[[1]](#footnote-1)

A Multi-Threaded Neural Networks Template Library with Back-Propagation Algorithms

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*Abstract*—This report is related to a newly developed neural network programming library (BeefNet), which take the advantage of multi-thread in multicore machine and the comparison among different learning algorithms. In past three decades, learning algorithms for neural network have been evolving to be more accurate in searching for local minima between error function versus weight following gradient descent rules. On the other side, parallel computing is getting mature with state-of-the-arts distributed architectures such as Cloud Computing, Map-Reduce, etc. This brings an opportunity to reduce time consumption for learning algorithms. BeefNet library takes the advantage of generic programming in choosing various network configurations and makes it flexible in being transplanted among different operating systems or architectures.

*Index Terms*—Algorithm, Back-Propagation, Neural Network, Parallel Computing, Generic Programming

# Introduction

A

rtificial neural networks are widely used in research and application over past three decades. The network topology and propagation algorithms are evolving in order to adapt with different application scenarios. Researchers usually spend much time struggling on preparing network architectures and waiting for training results. Huge numbers of other aspects, for example, over-fitting, network size, memory space need to be considered across the whole training procedure. This may shifts researchers from their original topics to too much network reliability considerations.

Benefited from generic programming, researchers can easily configure their own neural networks or try among different configurations through a design pattern, as known as the strategy pattern, which makes everything instantiable modules. This library currently provides 4 types of networks, which are 1, 2, 3-hidden layer networks and recurrent network, 4 types of weight update algorithms, classic back-propagation (BP), quick propagation (QP), resilient propagation (RP) and Levenberg-Marquardt algorithms (LM). Besides these build-in learning models, researchers can connect or prune perceptrons (using neuron instead of perceptron in rest of the article for convenience) and weights to customize any type of network topology.

With the increase number of cores or processors, appropriate parallelization and data partition can maximum training speed. The BeefNet library provides the interface for fast local file access using memory map and a potential interface for Map-Reduce application. All of these operations and inner data flows during training are implemented on stack memory to avoid wasting time on dynamic allocation and access. The only restriction of network size depends on the stack pre-allocation of compiler, which normally can be adjusted by compilers.

# Propagation Algorithms

Back-Propagation is the most popular algorithm for supervised learning not only applied in multi-layered feed-forward networks but also in recurrent networks. Most of the neural networks have a unique forward path.

where is the outputs from the neuron in previous layer, which is regarded as the inputs of neuron , is the weight from all previous neuron to neuron , is calculated as the weighted sum of all the inputs, and is the output after filtered by the transfer function , which is also regarded as one of the input of next layer.

The backward path follows gradient descent calculated by chain rule.

If error function is chosen as the mean squared error in batch training mode,

where contributes to each input training pattern, represents the total number of training pattern, is target, and is predicted output (same as the output of last layer). The gradient can be calculated as follows.

For any hidden neuron, its gradient is affected by all of its successors. To consistently express the gradient of output nodes and hidden nodes, let

where contributes to next layer.

## Classic Back-Propagation (BP)

By selecting appropriate learning rate , the update equation of neuron from epoch to can be obtained. (neuron index and will be omitted in following equations except specified.)

In this weight update rule, learning rate is a fixed value, which scales weight update steps [ref\_rp]. If it’s too small, more epochs need to be taken to reach local minima, if it’s too large, the error could oscillate or even diverge.

