Appendix A: Math & Python Mini-Refresher

This appendix provides a concise refresher on key mathematical concepts and Python programming skills that are essential for understanding the neuroAI content in this handbook.

A.1 Mathematical Foundations

Linear Algebra Essentials

Linear algebra forms the backbone of modern machine learning and neural data analysis.

Vectors and Matrices

```python
import numpy as np

# Creating vectors
v = np.array([1, 2, 3])
w = np.array([4, 5, 6])

# Vector operations
dot_product = np.dot(v, w)      # Dot product: 32
norm = np.linalg.norm(v)        # Euclidean norm: 3.74
unit_v = v / np.linalg.norm(v)  # Unit vector

# Creating matrices
A = np.array([[1, 2], [3, 4], [5, 6]])  # 3x2 matrix
B = np.array([[1, 2, 3], [4, 5, 6]])    # 2x3 matrix

# Matrix operations
C = np.dot(B, A)  # Matrix multiplication: 2x2 matrix
transpose = A.T   # Transpose: 2x3 matrix
```

Matrix Operations and Decompositions

```
import numpy as np

# Square matrix for demonstration
M = np.array([[4, 2], [2, 3]])

# Matrix inverse
M_inv = np.linalg.inv(M)
print("M * M^-1 =\n", np.dot(M, M_inv))  # Should be identity matrix

# Matrix determinant
det = np.linalg.det(M)  # 8.0

# Singular Value Decomposition (SVD)
U, S, Vt = np.linalg.svd(M)
# Reconstruct original matrix
M_reconstructed = np.dot(U, np.dot(np.diag(S), Vt))

# Eigenvalues and eigenvectors
eigenvalues, eigenvectors = np.linalg.eig(M)
print("Eigenvalues:", eigenvalues)
print("Eigenvectors:\n", eigenvectors)

# Principal Component Analysis (simplified)
def simple_pca(X, n_components=2):
    """
    Perform PCA on data matrix X

    Parameters:
    - X: Data matrix (samples x features)
    - n_components: Number of principal components to keep

    Returns:
    - X_reduced: Data projected onto principal components
    - components: Principal components
    """
    # Center the data
    X_centered = X - np.mean(X, axis=0)

    # Compute covariance matrix
    cov_matrix = np.cov(X_centered, rowvar=False)

    # Eigendecomposition
    eigenvalues, eigenvectors = np.linalg.eigh(cov_matrix)

    # Sort eigenvalues and eigenvectors in descending order
    idx = eigenvalues.argsort()[::-1]
    eigenvalues = eigenvalues[idx]
    eigenvectors = eigenvectors[:, idx]

    # Select top n_components
    components = eigenvectors[:, :n_components]
```

```
    # Project data onto principal components
    X_reduced = np.dot(X_centered, components)

    return X_reduced, components
```

Calculus Fundamentals

Calculus concepts are critical for understanding neural network training and many neuroscience models.

Derivatives and Gradients

```
import numpy as np
import matplotlib.pyplot as plt
from matplotlib import cm
from mpl_toolkits.mplot3d import Axes3D

# Define a simple function
def f(x):
    return x**2

# Plot function and its derivative
x = np.linspace(-5, 5, 100)
y = f(x)
dydx = 2*x  # Analytical derivative

plt.figure(figsize=(10, 6))
plt.plot(x, y, label='f(x) = x²')
plt.plot(x, dydx, label='f\'(x) = 2x')
plt.grid(True)
plt.legend()
plt.title('Function and its Derivative')
plt.xlabel('x')
plt.ylabel('y')

# Multivariate function and gradient
def g(x, y):
    return x**2 + y**2

# Analytical gradient
def grad_g(x, y):
    return np.array([2*x, 2*y])

# Example of gradient descent
def gradient_descent(grad_func, start, learning_rate, n_iterations):
    """Simple gradient descent implementation"""
    path = [start]
    point = start.copy()

    for _ in range(n_iterations):
        gradient = grad_func(point[0], point[1])
        point = point - learning_rate * gradient
        path.append(point.copy())

    return np.array(path)

# Run gradient descent
start = np.array([4.0, 4.0])
path = gradient_descent(grad_g, start, 0.1, 20)

# Plot the function and gradient descent path
x = np.linspace(-5, 5, 100)
y = np.linspace(-5, 5, 100)
```

```python
X, Y = np.meshgrid(x, y)
Z = g(X, Y)

fig = plt.figure(figsize=(12, 8))
ax = fig.add_subplot(111, projection='3d')
surf = ax.plot_surface(X, Y, Z, cmap=cm.coolwarm, alpha=0.6)
ax.scatter(path[:, 0], path[:, 1], g(path[:, 0], path[:, 1]),
           color='black', s=50, label='Gradient Descent Path')
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
ax.set_title('Gradient Descent Optimization')
```

