Objective
The objective of this 'experiment' is to provide a modest design exercise. Design is an art which involves making considered, reasoned choices to realize a specified objective. Merely substituting numbers in formulas while following an algorithmic procedure is a calculation, not a design. There really is no single formal design procedure universally applicable. What is obscure to one designer may be obvious to another, and yet both can produce good designs given the same specifications. Certainly there are some general guidelines which common sense and experience recommends as 'good practice'. Not infrequently uniform 'standard practice' guidelines are defined, particularly for large-scale projects, to help maintain a minimum consistency in communication between subsystem design groups.

Nevertheless, ultimately, 'design' requires choosing between alternatives on the basis of criteria which themselves often are the result of choices. Design is a skill which, presuming a thorough understanding of the technical matters involved, is developed best by exercise. The notes following the design specification provide a semi-quantitative illustrative outline of a design procedure. You should evaluate these remarks critically, and modify or even discard them to suit your own design philosophy. However whatever your own design philosophy turns out to be you should be prepared to explain every detail of your design, with particular emphasis on what choices you made. You should know where you had to make a choice, what the various options that you chose from among were, and why you made the particular choice that you did. It is not adequate simply to say you tried it and it worked. That generally means you didn't understand what you were doing but you were lucky. From these remarks it should be clear that the report describing and explaining your design is the primary 'product' for this experiment. It is possible to have a good report on a design which didn't meet specifications; it is not acceptable to substitute a design that met specifications for a good report. In this respect keep in mind that report must communicate its content. If some important information is in the report physically but not reasonably able to be found it is effectively not in the report. Direct your report toward a reader who is technically knowledgeable but not necessarily knowledgeable of the particular subject of the design; do not offend this reader by telling him/her, for example, that 2x3=6 or explaining Ohm's Law. Skip the padding and boilerplate in favor of meaningful content.

For this experiment you shall design a simplified discrete BJT amplifier. Quite likely you could meet the specifications using an off-the-shelf amplifier, e.g., a 741, more economically, and more reliably than does your design. However the focus of the experiment is on the design process not the amplifier; the amplifier is merely the vehicle for the process.

Prepare the design before the start of the laboratory period in which it will be assembled, including a clear circuit diagram and a computer analysis of circuit performance of the final design. Experimental 'tweaking' of a design to fine-tune performance is one thing. Replacing components 'by guess and by golly' until the circuit 'works' is quite another. The essential difference between the two methods is whether you know what you are doing or you do not. (Incidentally fine-tuning a design should be done first with a computer simulation; it is a lot easier and quicker. Device models used by current analysis programs represent real devices remarkably well.)
Amplifier Project Specifications
Design a discrete BJT amplifier to the following specifications:

a) $V_{cc} = 15$ Volts.

b) DC coupling between stages, and AC coupling to a $470 \Omega$ load resistor.

c) Capacitor bypassing may be used, but is not required.

d) The signal source is provided by the laboratory function generator with additional circuitry as shown. Note that $56 \Omega$ is a nominal 0.56% of a ±5% 10 kΩ resistor. As far as your amplifier design is concerned the source is essentially the circuit on the right.

![Experimental Signal source](image)

Fig. 28.1 Experimental Signal source

e) The amplifier 'midband' voltage gain shall be be 30 db ± 1 db. The 30 db specification is a nominal value, i.e., 29-31 db or so is acceptable. However the ±1 db variation allowed applies to the nominal gain. ( ± 1 db ≈ ±12%, a rather loose requirement).

f) The amplifier shall provide a 7 volts peak-to-peak undistorted sinusoidal signal across the $470 \Omega$ load.

g) The report shall include a well-written description of the design, showing calculations and computations clearly, together with the reasons for making such design choices as are made. A comparison of calculated and computed design values and goals (bias voltages and currents, voltage gain, Monte Carlo statistical analysis, etc.) shall be included in the report. As a general criterion to evaluate appropriate report content assume the report will be read a year from now by a student in this course who is charged with explaining what you did to his/her classmates; consider what you would want in the report if you were that student.

Notes

Note on Notes: The following remarks are meant to be illustrative; numerical estimates and illustrations in these notes are used in your design at your peril.