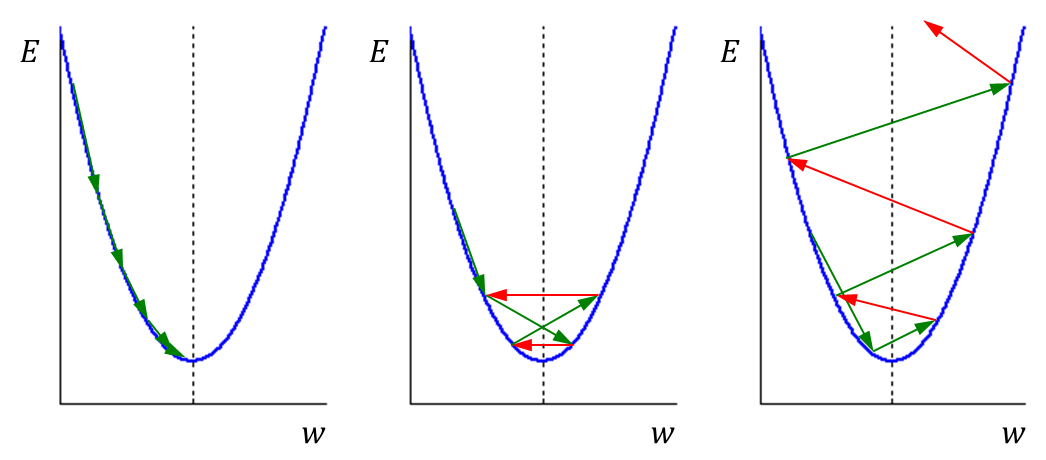


Fig. . Possible weight update trends, includes convergence (left), oscillation (middle) and divergence (right). The solid curve represents error vs. weight, local minimum is at the intersection between the solid curve and the dash line, red arrows represent weight update with positive gradient, and green arrows represent weight update with negative gradient.

To avoid complicate choices among learning rates, some local adaptive learning algorithms have been developed.

## Quick Propagation (QP)

The target of quick-propagation is to take the largest steps possible to local minima without overshooting [ref\_qp]. The basic idea is to directly jump to a local minimum closely enough. Risky assumption is made as the error versus weight curve for each weight can be approximated by a parabola whose arms open upward [ref\_qp], which means its second derivative is approximate a line with positive slope . For a parabola curve, the minimum value is where its second derivative equals to .

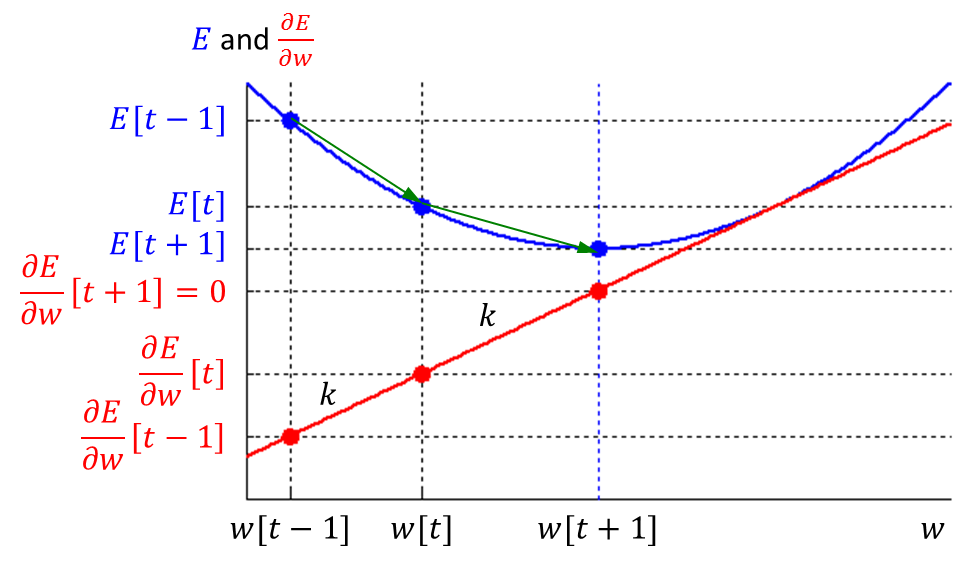


Fig. . Gradient (blue solid parabola) and its first derivative (red solid line). Minimum error is reached at which the first derivative equals to zero.

Considering the slope equation of both previous weight update and current weight update, it is a second-order method [ref\_qp].

According to above equation, if is approximate the same as , will reach an infinite value, which leads to an infinite step or towards a local maximum. To restrain weight change, a maximum growth factor is defined in order that no weight step is allowed to be greater in magnitude than times the previous step. A fit-to-all value of is [ref\_qp].

## Resilient Propagation (RP)

The basic idea of resilient propagation is that every time the gradient changes its sign, which indicates the last update was so big that jumped over a local minimum. Thus, the weight update absolute value needs to be reduced by factor , where . Contrarily, if the gradient remains the same sign as previous, a larger step of can be increased by factor , where . The algorithm can be implemented in following approach [ref\_rp].

for all weights of neurons and bias

{

if

{

}

else if

{

}

else

{

}

store current state variables to next epoch

}

Intuitively, the algorithm makes it confident for the weights updated to reach local minima.