The Chain Rule and Backpropagation

The chain rule is the foundation of backpropagation, the algorithm used to train neural networks:

```python
def chain_rule_example():
    """
    Demonstrate the chain rule for a simple neural network with:
    - Input x
    - Hidden layer h = sigmoid(w1*x + b1)
    - Output y = w2*h + b2
    - Loss L = (y - target)²
    """
    def sigmoid(z):
        return 1 / (1 + np.exp(-z))

    def forward_pass(x, w1, b1, w2, b2):
        # Hidden layer
        z1 = w1 * x + b1
        h = sigmoid(z1)

        # Output layer
        y = w2 * h + b2

        return y, h, z1

    def compute_gradients(x, target, w1, b1, w2, b2):
        # Forward pass
        y, h, z1 = forward_pass(x, w1, b1, w2, b2)

        # Compute loss
        loss = (y - target)**2

        # Backpropagation
        # dL/dy = 2(y - target)
        dL_dy = 2 * (y - target)

        # dy/dw2 = h
        dL_dw2 = dL_dy * h

        # dy/db2 = 1
        dL_db2 = dL_dy * 1

        # dy/dh = w2
        dL_dh = dL_dy * w2

        # dh/dz1 = h * (1 - h)  [derivative of sigmoid]
        dh_dz1 = h * (1 - h)

        # dz1/dw1 = x
        dL_dw1 = dL_dh * dh_dz1 * x

        # dz1/db1 = 1
        dL_db1 = dL_dh * dh_dz1 * 1

        return loss, dL_dw1, dL_db1, dL_dw2, dL_db2

    # Initialize parameters
```

```
    x = 2.0
    target = 0.5
    w1, b1 = 0.1, 0.1
    w2, b2 = 0.2, 0.2

    # Compute gradients
    loss, dL_dw1, dL_db1, dL_dw2, dL_db2 = compute_gradients(x, target, w1, b1, w

    print(f"Loss: {loss:.4f}")
    print(f"Gradients:")
    print(f"  dL/dw1: {dL_dw1:.4f}")
    print(f"  dL/db1: {dL_db1:.4f}")
    print(f"  dL/dw2: {dL_dw2:.4f}")
    print(f"  dL/db2: {dL_db2:.4f}")

    return loss, dL_dw1, dL_db1, dL_dw2, dL_db2
```

Probability and Statistics

Probability theory is essential for understanding generative models, variational inference, and neural coding.

```python
import numpy as np
import matplotlib.pyplot as plt
from scipy import stats

# Normal distribution
mu, sigma = 0, 1
x = np.linspace(-5, 5, 1000)
pdf = stats.norm.pdf(x, mu, sigma)

plt.figure(figsize=(10, 6))
plt.plot(x, pdf)
plt.fill_between(x, pdf, alpha=0.3)
plt.title('Normal Distribution')
plt.xlabel('x')
plt.ylabel('Probability Density')
plt.grid(True)

# Bayes' theorem example: Disease testing
def bayes_theorem_example():
    """
    Example using Bayes' theorem for medical testing:
    - Prior probability of disease: P(D) = 0.01
    - True positive rate: P(+|D) = 0.95
    - False positive rate: P(+|¬D) = 0.05
    - What is the probability of disease given positive test? P(D|+)
    """
    # Prior probability of disease
    p_disease = 0.01

    # Conditional probabilities
    p_positive_given_disease = 0.95        # True positive rate
    p_positive_given_no_disease = 0.05     # False positive rate

    # Calculate joint probabilities
    p_disease_and_positive = p_disease * p_positive_given_disease
    p_no_disease_and_positive = (1 - p_disease) * p_positive_given_no_disease

    # Calculate marginal probability of positive test
    p_positive = p_disease_and_positive + p_no_disease_and_positive

    # Apply Bayes' theorem
    p_disease_given_positive = p_disease_and_positive / p_positive

    print(f"Probability of disease given positive test: {p_disease_given_positive

    return p_disease_given_positive

# Information theory - Entropy and KL divergence
def information_theory_example():
    """
    Calculate entropy and KL divergence for discrete distributions
    """
    # Two probability distributions
```

```python
    p = np.array([0.2, 0.5, 0.3])
    q = np.array([0.1, 0.4, 0.5])

    # Entropy of p
    entropy_p = -np.sum(p * np.log2(p))

    # KL divergence between p and q
    kl_div = np.sum(p * np.log2(p / q))

    print(f"Entropy of p: {entropy_p:.4f} bits")
    print(f"KL divergence from p to q: {kl_div:.4f} bits")

    return entropy_p, kl_div
```

A.2 Python Fundamentals

Core Python

Python's simplicity and readability make it ideal for neuroscience and AI research.

```python
# Data structures
# Lists
my_list = [1, 2, 3, 'a', 'b']
my_list.append(4)
print(my_list[0])  # Indexing: 1
print(my_list[-1])  # Negative indexing: 4
print(my_list[1:3])  # Slicing: [2, 3]

# Dictionaries
my_dict = {'name': 'Neuron', 'type': 'Pyramidal', 'location': 'V1'}
print(my_dict['type'])  # Accessing value: Pyramidal
my_dict['active'] = True  # Adding new key-value pair

# List comprehension
squares = [x**2 for x in range(10)]
even_squares = [x**2 for x in range(10) if x % 2 == 0]

# Functions and lambda expressions
def calculate_firing_rate(spike_count, time_window):
    """Calculate firing rate in Hz"""
    return spike_count / time_window

# Lambda function for the same calculation
firing_rate = lambda spike_count, time_window: spike_count / time_window

# Classes and OOP
class Neuron:
    """Simple neuron model"""

    def __init__(self, rest_potential=-70, threshold=-55):
        self.membrane_potential = rest_potential
        self.rest_potential = rest_potential
        self.threshold = threshold
        self.spike_history = []

    def receive_input(self, input_current):
        """Process input current and update membrane potential"""
        self.membrane_potential += input_current
        if self.membrane_potential >= self.threshold:
            self.spike()
            return True
        return False

    def spike(self):
        """Generate an action potential"""
        self.spike_history.append(1)
        self.membrane_potential = self.rest_potential

    def reset(self):
        """Reset neuron state"""
        self.membrane_potential = self.rest_potential
        self.spike_history = []
```

```python
# Creating and using a neuron instance
my_neuron = Neuron()
my_neuron.receive_input(20)
print(f"Membrane potential: {my_neuron.membrane_potential} mV")
```

Scientific Python Ecosystem

The scientific Python ecosystem provides powerful tools for data analysis, visualization, and modeling.