1) Where best to begin a design always is a good question; the appropriate answer generally is 'It depends'. One of the subjective considerations it depends on is who is doing the designing. But if you can't decide on the absolute 'best' place to begin start with the best place you can think of. Or just start anywhere, but just start. It is not at all unlikely that what you do first may turn out to lead into a dead end; then start again, this time using whatever insight was provided by the earlier work. At least avoid the same dead end. Almost inevitably you will find generally quickly a workable starting point from which you can begin to develop your design. It is not too likely that you will produce a workable design on a first try. This is not at all unusual. Simply evaluate what you did and use that evaluation to decide on your next move.

2) Since this is likely to be more or less the first design exercise for most students you might start with a broad consideration, say ruminations over some idealized amplifier configurations. The figure below shows idealized opamp amplifier configurations for inverting and non-inverting amplifiers respectively. Estimates for RF and RE can be based on the voltage-gain specification.

![Illustrative idealized amplifier configurations](image)

Fig. 28.2 Illustrative idealized amplifier configurations
The amplifier you design to take the place of the opamp will be less than ideal of course. Estimates of the effect of such departures from idealization as finite input resistance and gain can be made as described in the lectures and in the opamp laboratory experiment notes. Note that the opamp gain (and the gain of your replacement) almost certainly will have a large gain tolerance. You will have to estimate the minimum gain needed to provide the specified stability when the feedback resistors are added. That stability requirement has to be built into the design, not left to chance.

For this assignment either an inverting or a non-inverting configuration can be used since this is not defined by the specifications. This should not be regarded as a license to make a random choice. Rather try to choose one or the other to provide some advantage in realizing the design. For example the inverting circuit 'converts' the source voltage to a current using the low input resistance provided by the virtual ground at the inverting input; that current is used to provide the output voltage. The non-inverting configuration, on the other hand, uses the high input resistance of the amplifier to force the voltage at the inverting input to be (nearly) equal to the source voltage. This is reflected in the dependance of the voltage gain on the source resistance, directly in the one case and less so in the other. Should the amplifier design depend on the source resistance? What happens if the source is changed? These considerations are crucial to the design because the source description does not allow for variations. Nevertheless you should adopt the attitude that the freedom to make a choice is an opportunity to take a design advantage.

3) There is now (assuming the suggested estimates or their equivalents have been completed) a fair amount of design information available, enough to mount a trial design. A basic configuration has been selected (say either the inverting or noninverting configuration drawn before, although there are others that can be considered), estimates of RF and/or RE can be made on the basis of an idealized opamp configuration (perhaps adding some allowance for a nonidealized amplifier), and an estimate of a trial gain specification for the opamp can be made to meet the stability specification.

4) Now select an 'opamp' gain stage configuration. A straightforward CE amplifier stage configuration is drawn to the right. Note that the emitter resistor is bypassed to increase the incremental gain while still retaining the DC emitter current stabilization effect. Most likely more than one stage will be necessary. However cascading two (or more) stages with DC coupling required presents some difficulties, e.g., the DC base bias voltage required (and so the collector voltage) increases from stage to stage.

To compensate for this increase a complementary-pair amplifier stage might be used; a representative configuration is illustrated to the left. Note that the illustration includes some incremental emitter feedback to stabilize the voltage gain for each stage, i.e., the DC emitter current stabilization resistors are not completely bypassed.
Illustrative DC coupled amplifiers (but with the specified AC coupled load not yet included) are drawn below. The amplifier circuit on the left side is a two-stage CE cascade, connected as a non-inverting amplifier. As noted before there may be problems in realizing the specified voltage gain with this configuration. A complementary-pair modification which adds an additional amplification stage is drawn on the right side of the figure. Note that the 'opamp' feedback is from a noninverting output (T3 emitter) while the output voltage output is taken from an inverting output (collector of T3).

5) Estimate the gain of a single stage as a prelude to estimating the number of stages needed.

For example from a simplified model of the CE stage estimate (roughly) the voltage gain across the stage as $\approx -(\beta/r_{be})RC = -(q_{e}/kT)(ICRC)$. This ignores the effect of the biasing resistors, but presumably these would be designed to have small effect. Use $q_{e}/kT \approx 40$ at room temperature, and (biasing for a max symmetrical collector voltage swing)

$$ICRC \approx \frac{VCC}{2} = 7.5$$

(VCC = 15 volts specified). An optimistic stage gain estimate then is (roughly) -300. Allowing for input transfer losses perhaps a gain of -200 would be better. Of course since this gain is proportional to $\beta$ it has a 2:1 or so variation because of manufacturing tolerances and allowance for temperature changes. Perhaps, to be conservative, one might use an estimate of, say, -150.

