immediate relevance for the theory and skills that they are learning in class. Since most of the necessary equipment is already available to our students, we have found that many students continue their experimentation outside of the traditional lab setting. This has led to both a greater interest in, and better understanding of, the course material.

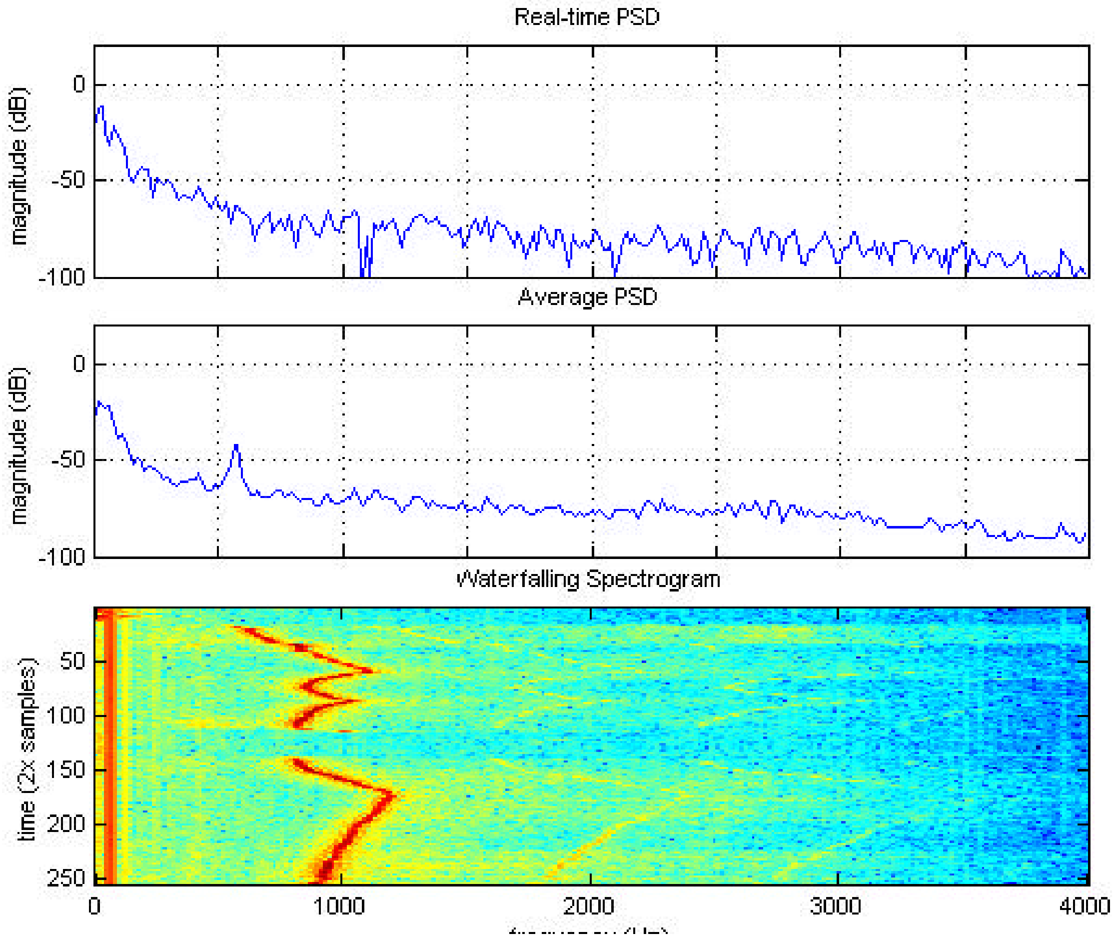

Figure 1. A real-time spectrum analyzer display.