NumPy: Numerical Computing

```python
import numpy as np

# Creating arrays
a = np.array([1, 2, 3, 4, 5])
b = np.arange(10)  # [0, 1, 2, ..., 9]
c = np.linspace(0, 1, 5)  # [0.0, 0.25, 0.5, 0.75, 1.0]
zeros = np.zeros((3, 3))  # 3x3 matrix of zeros
ones = np.ones((2, 2))  # 2x2 matrix of ones
rand = np.random.rand(2, 2)  # 2x2 matrix of random numbers from U(0,1)

# Array operations
a + 2  # Element-wise addition: [3, 4, 5, 6, 7]
a * 2  # Element-wise multiplication: [2, 4, 6, 8, 10]
a * a  # Element-wise product: [1, 4, 9, 16, 25]

# Matrix operations
M = np.array([[1, 2], [3, 4]])
v = np.array([1, 2])
np.dot(M, v)  # Matrix-vector product: [5, 11]
eigvals, eigvecs = np.linalg.eig(M)  # Eigendecomposition

# Statistical operations
np.mean(a)  # Mean: 3.0
np.std(a)   # Standard deviation: ~1.41
np.max(a)   # Maximum: 5
np.min(a)   # Minimum: 1
```

Matplotlib: Visualization

```
import matplotlib.pyplot as plt
import numpy as np

# Basic line plot
x = np.linspace(0, 10, 100)
y = np.sin(x)
plt.figure(figsize=(10, 6))
plt.plot(x, y, 'b-', label='sin(x)')
plt.title('Sine Function')
plt.xlabel('x')
plt.ylabel('sin(x)')
plt.grid(True)
plt.legend()
plt.show()

# Scatter plot with coloring
n = 100
x = np.random.rand(n)
y = np.random.rand(n)
colors = np.random.rand(n)
sizes = 1000 * np.random.rand(n)

plt.figure(figsize=(10, 6))
plt.scatter(x, y, c=colors, s=sizes, alpha=0.5)
plt.title('Scatter Plot with Size and Color Mapping')
plt.grid(True)
plt.colorbar(label='Color Value')
plt.show()

# Multiple plots in a grid
fig, axs = plt.subplots(2, 2, figsize=(10, 8))

# First plot: line
axs[0, 0].plot(x, y)
axs[0, 0].set_title('Line Plot')

# Second plot: scatter
axs[0, 1].scatter(x, y, c=colors)
axs[0, 1].set_title('Scatter Plot')

# Third plot: histogram
axs[1, 0].hist(y, bins=20)
axs[1, 0].set_title('Histogram')

# Fourth plot: bar chart
axs[1, 1].bar(range(5), np.random.rand(5))
axs[1, 1].set_title('Bar Chart')

plt.tight_layout()
plt.show()
```

Pandas: Data Manipulation

```python
import pandas as pd
import numpy as np

# Creating a DataFrame
data = {
    'neuron_id': np.arange(1, 6),
    'type': ['Pyramidal', 'Stellate', 'Pyramidal', 'Basket', 'Pyramidal'],
    'resting_potential': [-70, -65, -72, -68, -71],
    'firing_rate': [5.2, 10.1, 3.5, 15.0, 4.8],
    'location': ['V1', 'V2', 'V1', 'V2', 'MT']
}

df = pd.DataFrame(data)
print(df.head())

# Basic operations
print(df.describe())  # Summary statistics
print(df['firing_rate'].mean())  # Mean of a column

# Filtering
pyramidal_neurons = df[df['type'] == 'Pyramidal']
high_firing = df[df['firing_rate'] > 10]

# Grouping and aggregation
type_stats = df.groupby('type').agg({
    'resting_potential': 'mean',
    'firing_rate': ['mean', 'std', 'count']
})
print(type_stats)

# Adding a new column
df['active'] = df['firing_rate'] > 5
```

SciPy: Scientific Computing

```python
from scipy import stats, optimize, integrate, signal
import numpy as np
import matplotlib.pyplot as plt

# Statistical tests
x = np.random.normal(0, 1, 100)
y = np.random.normal(2, 1, 100)
t_stat, p_value = stats.ttest_ind(x, y)
print(f"t-statistic: {t_stat:.4f}, p-value: {p_value:.4f}")

# Optimization
def objective(x):
    return x[0]**2 + x[1]**2

result = optimize.minimize(objective, [1, 1])
print(f"Minimum found at: {result.x}")
print(f"Minimum value: {result.fun}")

# Integration
def f(x):
    return x**2

integral, error = integrate.quad(f, 0, 1)
print(f"Integral of x^2 from 0 to 1: {integral:.6f} ± {error:.6f}")

# Signal processing: filtering
t = np.linspace(0, 1, 1000, endpoint=False)
noise = np.random.normal(0, 0.1, t.shape)
signal_clean = np.sin(2 * np.pi * 10 * t)  # 10 Hz sine wave
signal_noisy = signal_clean + noise

# Design a low-pass filter
b, a = signal.butter(4, 0.2)  # 4th order Butterworth filter with cutoff at 0.2 *
filtered_signal = signal.filtfilt(b, a, signal_noisy)

plt.figure(figsize=(10, 6))
plt.plot(t, signal_noisy, 'gray', alpha=0.6, label='Noisy signal')
plt.plot(t, signal_clean, 'g--', linewidth=2, label='Original signal')
plt.plot(t, filtered_signal, 'b-', linewidth=1.5, label='Filtered signal')
plt.legend()
plt.xlabel('Time [s]')
plt.title('Signal Filtering Example')
plt.grid(True)
plt.show()
```