The preceding estimate assumes the emitter current stabilizing resistor is bypassed. On the other hand if $RE$ were not bypassed the stage gain estimate becomes approximately $-RC/RE$. This gain is much better defined since it depends only on the resistance ratio. On the other hand the gain is more likely to be -5 or -10 rather than -200.

Remember as you estimate the number of stages needed that while the specification calls for a net gain of $30 \pm 1$ db (31.6 ± 12%), you will need an amplifier 'without feedback' with significantly more gain to meet the stability specification. Your report should include your estimates of how much more gain is needed.

6) The specifications call for 7 volts p-p across a 470 $\Omega$ load; this corresponds to a load signal current of $7/47 \approx 15$ ma p-p. Care has to be taken to set Q points properly or the amplifier will saturate or cut-off (or it will come close enough to one or the other of these extremes for significant distortion to occur). Consider the circuit fragment drawn to the right. Signal current is to flow through the 470 $\Omega$ to produce the 7 volt p-p voltage required. But this means an additional emitter (p-p) signal current of $7/RE$ is needed since the load voltage also appears across RE. The DC emitter current must

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allow for the combined signal currents. Since the DC current must be greater than 7.5 ma to support just the load signal current, RE necessarily will be smaller than \( \frac{15}{7.5} = 2 \) k\(\Omega\). Hence the additional DC current needed because of the incremental current flow through RE will be significant and must be taken into account. Some trial-and-error estimating is likely to be needed to resolve this consideration.

Incidentally the stage 'driving' the transistor above must supply the 7 volt p-p AC signal to the base; this has some implications for the biasing of the preceding stage. The point here is that there is an interaction between the parts of the amplifier; you won't be able to isolate the design for each stage entirely. Some trial and error is certain.

7) Clearly the design process is an iterative one; the cycle of making a trial choice (not a random guess) of a parameter value whose computed consequences then guide a revised choice is repeated until the process converges on an acceptable design (or possibly on the realization that the design specifications can't be achieved). And, of course, as experience develops so does skill and judgement in making the initial trial choices and reducing the number of iterations needed.

The two circuits below illustrate one kind of revision that might be made. The circuit on the left is a two-stage CE-CC amplifier whose gain falls short of what is desired. To adjust for this the circuit on the right adds a CC input stage to pick up transconductance gain (note that a reconsideration of biasing requirements is necessary).

8) Once preliminary estimates are completed, indeed to some extent even in the course of making estimates, a computer analysis provides at least a convenient preliminary to experimental prototyping; use computer simulation to test your design and to make final computational adjustments. You have selected some critical resistor value to be 3.3 k\(\Omega\). Compute the amplifier performance using this resistance value. Recompute with, say 2.7 k\(\Omega\) and 3.9 k\(\Omega\) to test just how critical the choice is. Run a Monte Carlo analysis with tolerances added for critical circuit elements. (Tolerances already included in the 2N3904 BJT model).

The design specification is not difficult to meet but it is more likely to be met through understanding and informed choice than by extensive trial and error.

9) After an experimental prototype is assembled check operation step by step rather than jumping directly to a gain test. If the DC bias voltages are not what they should be it is not likely the circuit
will amplify, and even if it did there would be the problem in explaining why it does. If the gain is not reasonably close to what you expected check the signal transfer across each stage. The idea is to isolate the problem to identify its cause (or one of its causes), and then fix that before going on. What sometimes appears to be an almost psychic identification and location of a problem by a skilled technician often turns out to be the result of a process of elimination based on observed circuit behavior and an understanding of the technical issues involved.

Addendum
Just for emphasis. The technical design is of course an important matter. No less important is the report describing the design and testing. Providing clear circuit diagrams and explicit element values goes without saying, but it is not enough. Comparisons between calculated, computed, and measured values are necessary but also not enough. A clear explanation of the design choices, what they are and why they are made is also very important.