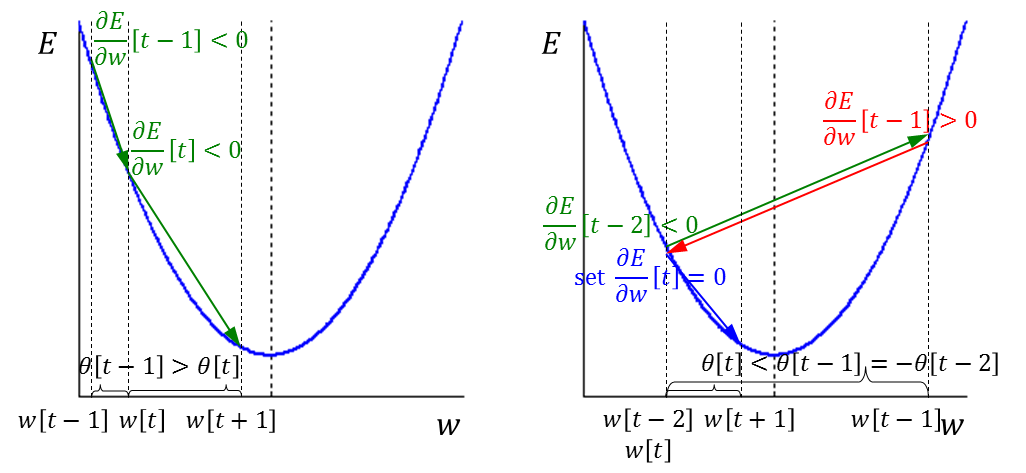


Fig. . When gradient doesn’t change its sign (left), weight takes a larger step by a ratio to update. When gradient changes its sign (right), weight doesn’t update at this epoch but will take a smaller step by a ratio to update at next epoch.

Concluded after some experiments [ref\_rp], slight variation of or will neither improve nor deteriorate convergence time. These two factors are fixed to and . As a similar consequence, the initial value of all is set to .

## Levenberg-Marquardt Algorithm (LM)

Mathematically, Levenberg-Marquardt algorithm aims at solving out non-linear least square problem. It is much more efficient than other techniques applied to a neural network no more than hundreds of weights, even if the computation requirements are higher than other algorithms within iterations [ref\_lm].

Theoretically, if a weight is updated by a very small value, the network function can be approximately described as following.

The purpose is to minimize the mean squared error after weight updated, thus, error function is defined as,

Chain rule applied to the calculation of ,

Levenberg and Marquardt’s contribution is to modified above equation in order to make a larger movement along the direction where gradient is smaller.

where is a changeable damping parameter. will increase if squared error increases, will decrease if squared error reduced, that is,

A good try for initial value of could be and the factor could be .

# Parallelization

According to Moore’s law, the density of circuits doubling every generation [ref\_mr]. With the increase number of processing cores on a fixed size chip and fixed frequency, if the algorithm can be parallelized, its processing speed can be theoretically doubled. As an application, neural networks running on multithreaded and multicore CPUs with shared memory is the architecture of obtaining significant increases in CPU performance, especially for very large training datasets [ref\_parallel]. The most common approach of parallelization is applied while training in batch mode, that is assigning a part of training dataset to each thread and train them simultaneously [ref\_parallel]. Weight will be updated after all threads finish.

Reference to Map-Reduce architecture, the assigning procedure can be regarded as a map operation. To ensure consistent functionality among different mappers (copy of images), which requires the forward path of these parallel images should output same result whichever a single input pattern fed in, all weights in training network need to be copied to network images during map operation.

On the other bank, a reducer sums up all weight changes after gradient descent (backward path) in each network images.

Finally, weights will be updated in training network by choosing an appropriate algorithm. The whole procedure will be recursively conducted until satisfying user defined stop criteria exerted on the training network.

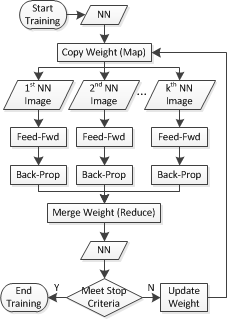


Fig. . Multi-Thread training procedure is a modification of traditional batch mode training. Weights will copy to several network images. Each image will feed-forward its training patterns and back-propagate gradients. Gradients of different network images will then merged together to be updated. The whole runs in a loop until stop criteria is met.

# Library Implementation

On the software development perspective, a neuron network layer can be regarded as a constraint, a virtual unit. It only specifies the propagation order of neurons in a global view. There’s no layer instance in this library, thus it is described as virtual. Neurons within a virtual layer can be operated in any order, whereas, neurons grouped by different virtual layers should be operated following specified order.