Machine Learning Libraries

PyTorch Fundamentals

```
import torch
import torch.nn as nn
import torch.optim as optim
import numpy as np
import matplotlib.pyplot as plt

# Create a simple neural network
class SimpleNN(nn.Module):
    def __init__(self, input_size, hidden_size, output_size):
        super(SimpleNN, self).__init__()
        self.layer1 = nn.Linear(input_size, hidden_size)
        self.relu = nn.ReLU()
        self.layer2 = nn.Linear(hidden_size, output_size)

    def forward(self, x):
        x = self.layer1(x)
        x = self.relu(x)
        x = self.layer2(x)
        return x

# Create a synthetic dataset
def generate_data(n_samples=100):
    # Generate two-class classification data
    np.random.seed(42)
    X = np.random.randn(n_samples, 2)
    y = (X[:, 0] + X[:, 1] > 0).astype(np.int64)

    # Convert to PyTorch tensors
    X_tensor = torch.FloatTensor(X)
    y_tensor = torch.LongTensor(y)

    return X_tensor, y_tensor

# Training function
def train_model(model, X, y, epochs=1000, lr=0.01):
    criterion = nn.CrossEntropyLoss()
    optimizer = optim.SGD(model.parameters(), lr=lr)

    # Track losses
    losses = []

    for epoch in range(epochs):
        # Forward pass
        outputs = model(X)
        loss = criterion(outputs, y)
```

```python
        # Backward pass and optimize
        optimizer.zero_grad()
        loss.backward()
        optimizer.step()

        # Save loss
        losses.append(loss.item())

        # Print progress
        if (epoch+1) % 100 == 0:
            print(f'Epoch {epoch+1}/{epochs}, Loss: {loss.item():.4f}')

    return losses

# Prepare data
X, y = generate_data(100)

# Create and train model
model = SimpleNN(input_size=2, hidden_size=10, output_size=2)
losses = train_model(model, X, y)

# Plot decision boundary
def plot_decision_boundary(model, X, y):
    # Define grid for plotting
    x_min, x_max = X[:, 0].min() - 1, X[:, 0].max() + 1
    y_min, y_max = X[:, 1].min() - 1, X[:, 1].max() + 1
    xx, yy = np.meshgrid(np.arange(x_min, x_max, 0.01),
                         np.arange(y_min, y_max, 0.01))

    # Get predictions for all grid points
    grid = torch.FloatTensor(np.c_[xx.ravel(), yy.ravel()])
    with torch.no_grad():
        outputs = model(grid)
        _, predictions = torch.max(outputs, 1)

    # Reshape predictions back to grid
    predictions = predictions.reshape(xx.shape)

    # Plot decision boundary
    plt.figure(figsize=(10, 6))
    plt.contourf(xx, yy, predictions, alpha=0.3)

    # Plot training points
    scatter = plt.scatter(X[:, 0], X[:, 1], c=y, edgecolors='k', s=50)
    plt.legend(*scatter.legend_elements(), title="Classes")

    plt.xlabel('Feature 1')
    plt.ylabel('Feature 2')
    plt.title('Decision Boundary')
    plt.grid(True)
    plt.show()

# Plot results
plt.figure(figsize=(10, 6))
```

```python
plt.plot(losses)
plt.xlabel('Epoch')
plt.ylabel('Loss')
plt.title('Training Loss')
plt.grid(True)
plt.show()

plot_decision_boundary(model, X, y)
```

TensorFlow/Keras Example

```
import tensorflow as tf
from tensorflow import keras
import numpy as np
import matplotlib.pyplot as plt

# Load a built-in dataset (MNIST)
(x_train, y_train), (x_test, y_test) = keras.datasets.mnist.load_data()

# Preprocess data
x_train = x_train.astype('float32') / 255.0
x_test = x_test.astype('float32') / 255.0

# Build a convolutional neural network
model = keras.Sequential([
    keras.layers.Input(shape=(28, 28)),
    keras.layers.Reshape((28, 28, 1)),
    keras.layers.Conv2D(32, kernel_size=(3, 3), activation='relu'),
    keras.layers.MaxPooling2D(pool_size=(2, 2)),
    keras.layers.Conv2D(64, kernel_size=(3, 3), activation='relu'),
    keras.layers.MaxPooling2D(pool_size=(2, 2)),
    keras.layers.Flatten(),
    keras.layers.Dense(128, activation='relu'),
    keras.layers.Dropout(0.5),
    keras.layers.Dense(10, activation='softmax')
])

# Compile the model
model.compile(optimizer='adam',
              loss='sparse_categorical_crossentropy',
              metrics=['accuracy'])

# Train the model (using a subset for demonstration)
history = model.fit(x_train[:10000], y_train[:10000],
                    validation_split=0.2,
                    batch_size=128,
                    epochs=5)

# Evaluate on test data
test_loss, test_acc = model.evaluate(x_test, y_test)
print(f'Test accuracy: {test_acc:.4f}')

# Plot training history
plt.figure(figsize=(12, 4))

plt.subplot(1, 2, 1)
plt.plot(history.history['loss'], label='Training Loss')
plt.plot(history.history['val_loss'], label='Validation Loss')
plt.xlabel('Epoch')
plt.ylabel('Loss')
plt.legend()
```

```
plt.subplot(1, 2, 2)
plt.plot(history.history['accuracy'], label='Training Accuracy')
plt.plot(history.history['val_accuracy'], label='Validation Accuracy')
plt.xlabel('Epoch')
plt.ylabel('Accuracy')
plt.legend()

plt.tight_layout()
plt.show()

# Visualize predictions
def plot_predictions(model, x_test, y_test, n=5):
    # Get model predictions
    predictions = model.predict(x_test[:n])
    predicted_classes = np.argmax(predictions, axis=1)

    plt.figure(figsize=(12, 4))
    for i in range(n):
        plt.subplot(1, n, i+1)
        plt.imshow(x_test[i], cmap='gray')
        color = 'green' if predicted_classes[i] == y_test[i] else 'red'
        plt.title(f"Pred: {predicted_classes[i]}\nTrue: {y_test[i]}", color=color
        plt.axis('off')
    plt.tight_layout()
    plt.show()

plot_predictions(model, x_test, y_test)
```