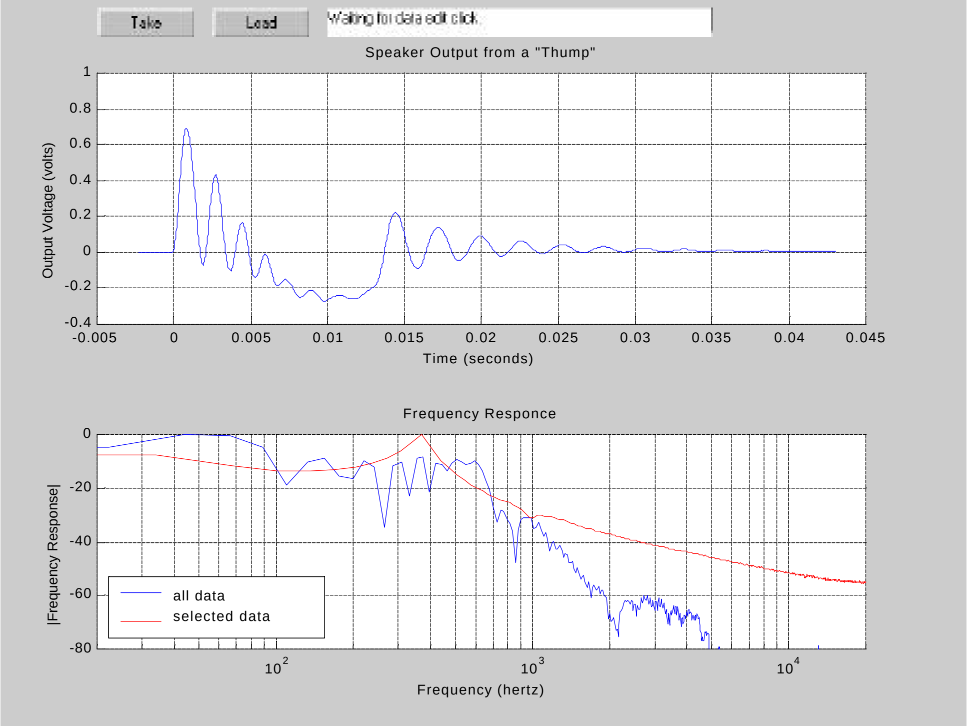
Waiting for data edit click

Figure 2. The speaker’s response to a dropped pen.

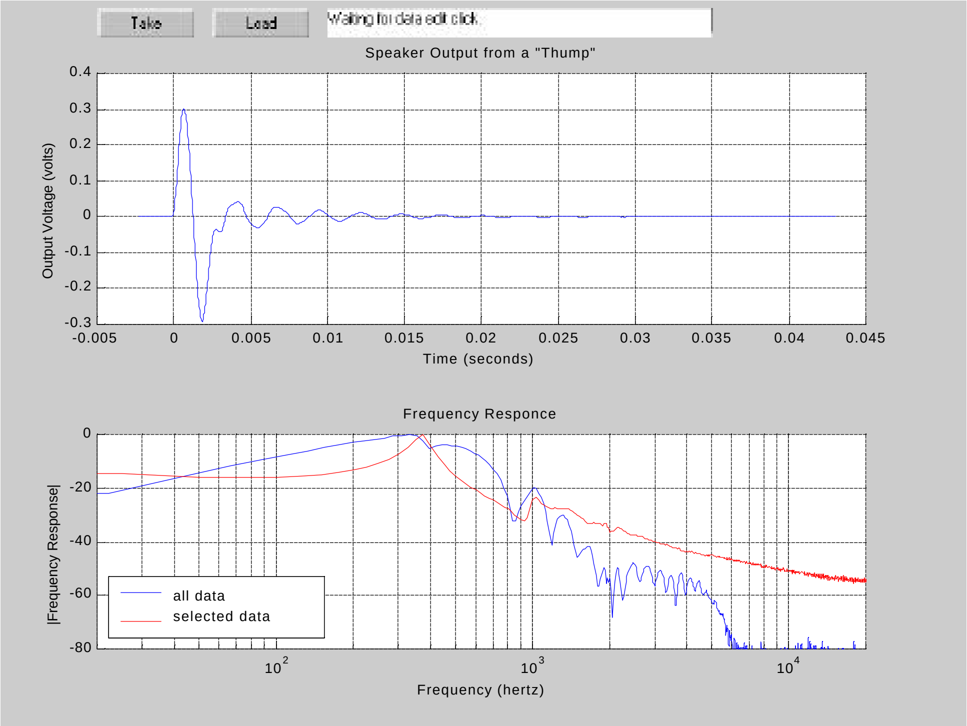
Waiting for data edit click

Figure 3. The speaker’s response to a dropped pen cap.