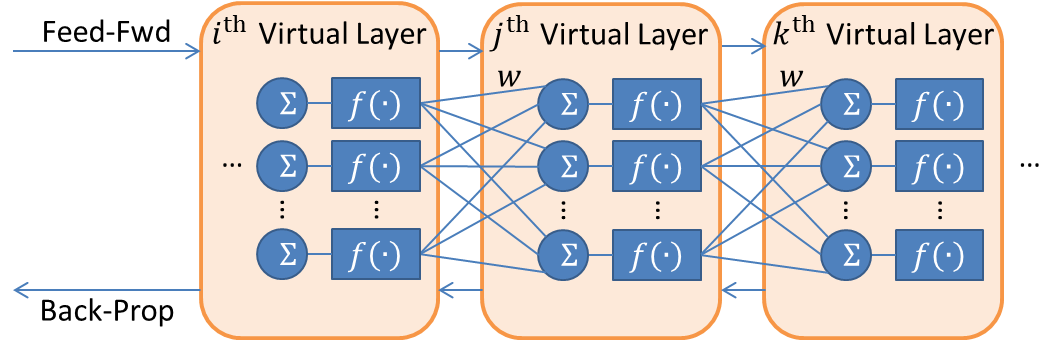


Fig. . Neurons are grouped by three virtual layers. Input patterns will be fed-forward with the order of th, th then th layer regardless of the order inside each of them. Gradients will be back-propagated with the order of th, th then th layer regardless of the order inside each of them. Weights can be updated regardless of any restriction.

## Abstraction

Abstraction is a very critical and powerful concept in object-oriented programming which means to abstract as much objects, whose has similar functions as possible. According to this motivation, weight can also be considered as similar as neuron which has only one input axon and one output axon, i.e., the input axon of a weight connects the output axon of previous neuron, and the output axon of a weight is connected by the input axon of next neuron. The transfer function of a weight is defined as follows.

As the same reason, an input feature to a neural network can also be treated similar as a neuron, whose has equal number of output axons to the first hidden layer but no input axon. What’s more, bias of a virtual layer can also be handled in this way.

Contrarily, an output feature can have one input axon connected to the output of a neural network but no output axon.

where is the target value of this output feature.

To sum up above abstraction, input, bias, weight, neuron and target will be aliased as node in following context. The connection among nodes therefore can be equivalently looked upon while programming.

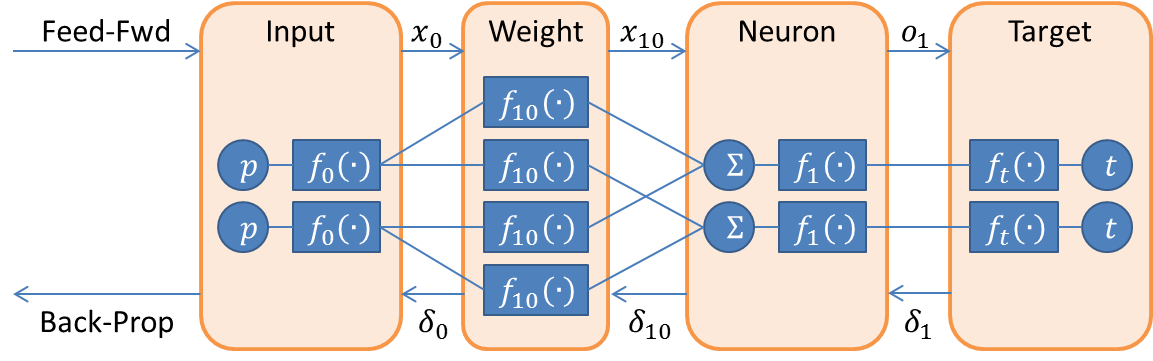


Fig. . Topology among nodes will helps further gets rid of the concept of layer, so as to simplify programming considerations.

Current input and output of a node will be stored for each input pattern in order to provide any convenience in processing weight update algorithm. Value is prepared for intermediate calculated variable, for example, or .