A.3 Neuroscience Data Processing

Common Data Formats

Neuroscience data comes in various formats, each with its own characteristics:

Spike Trains and Rasters

```
import numpy as np
import matplotlib.pyplot as plt

# Simulate spike trains for 5 neurons over 1 second
def simulate_poisson_spike_train(rate, t_max, dt):
    """Simulate a Poisson spike train"""
    t = np.arange(0, t_max, dt)
    n_steps = len(t)

    # Probability of spike in each time bin
    prob_spike = rate * dt

    # Generate spikes
    spikes = np.random.rand(n_steps) < prob_spike

    # Get spike times
    spike_times = t[spikes]

    return spike_times, spikes

# Simulation parameters
t_max = 1.0  # seconds
dt = 0.001   # 1 ms resolution
n_neurons = 5
firing_rates = [5, 10, 15, 20, 25]  # Hz

# Generate spike trains
spike_trains = []
spike_rasters = []

for rate in firing_rates:
    spike_times, spikes = simulate_poisson_spike_train(rate, t_max, dt)
    spike_trains.append(spike_times)
    spike_rasters.append(spikes)

# Plot raster plot
plt.figure(figsize=(12, 6))

# Plot spike raster
plt.subplot(2, 1, 1)
for i, (rate, spike_times) in enumerate(zip(firing_rates, spike_trains)):
    plt.plot(spike_times, np.ones_like(spike_times) * i, '|', markersize=10)
plt.yticks(range(n_neurons), [f'{rate} Hz' for rate in firing_rates])
plt.xlabel('Time (s)')
plt.ylabel('Neuron')
plt.title('Spike Raster Plot')

# Plot PSTH (Peri-Stimulus Time Histogram)
plt.subplot(2, 1, 2)
bin_size = 0.05  # 50 ms bins
bins = np.arange(0, t_max + bin_size, bin_size)
```

```python
t = np.arange(0, t_max, dt)

for i, spikes in enumerate(spike_rasters):
    counts, _ = np.histogram(t[spikes], bins=bins)
    rate = counts / bin_size  # Convert to Hz
    plt.step(bins[:-1], rate, label=f'Neuron {i+1}')

plt.xlabel('Time (s)')
plt.ylabel('Firing Rate (Hz)')
plt.title('Peri-Stimulus Time Histogram (PSTH)')
plt.legend()
plt.tight_layout()
plt.show()
```

Time Series Data

```
import numpy as np
import matplotlib.pyplot as plt
from scipy import signal

# Simulate EEG data (multi-channel time series)
def simulate_eeg(fs=250, duration=5, n_channels=4):
    """
    Simulate multi-channel EEG data with different frequency bands

    Parameters:
    - fs: Sampling frequency (Hz)
    - duration: Duration of the signal (seconds)
    - n_channels: Number of channels

    Returns:
    - time: Time points
    - eeg: Simulated EEG data (channels x time points)
    """
    t = np.arange(0, duration, 1/fs)
    n_points = len(t)

    # Generate different frequency components
    delta = np.sin(2 * np.pi * 2 * t)  # 2 Hz (delta band: 0.5-4 Hz)
    theta = 0.5 * np.sin(2 * np.pi * 6 * t)  # 6 Hz (theta band: 4-8 Hz)
    alpha = 0.3 * np.sin(2 * np.pi * 10 * t)  # 10 Hz (alpha band: 8-13 Hz)
    beta = 0.2 * np.sin(2 * np.pi * 20 * t)  # 20 Hz (beta band: 13-30 Hz)
    gamma = 0.1 * np.sin(2 * np.pi * 40 * t)  # 40 Hz (gamma band: >30 Hz)

    # Create channels with different mixtures of frequency components
    eeg = np.zeros((n_channels, n_points))

    # Channel 1: Mostly delta and theta
    eeg[0] = delta + 0.5*theta + 0.2*alpha + 0.1*beta + 0.05*gamma + 0.2*np.rando

    # Channel 2: Mostly alpha
    eeg[1] = 0.2*delta + 0.3*theta + alpha + 0.2*beta + 0.1*gamma + 0.2*np.random

    # Channel 3: Mostly beta
    eeg[2] = 0.1*delta + 0.2*theta + 0.3*alpha + beta + 0.3*gamma + 0.2*np.random

    # Channel 4: Mostly gamma
    eeg[3] = 0.05*delta + 0.1*theta + 0.2*alpha + 0.3*beta + gamma + 0.2*np.rando

    return t, eeg

# Simulate EEG data
fs = 250  # sampling frequency (Hz)
t, eeg = simulate_eeg(fs=fs, duration=5, n_channels=4)

# Plot time domain signals
plt.figure(figsize=(12, 8))
```

```
channel_names = ['Frontal (Fz)', 'Central (Cz)', 'Parietal (Pz)', 'Occipital (Oz)

for i in range(4):
    plt.subplot(4, 1, i+1)
    plt.plot(t, eeg[i])
    plt.ylabel(channel_names[i])
    if i == 0:
        plt.title('Simulated EEG Data')
    if i == 3:
        plt.xlabel('Time (s)')
plt.tight_layout()
plt.show()

# Compute and plot power spectrum
plt.figure(figsize=(12, 6))

for i in range(4):
    plt.subplot(2, 2, i+1)

    # Compute power spectrum
    f, Pxx = signal.welch(eeg[i], fs=fs, nperseg=fs)

    # Plot power spectrum
    plt.semilogy(f, Pxx)
    plt.xlabel('Frequency (Hz)')
    plt.ylabel('Power Spectral Density')
    plt.title(f'Channel: {channel_names[i]}')
    plt.grid(True)
    plt.axvline(x=4, color='r', linestyle='--', alpha=0.3)
    plt.axvline(x=8, color='r', linestyle='--', alpha=0.3)
    plt.axvline(x=13, color='r', linestyle='--', alpha=0.3)
    plt.axvline(x=30, color='r', linestyle='--', alpha=0.3)
    plt.xticks([0, 4, 8, 13, 30, 50])
    plt.xlim(0, 50)

plt.tight_layout()
plt.show()
```