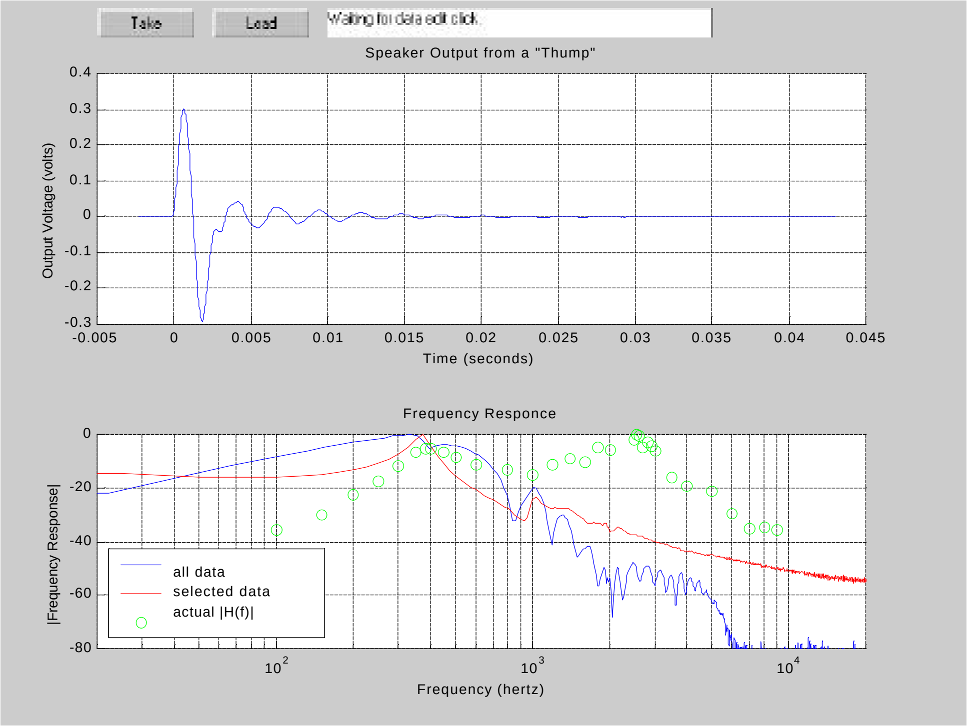

Figure 4. The speaker’s response to a dropped pen cap. The actual frequency response is also plotted.

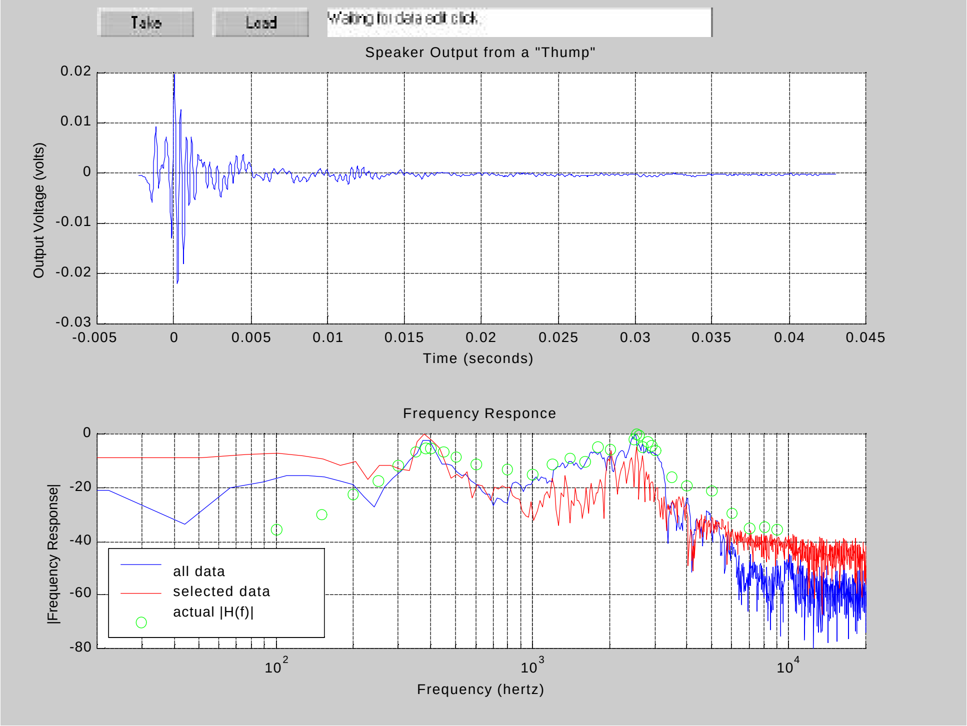

Figure 5. The speaker's response to a "hand clap". The actual frequency response is also plotted.