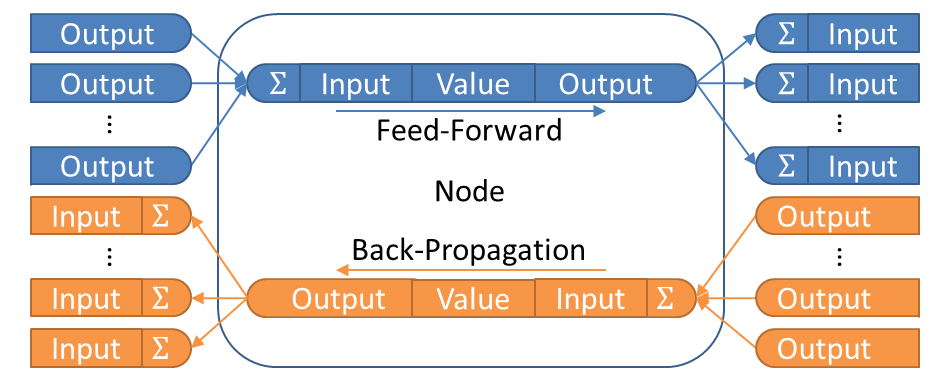


Fig. . A microscopic view of node, it connects to others’ outputs and inputs in above way.

## Generalization

Generic programming is one of the best implementation approaches to generalize any type of replaceable functional unit in neural networks, in which architecture is written in terms of types to-be-specified-later [ref\_wiki] that are then instantiated when needed for specific types provided as parameters. Thanks to template mechanism in C++, it is a good candidate for coping with combinatorial behaviors, which corresponding to algorithms, neuron numbers, and error functions here, because behaviors can be deduced statically during compiling period [ref\_book]. This technique avoids extra time consumption during each loop to determine the running type of an object through looking up its virtual table. For example, weight will provide forward, backward, update, map and reduce interfaces. User can easily specify an appropriate update strategy of weight during coding without modifying rest part of the code. The compiler will compile a made-to-order target file related to customized weight.

In terms of design pattern, this generalization approach is as known as policy based class design [ref\_book]. In the library implementation, each update algorithm is defined as a kind of update policy, each error function is defined as a kind of error policy, even the number of neurons, input, target can also be considered as policies.

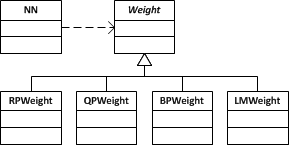


Fig. . Generalization UML example of weight component in a neural network class, RPWeight, QPWeight, BPWeight, LMWeight are different behaviors (algorithms) which could be replaced before compiling period.

# Experiment Result and Performance

Briefly sum up previous techniques, this library implements three back-propagation algorithms, parallelization, abstraction and generalization. In order to evaluate the performance of such techniques, several experiments have been conducted by controlling variables. All following experiments are running on a 2.3GHz quad-core 8-thread CPU with 8G RAM machine installing 64-bit operating system.

## Multi-Thread Efficiency

Theoretically, multiple processors and cores can simulate almost any number of threads running simultaneously regardless of very large system specified limit. However, the communication between threads is usually implemented by a pooling approach. As a result, it will consume certain amount of time to synchronize all the image threads to main network thread. Intuitively, the most efficient number of threads should be equal to the number of cores, since running time of multi-threads on the same core will add up to no less than the running time of single thread even though any kind of thread scheduling applied.

Here is the experiment result using the same network configuration and same amount of data but different numbers of threads doubled from as .

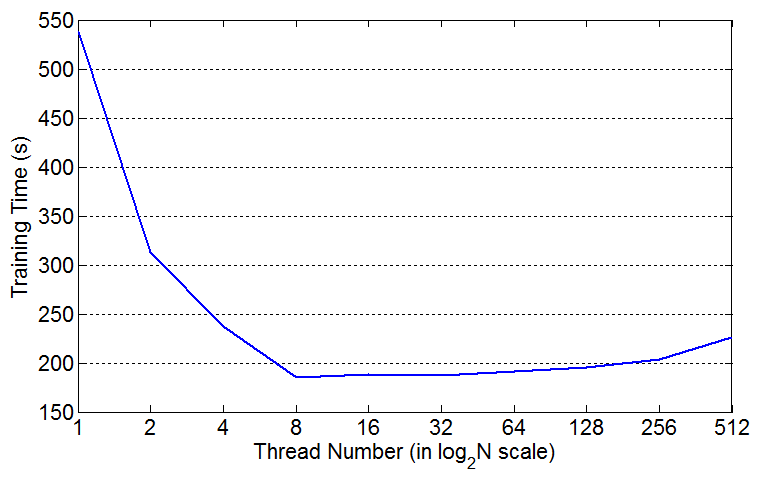


Fig. . The curve shows training time versus different numbers of threads. Training data include 88000 patterns. 2000 epochs are taken at each training task and 10 measurements have been taken and the average time consumption is plotted.