Preprocessing Techniques

Preprocessing is a critical step in neuroscience data analysis:

```python
import numpy as np
import matplotlib.pyplot as plt
from scipy import signal

# Generate noisy signal
def generate_noisy_eeg(fs=250, duration=5):
    """Generate a noisy EEG-like signal with various artifacts"""
    t = np.arange(0, duration, 1/fs)
    n_points = len(t)

    # Generate clean signal (mixture of oscillations)
    clean = (0.5 * np.sin(2 * np.pi * 10 * t) +  # Alpha (10 Hz)
             0.25 * np.sin(2 * np.pi * 5 * t) +  # Theta (5 Hz)
             0.1 * np.sin(2 * np.pi * 20 * t))   # Beta (20 Hz)

    # Add noise
    noise = 0.2 * np.random.randn(n_points)

    # Add power line noise (50 Hz)
    line_noise = 0.15 * np.sin(2 * np.pi * 50 * t)

    # Add ocular artifact (slow wave at specific timepoints)
    artifact = np.zeros(n_points)
    artifact_times = [1.2, 3.7]  # Times of artifacts (seconds)

    for art_time in artifact_times:
        idx = int(art_time * fs)
        # Create a slow wave artifact
        window = signal.gaussian(100, std=20)
        if idx + len(window) <= n_points:
            artifact[idx:idx+len(window)] += 2 * window

    # Combine all components
    noisy_signal = clean + noise + line_noise + artifact

    return t, clean, noisy_signal, artifact

# Generate signal
fs = 250
t, clean, noisy, artifact = generate_noisy_eeg(fs=fs)

# Plot raw signals
plt.figure(figsize=(12, 8))
plt.subplot(3, 1, 1)
plt.plot(t, clean)
plt.title('Clean EEG Signal')
plt.ylabel('Amplitude')

plt.subplot(3, 1, 2)
plt.plot(t, noisy)
plt.title('Noisy EEG Signal with Artifacts')
plt.ylabel('Amplitude')
```

```
plt.subplot(3, 1, 3)
plt.plot(t, artifact)
plt.title('Artifacts Component')
plt.xlabel('Time (s)')
plt.ylabel('Amplitude')

plt.tight_layout()
plt.show()

# Apply filtering
def apply_filters(signal_data, fs):
    """Apply various filters to the signal"""
    # Notch filter for line noise (50 Hz)
    b_notch, a_notch = signal.iirnotch(50, 30, fs)
    notch_filtered = signal.filtfilt(b_notch, a_notch, signal_data)

    # Bandpass filter for EEG frequencies of interest (1-40 Hz)
    b_bandpass, a_bandpass = signal.butter(4, [1, 40], fs=fs, btype='bandpass')
    bandpass_filtered = signal.filtfilt(b_bandpass, a_bandpass, notch_filtered)

    return notch_filtered, bandpass_filtered

# Apply filters
notch_filtered, bandpass_filtered = apply_filters(noisy, fs)

# Plot filtered signals
plt.figure(figsize=(12, 10))
plt.subplot(4, 1, 1)
plt.plot(t, clean)
plt.title('Original Clean EEG Signal')
plt.ylabel('Amplitude')

plt.subplot(4, 1, 2)
plt.plot(t, noisy)
plt.title('Noisy EEG Signal with Artifacts')
plt.ylabel('Amplitude')

plt.subplot(4, 1, 3)
plt.plot(t, notch_filtered)
plt.title('After Notch Filter (50 Hz removed)')
plt.ylabel('Amplitude')

plt.subplot(4, 1, 4)
plt.plot(t, bandpass_filtered)
plt.title('After Bandpass Filter (1-40 Hz)')
plt.xlabel('Time (s)')
plt.ylabel('Amplitude')

plt.tight_layout()
plt.show()

# Compute and plot spectrograms
plt.figure(figsize=(12, 10))
```

```
plt.subplot(3, 1, 1)
f, t_spec, Sxx = signal.spectrogram(noisy, fs=fs, nperseg=fs//2, noverlap=fs//4)
plt.pcolormesh(t_spec, f, 10 * np.log10(Sxx), shading='gouraud')
plt.ylabel('Frequency [Hz]')
plt.title('Spectrogram of Noisy Signal')
plt.colorbar(label='PSD [dB]')
plt.ylim(0, 60)

plt.subplot(3, 1, 2)
f, t_spec, Sxx = signal.spectrogram(notch_filtered, fs=fs, nperseg=fs//2, noverla
plt.pcolormesh(t_spec, f, 10 * np.log10(Sxx), shading='gouraud')
plt.ylabel('Frequency [Hz]')
plt.title('Spectrogram after Notch Filter')
plt.colorbar(label='PSD [dB]')
plt.ylim(0, 60)

plt.subplot(3, 1, 3)
f, t_spec, Sxx = signal.spectrogram(bandpass_filtered, fs=fs, nperseg=fs//2, nove
plt.pcolormesh(t_spec, f, 10 * np.log10(Sxx), shading='gouraud')
plt.xlabel('Time [s]')
plt.ylabel('Frequency [Hz]')
plt.title('Spectrogram after Bandpass Filter')
plt.colorbar(label='PSD [dB]')
plt.ylim(0, 60)

plt.tight_layout()
plt.show()
```

A.4 Code Examples

Here are some integrated examples demonstrating common tasks in computational neuroscience and AI:

Neural Decoding Example

```
import numpy as np
import matplotlib.pyplot as plt
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import StandardScaler
from sklearn.metrics import accuracy_score, confusion_matrix
import torch
import torch.nn as nn
import torch.optim as optim
from torch.utils.data import DataLoader, TensorDataset

# Simulate neural data and behavior
def simulate_neural_decoding_data(n_neurons=50, n_samples=1000, n_classes=3):
    """
    Simulate neural population activity encoding different behaviors

    Parameters:
    - n_neurons: Number of neurons
    - n_samples: Number of samples (trials)
    - n_classes: Number of behavioral classes

    Returns:
    - X: Neural activity data (n_samples, n_neurons)
    - y: Behavioral labels (n_samples,)
    """
    np.random.seed(42)

    # Create class-specific activity patterns
    neuron_templates = np.random.randn(n_classes, n_neurons) * 2

    # Initialize data
    X = np.zeros((n_samples, n_neurons))
    y = np.zeros(n_samples, dtype=int)

    # Generate samples
    samples_per_class = n_samples // n_classes
    for c in range(n_classes):
        start_idx = c * samples_per_class
        end_idx = (c + 1) * samples_per_class if c < n_classes - 1 else n_samples

        # Assign class labels
        y[start_idx:end_idx] = c

        # Generate neural activity based on class template
        for i in range(start_idx, end_idx):
            # Add noise to template
            X[i] = neuron_templates[c] + np.random.randn(n_neurons) * 0.5

    return X, y

# Generate simulated data
X, y = simulate_neural_decoding_data(n_neurons=100, n_samples=1000, n_classes=4)
```

```
# Preprocess data
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_s

# Standardize features
scaler = StandardScaler()
X_train = scaler.fit_transform(X_train)
X_test = scaler.transform(X_test)

# Convert to PyTorch tensors
X_train_tensor = torch.FloatTensor(X_train)
y_train_tensor = torch.LongTensor(y_train)
X_test_tensor = torch.FloatTensor(X_test)
y_test_tensor = torch.LongTensor(y_test)

# Create dataset and dataloader
train_dataset = TensorDataset(X_train_tensor, y_train_tensor)
train_loader = DataLoader(train_dataset, batch_size=32, shuffle=True)

# Define neural network model
class NeuralDecoder(nn.Module):
    def __init__(self, n_neurons, n_hidden, n_classes):
        super(NeuralDecoder, self).__init__()
        self.fc1 = nn.Linear(n_neurons, n_hidden)
        self.relu = nn.ReLU()
        self.dropout = nn.Dropout(0.5)
        self.fc2 = nn.Linear(n_hidden, n_classes)

    def forward(self, x):
        x = self.fc1(x)
        x = self.relu(x)
        x = self.dropout(x)
        x = self.fc2(x)
        return x

# Initialize model and optimizer
n_neurons = X_train.shape[1]
n_hidden = 64
n_classes = len(np.unique(y))
model = NeuralDecoder(n_neurons, n_hidden, n_classes)
criterion = nn.CrossEntropyLoss()
optimizer = optim.Adam(model.parameters(), lr=0.001)

# Train the model
n_epochs = 20
train_losses = []

for epoch in range(n_epochs):
    model.train()
    epoch_loss = 0

    for inputs, labels in train_loader:
        # Forward pass
        outputs = model(inputs)
```

```
        loss = criterion(outputs, labels)

        # Backward pass and optimization
        optimizer.zero_grad()
        loss.backward()
        optimizer.step()

        epoch_loss += loss.item()

    avg_loss = epoch_loss / len(train_loader)
    train_losses.append(avg_loss)
    print(f'Epoch {epoch+1}/{n_epochs}, Loss: {avg_loss:.4f}')

# Evaluate model
model.eval()
with torch.no_grad():
    y_pred = model(X_test_tensor)
    _, predicted = torch.max(y_pred, 1)

accuracy = accuracy_score(y_test, predicted.numpy())
conf_matrix = confusion_matrix(y_test, predicted.numpy())

print(f'Test Accuracy: {accuracy:.4f}')

# Visualize results
plt.figure(figsize=(15, 5))

# Plot training loss
plt.subplot(1, 2, 1)
plt.plot(train_losses)
plt.xlabel('Epoch')
plt.ylabel('Loss')
plt.title('Training Loss')
plt.grid(True)

# Plot confusion matrix
plt.subplot(1, 2, 2)
plt.imshow(conf_matrix, cmap='Blues')
plt.colorbar()
plt.xlabel('Predicted Label')
plt.ylabel('True Label')
plt.title('Confusion Matrix')
plt.xticks(np.arange(n_classes))
plt.yticks(np.arange(n_classes))

# Add text annotations to confusion matrix
thresh = conf_matrix.max() / 2
for i in range(conf_matrix.shape[0]):
    for j in range(conf_matrix.shape[1]):
        plt.text(j, i, f'{conf_matrix[i, j]}',
                 ha="center", va="center",
                 color="white" if conf_matrix[i, j] > thresh else "black")
```

```
plt.tight_layout()
plt.show()
```

Simple Neuron Simulation

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.integrate import odeint

# Hodgkin-Huxley Neuron Model
class HodgkinHuxleyNeuron:
    """
    Implementation of the Hodgkin-Huxley neuron model

    The model describes the evolution of membrane voltage V and
    three gating variables m, n, and h using a system of ODEs
    """

    def __init__(self):
        # Maximal conductances (mS/cm^2)
        self.g_Na = 120.0  # Sodium
        self.g_K = 36.0    # Potassium
        self.g_L = 0.3     # Leak

        # Reversal potentials (mV)
        self.E_Na = 50.0   # Sodium
        self.E_K = -77.0   # Potassium
        self.E_L = -54.387 # Leak