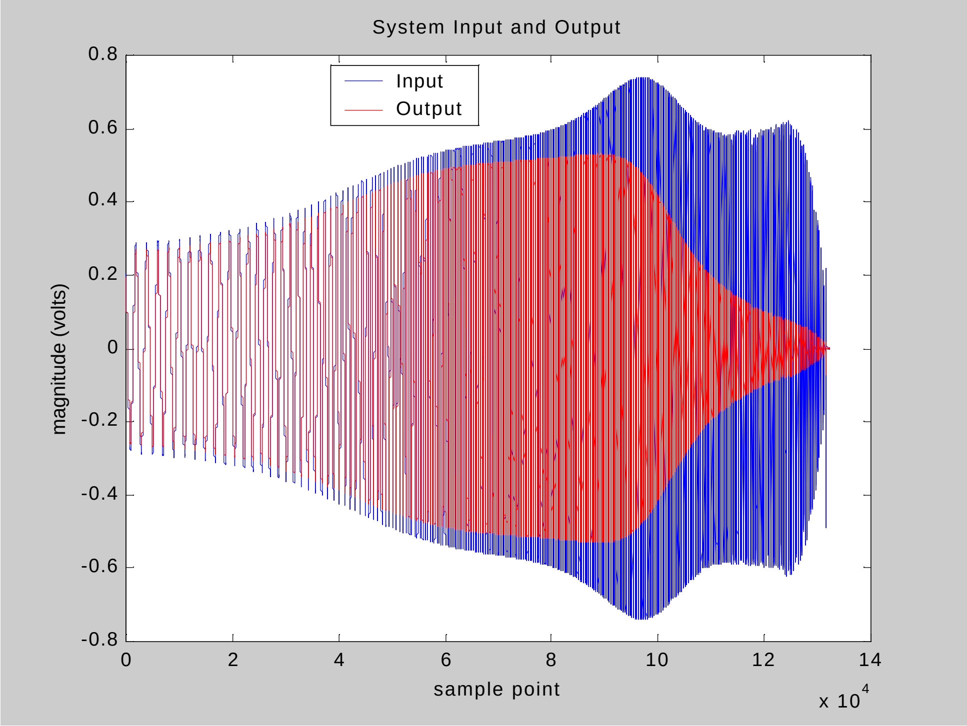

Figure 6. The lowpass filter's input and output voltages.

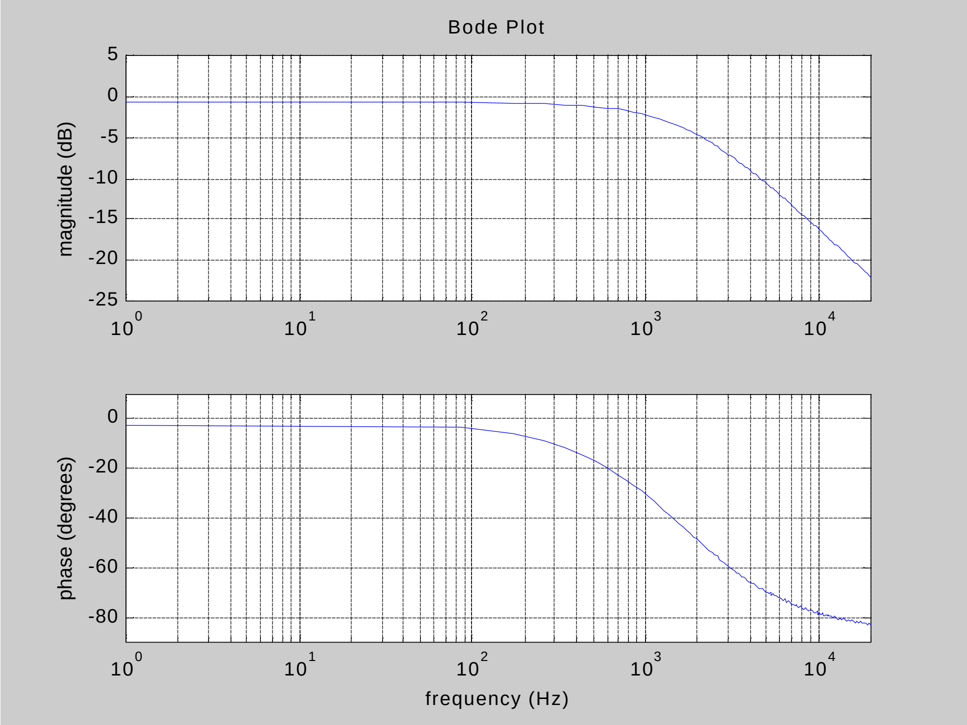

Figure 7. The calculated frequency response for the lowpass filter.