TABLE   
Neural Network Configuration  
for Multi-Thread Efficiency Experiment

|  |  |
| --- | --- |
| Parameter | Configuration |
| input node number | 8 |
| hidden layer number | 2 |
| hidden node number | 10 |
| hidden layer transfer function | log-sigmoid |
| output node number | 1 |
| output layer transfer function | linear |
| back-propagation algorithm | BP |
| stop early | no |

The result demonstrates that the fastest thread configuration number is at 8, which equals to the thread number of CPU in this case. It is approximately 3 times faster than training with single thread but not able to reach an ideal 8 times because of communication problem mentioned before. With the increase number of threads more than 8, training time slightly goes up because of scheduling problem mentioned before.

## Algorithms Efficiency

Converge epochs and converge error, as known as the error at converge epoch are two measurements of efficiency among different back-propagation algorithms. All algorithms participate in the comparison experiment here.

## Algorithms Time Efficiency

# Conclusion

References

# Guidelines For Manuscript Preparation

When you open TRANS-JOUR.DOC, select “Page Layout” from the “View” menu in the menu bar (View | Page Layout), (these instructions assume MS 6.0. Some versions may have alternate ways to access the same functionalities noted here). Then, type over sections of TRANS-JOUR.DOC or cut and paste from another document and use markup styles. The pull-down style menu is at the left of the Formatting Toolbar at the top of your *Word* window (for example, the style at this point in the document is “Text”). Highlight a section that you want to designate with a certain style, then select the appropriate name on the style menu. The style will adjust your fonts and line spacing. Do not change the font sizes or line spacing to squeeze more text into a limited number of pages.Use italics for emphasis; do not underline.

To insert images in *Word,* position the cursor at the insertion point and either use Insert | Picture | From File or copy the image to the Windows clipboard and then Edit | Paste Special | Picture (with “float over text” unchecked).

IEEE will do the final formatting of your paper. If your paper is intended for a conference, please observe the conference page limits.

## Abbreviations and Acronyms

Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract. Abbreviations such as IEEE, SI, ac, and dc do not have to be defined. Abbreviations that incorporate periods should not have spaces: write “C.N.R.S.,” not “C. N. R. S.” Do not use abbreviations in the title unless they are unavoidable (for example, “IEEE” in the title of this article).

## Other Recommendations

Use one space after periods and colons. Hyphenate complex modifiers: “zero-field-cooled magnetization.” Avoid dangling participles, such as, “Using (1), the potential was calculated.” [It is not clear who or what used (1).] Write instead, “The potential was calculated by using (1),” or “Using (1), we calculated the potential.”

Use a zero before decimal points: “0.25,” not “.25.” Use “cm3,” not “cc.” Indicate sample dimensions as “0.1 cm × 0.2 cm,” not “0.1 × 0.2 cm2.” The abbreviation for “seconds” is “s,” not “sec.” Use “Wb/m2” or “webers per square meter,” not “webers/m2.” When expressing a range of values, write “7 to 9” or “7-9,” not “7~9.”

A parenthetical statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.) In American English, periods and commas are within quotation marks, like “this period.” Other punctuation is “outside”! Avoid contractions; for example, write “do not” instead of “don’t.” The serial comma is preferred: “A, B, and C” instead of “A, B and C.”

If you wish, you may write in the first person singular or plural and use the active voice (“I observed that ...” or “We observed that ...” instead of “It was observed that ...”). Remember to check spelling. If your native language is not English, please get a native English-speaking colleague to carefully proofread your paper.

## How to Create a PostScript File

First, download a PostScript printer driver from <http://www.adobe.com/support/downloads/pdrvwin.htm> (for Windows) or from [http://www.adobe.com/support/downloads/ pdrvmac.htm](http://www.adobe.com/support/downloads/) (for Macintosh) and install the “Generic PostScript Printer” definition. In *Word,* paste your figure into a new document. Print to a file using the PostScript printer driver. File names should be of the form “fig5.ps.” Use Open Type fonts when creating your figures, if possible. A listing of the acceptable fonts are as follows: Open Type Fonts: Times Roman, Helvetica, Helvetica Narrow, Courier, Symbol, Palatino, Avant Garde, Bookman, Zapf Chancery, Zapf Dingbats, and New Century Schoolbook.