        # Membrane capacitance (μF/cm^2)
        self.C_m = 1.0

    def alpha_m(self, V):
        """Na+ activation rate"""
        return 0.1 * (V + 40.0) / (1.0 - np.exp(-(V + 40.0) / 10.0))

    def beta_m(self, V):
        """Na+ deactivation rate"""
        return 4.0 * np.exp(-(V + 65.0) / 18.0)

    def alpha_h(self, V):
        """Na+ inactivation rate"""
        return 0.07 * np.exp(-(V + 65.0) / 20.0)

    def beta_h(self, V):
        """Na+ deinactivation rate"""
        return 1.0 / (1.0 + np.exp(-(V + 35.0) / 10.0))

    def alpha_n(self, V):
        """K+ activation rate"""
        return 0.01 * (V + 55.0) / (1.0 - np.exp(-(V + 55.0) / 10.0))

    def beta_n(self, V):
        """K+ deactivation rate"""
        return 0.125 * np.exp(-(V + 65) / 80.0)
```

```python
    def I_Na(self, V, m, h):
        """Na+ current"""
        return self.g_Na * m**3 * h * (V - self.E_Na)

    def I_K(self, V, n):
        """K+ current"""
        return self.g_K * n**4 * (V - self.E_K)

    def I_L(self, V):
        """Leak current"""
        return self.g_L * (V - self.E_L)

    def dALLdt(self, X, t, I_ext):
        """
        Compute derivatives for the complete system of ODEs

        Parameters:
        - X: State vector [V, m, h, n]
        - t: Time
        - I_ext: External current

        Returns:
        - dXdt: Derivatives [dV/dt, dm/dt, dh/dt, dn/dt]
        """
        V, m, h, n = X

        # Steady-state values
        m_inf = self.alpha_m(V) / (self.alpha_m(V) + self.beta_m(V))
        h_inf = self.alpha_h(V) / (self.alpha_h(V) + self.beta_h(V))
        n_inf = self.alpha_n(V) / (self.alpha_n(V) + self.beta_n(V))

        # Time constants
        tau_m = 1.0 / (self.alpha_m(V) + self.beta_m(V))
        tau_h = 1.0 / (self.alpha_h(V) + self.beta_h(V))
        tau_n = 1.0 / (self.alpha_n(V) + self.beta_n(V))

        # Ionic currents
        I_Na = self.I_Na(V, m, h)
        I_K = self.I_K(V, n)
        I_L = self.I_L(V)

        # Membrane voltage derivative
        dVdt = (I_ext - I_Na - I_K - I_L) / self.C_m

        # Gating variables derivatives
        dmdt = (m_inf - m) / tau_m
        dhdt = (h_inf - h) / tau_h
        dndt = (n_inf - n) / tau_n

        return [dVdt, dmdt, dhdt, dndt]

    def simulate(self, t, I_ext_func, V0=-65.0):
        """
        Simulate the neuron
```

```
        Parameters:
        - t: Time array
        - I_ext_func: Function that returns external current at time t
        - V0: Initial membrane voltage

        Returns:
        - result: Solution array with columns [V, m, h, n]
        """
        # Initial conditions [V, m, h, n]
        m0 = self.alpha_m(V0) / (self.alpha_m(V0) + self.beta_m(V0))
        h0 = self.alpha_h(V0) / (self.alpha_h(V0) + self.beta_h(V0))
        n0 = self.alpha_n(V0) / (self.alpha_n(V0) + self.beta_n(V0))
        X0 = [V0, m0, h0, n0]

        # Create I_ext array
        I_ext = np.array([I_ext_func(time) for time in t])

        # Solve ODE system for each time step
        result = np.zeros((len(t), 4))
        result[0] = X0

        for i in range(1, len(t)):
            t_span = [t[i-1], t[i]]
            sol = odeint(self.dALLdt, result[i-1], t_span, args=(I_ext[i],))
            result[i] = sol[-1]

        return result

# Create and simulate the Hodgkin-Huxley neuron
neuron = HodgkinHuxleyNeuron()

# Simulation parameters
t_max = 50.0  # ms
dt = 0.01  # ms
t = np.arange(0, t_max, dt)

# External current function (10μA/cm² pulse from 5ms to 30ms)
def I_ext(t):
    if 5 <= t <= 30:
        return 10.0
    else:
        return 0.0

# Run simulation
result = neuron.simulate(t, I_ext)
V, m, h, n = result.T

# Create I_ext array for plotting
I_ext_array = np.array([I_ext(time) for time in t])

# Plot results
plt.figure(figsize=(12, 10))
```

```
# Membrane voltage
plt.subplot(4, 1, 1)
plt.plot(t, V)
plt.ylabel('Voltage (mV)')
plt.title('Hodgkin-Huxley Neuron Model')

# Gating variables
plt.subplot(4, 1, 2)
plt.plot(t, m, 'r', label='m (Na+ activation)')
plt.plot(t, h, 'g', label='h (Na+ inactivation)')
plt.plot(t, n, 'b', label='n (K+ activation)')
plt.ylabel('Gating Value')
plt.legend()

# Ionic currents
I_Na = np.array([neuron.I_Na(V[i], m[i], h[i]) for i in range(len(t))])
I_K = np.array([neuron.I_K(V[i], n[i]) for i in range(len(t))])
I_L = np.array([neuron.I_L(V[i]) for i in range(len(t))])

plt.subplot(4, 1, 3)
plt.plot(t, I_Na, 'r', label='Na+ Current')
plt.plot(t, I_K, 'b', label='K+ Current')
plt.plot(t, I_L, 'g', label='Leak Current')
plt.ylabel('Current (μA/cm²)')
plt.legend()

# External current
plt.subplot(4, 1, 4)
plt.plot(t, I_ext_array, 'k')
plt.xlabel('Time (ms)')
plt.ylabel('Stimulus (μA/cm²)')

plt.tight_layout()
plt.show()
```

These examples and refreshers should provide the necessary background for understanding the more advanced concepts presented in the handbook chapters.