# MATH

If you are using *Word,* use either the Microsoft Equation Editor or the *MathType* add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation *or* MathType Equation). “Float over text” should *not* be selected.

## Equations

Number equations consecutively with equation numbers in parentheses flush with the right margin, as in (1). First use the equation editor to create the equation. Then select the “Equation” markup style. Press the tab key and write the equation number in parentheses. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

 (1)

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (*T* might refer to temperature, but T is the unit tesla). Refer to “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is ... .”

# Units

Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). This applies to papers in data storage**.** For example, write “15 Gb/cm2 (100 Gb/in2).” An exception is when English units are used as identifiers in trade, such as “3½-in disk drive.” Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength *H* is A/m. However, if you wish to use units of T, either refer to magnetic flux density *B* or magnetic field strength symbolized as µ0*H*. Use the center dot to separate compound units, e.g., “A·m2.”

# Some Common Mistakes

The word “data” is plural, not singular. The subscript for the permeability of vacuum µ0 is zero, not a lowercase letter “o.” The term for residual magnetization is “remanence”; the adjective is “remanent”; do not write “remnance” or “remnant.” Use the word “micrometer” instead of “micron.” A graph within a graph is an “inset,” not an “insert.” The word “alternatively” is preferred to the word “alternately” (unless you really mean something that alternates). Use the word “whereas” instead of “while” (unless you are referring to simultaneous events). Do not use the word “essentially” to mean “approximately” or “effectively.” Do not use the word “issue” as a euphemism for “problem.” When compositions are not specified, separate chemical symbols by en-dashes; for example, “NiMn” indicates the intermetallic compound Ni0.5Mn0.5 whereas “Ni–Mn” indicates an alloy of some composition NixMn1-x.

Be aware of the different meanings of the homophones “affect” (usually a verb) and “effect” (usually a noun), “complement” and “compliment,” “discreet” and “discrete,” “principal” (e.g., “principal investigator”) and “principle” (e.g., “principle of measurement”). Do not confuse “imply” and “infer.”

Prefixes such as “non,” “sub,” “micro,” “multi,” and “ultra” are not independent words; they should be joined to the words they modify, usually without a hyphen. There is no period after the “et” in the Latin abbreviation “*et al.*” (it is also italicized). The abbreviation “i.e.,” means “that is,” and the abbreviation “e.g.,” means “for example” (these abbreviations are not italicized).

A general IEEE styleguide is available at <http://www.ieee.org/web/publications/authors/transjnl/index.html>



Fig. 1. Magnetization as a function of applied field. Note that “Fig.” is abbreviated. There is a period after the figure number, followed by two spaces. It is good practice to explain the significance of the figure in the caption.

TABLE I

Units for Magnetic Properties

|  |  |  |
| --- | --- | --- |
| Symbol | Quantity | Conversion from Gaussian and  CGS EMU to SI a |
| Φ | magnetic flux | 1 Mx → 10−8 Wb = 10−8 V·s |
| *B* | magnetic flux density,  magnetic induction | 1 G → 10−4 T = 10−4 Wb/m2 |
| *H* | magnetic field strength | 1 Oe → 103/(4π) A/m |
| *m* | magnetic moment | 1 erg/G = 1 emu  → 10−3 A·m2 = 10−3 J/T |
| *M* | magnetization | 1 erg/(G·cm3) = 1 emu/cm3  → 103 A/m |
| 4π*M* | magnetization | 1 G → 103/(4π) A/m |
| σ | specific magnetization | 1 erg/(G·g) = 1 emu/g → 1 A·m2/kg |
| *j* | magnetic dipole  moment | 1 erg/G = 1 emu  → 4π × 10−10 Wb·m |
| *J* | magnetic polarization | 1 erg/(G·cm3) = 1 emu/cm3  → 4π × 10−4 T |
| χ*,* κ | susceptibility | 1 → 4π |
| χρ | mass susceptibility | 1 cm3/g → 4π × 10−3 m3/kg |
| μ | permeability | 1 → 4π × 10−7 H/m  = 4π × 10−7 Wb/(A·m) |
| μr | relative permeability | μ → μr |
| *w, W* | energy density | 1 erg/cm3 → 10−1 J/m3 |
| *N, D* | demagnetizing factor | 1 → 1/(4π) |

Vertical lines are optional in tables. Statements that serve as captions for the entire table do not need footnote letters.

aGaussian units are the same as cg emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

# Guidelines for Graphics Preparation and Submission

## Types of Graphics

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray:

### *Color/Grayscale figures*

### Figures that are meant to appear in color, or shades of black/gray. Such figures may include photographs, illustrations, multicolor graphs, and flowcharts.

### *Lineart figures*

### Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray. Only black and white.

### *Author photos*

### Head and shoulders shots of authors which appear at the end of our papers.

### *Tables* Data charts which are typically black and white, but sometimes include color.

## Multipart figures

Figures compiled of more than one sub-figure presented side-by-side, or stacked. If a multipart figure is made up of multiple figure types (one part is lineart, and another is grayscale or color) the figure should meet the stricter guidelines.

## File Formats For Graphics

Format and save your graphics using a suitable graphics processing program that will allow you to create the images as PostScript (PS), Encapsulated PostScript (.EPS), Tagged Image File Format (.TIFF), Portable Document Format (.PDF), or Portable Network Graphics (.PNG) sizes them, and adjusts the resolution settings. If you created your source files in one of the following programs you will be able to submit the graphics without converting to a PS, EPS, TIFF, PDF, or PNG file: Microsoft Word, Microsoft PowerPoint, or Microsoft Excel. When submitting your final paper, your graphics should all be submitted individually in one of these formats along with the manuscript.

## Sizing of Graphics

Most charts, graphs, and tables are one column wide (3.5 inches / 88 millimeters / 21 picas) or page wide (7.16 inches / 181 millimeters / 43 picas). The maximum depth a graphic can be is 8.5 inches (216 millimeters / 54 picas). When choosing the depth of a graphic, please allow space for a caption. Figures can be sized between column and page widths if the author chooses, however it is recommended that figures are not sized less than column width unless when necessary.

There is currently one publication with column measurements that don’t coincide with those listed above. Proceedings of the IEEE has a column measurement of 3.25 inches (82.5 millimeters / 19.5 picas).

The final printed size of author photographs is exactly   
1 inch wide by 1.25 inches tall (25 millimeters x 38 millimeters / 6 picas x 7.5 picas). Author photos printed in editorials measure 1.59 inches wide by 2 inches tall (40 millimeters x 50 millimeters / 9.5 picas x 12 picas).

## Resolution

The proper resolution of your figures will depend on the type of figure it is as defined in the “Types of Figures” section. Author photographs, color, and grayscale figures should be at least 300dpi. Lineart, including tables should be a minimum of 600dpi.

## Vector Art

While IEEE does accept vector artwork, it is our   
policy is to rasterize all figures for publication. This is done   
in order to preserve the figures’ integrity across multiple computer platforms.

## Color Space

The term color space refers to the entire sum of colors that can be represented within the said medium. For our purposes, the three main color spaces are Grayscale, RGB (red/green/blue) and CMYK (cyan/magenta/yellow/black). RGB is generally used with on-screen graphics, whereas CMYK is used for printing purposes.

All color figures should be generated in RGB or CMYK color space. Grayscale images should be submitted in Grayscale color space. Line art may be provided in grayscale OR bitmap colorspace. Note that “bitmap colorspace” and “bitmap file format” are not the same thing. When bitmap color space is selected, .TIF/.TIFF is the recommended file format.

## Accepted Fonts Within Figures

When preparing your graphics IEEE suggests that you use of one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, and Symbol. If you are supplying EPS, PS, or PDF files all fonts must be embedded. Some fonts may only be native to your operating system; without the fonts embedded, parts of the graphic may be distorted or missing.

A safe option when finalizing your figures is to strip out the fonts before you save the files, creating “outline” type. This converts fonts to artwork what will appear uniformly on any screen.

## Using Labels Within Figures

### Figure Axis labels

Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity “Magnetization,” or “Magnetization *M*,” not just “*M*.” Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write “Magnetization (A/m)” or “Magnetization (Am−1),” not just “A/m.” Do not label axes with a ratio of quantities and units. For example, write “Temperature (K),” not “Temperature/K.”

Multipliers can be especially confusing. Write “Magnetization (kA/m)” or “Magnetization (103 A/m).” Do not write “Magnetization (A/m) × 1000” because the reader would not know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 10 point type.

### Subfigure Labels in Multipart Figures and Tables

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