

# Today's Outline - February 20, 2013

# Today's Outline - February 20, 2013

- WKB approximation

# Today's Outline - February 20, 2013

- WKB approximation
- Examples

# Today's Outline - February 20, 2013

- WKB approximation
- Examples

Reading Assignment: Chapter 8.3

# The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

# The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

# The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\psi(x) = Ae^{\pm ikx}$$

## The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\psi(x) = Ae^{\pm ikx}$$

$$k \equiv \sqrt{2m(E - V)}/\hbar$$

# The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\psi(x) = Ae^{\pm ikx}$$

$$k \equiv \sqrt{2m(E - V)}/\hbar$$

$$\lambda = 2\pi/k$$

## The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\psi(x) = Ae^{\pm ikx}$$

$$k \equiv \sqrt{2m(E - V)}/\hbar$$

$$\lambda = 2\pi/k$$

similarly, if  $E < V$

## The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\begin{aligned}\psi(x) &= Ae^{\pm ikx} \\ k &\equiv \sqrt{2m(E - V)}/\hbar \\ \lambda &= 2\pi/k\end{aligned}$$

similarly, if  $E < V$

$$\psi(x) = Ae^{\pm \kappa x}$$

# The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\psi(x) = Ae^{\pm ikx}$$

$$k \equiv \sqrt{2m(E - V)}/\hbar$$

$$\lambda = 2\pi/k$$

similarly, if  $E < V$

$$\psi(x) = Ae^{\pm \kappa x}$$

$$\kappa \equiv \sqrt{2m(V - E)}/\hbar$$

## The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\begin{aligned}\psi(x) &= Ae^{\pm ikx} \\ k &\equiv \sqrt{2m(E - V)}/\hbar \\ \lambda &= 2\pi/k\end{aligned}$$

similarly, if  $E < V$

$$\begin{aligned}\psi(x) &= Ae^{\pm \kappa x} \\ \kappa &\equiv \sqrt{2m(V - E)}/\hbar\end{aligned}$$

If  $V(x)$  is now allowed to vary slowly compared to the scaling lengths  $\lambda$  and  $1/\kappa$ , we can make the approximation that the wavefunctions are still valid except for a slowly varying amplitude  $A(x)$  and  $\lambda(x)$  (or  $\kappa(x)$ ).

## The WKB approximation

The WKB approximation is useful in obtaining solutions for slowly varying potentials which cannot be solved exactly

suppose a particle of energy  $E$  is traversing a region of *constant* potential,  $V(x)$  and  $E > V$

$$\begin{aligned}\psi(x) &= Ae^{\pm ikx} \\ k &\equiv \sqrt{2m(E - V)}/\hbar \\ \lambda &= 2\pi/k\end{aligned}$$

similarly, if  $E < V$

$$\begin{aligned}\psi(x) &= Ae^{\pm \kappa x} \\ \kappa &\equiv \sqrt{2m(V - E)}/\hbar\end{aligned}$$

If  $V(x)$  is now allowed to vary slowly compared to the scaling lengths  $\lambda$  and  $1/\kappa$ , we can make the approximation that the wavefunctions are still valid except for a slowly varying amplitude  $A(x)$  and  $\lambda(x)$  (or  $\kappa(x)$ ).

Note: deal with turning points later...

# Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

we assume a trial wave-  
function of the form

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

we assume a trial wave-  
function of the form

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

$$\psi(x) = A(x)e^{i\phi(x)}$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

we assume a trial wave-  
function of the form

taking the derivatives

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

$$\psi(x) = A(x)e^{i\phi(x)}$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

we assume a trial wave-  
function of the form

taking the derivatives

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

$$\psi(x) = A(x)e^{i\phi(x)}$$

$$\frac{d\psi}{dx} = (A' + iA\phi')e^{i\phi}$$

## Classical regime

Starting with the  
Schrödinger equation  
and  $E > V(x)$

we assume a trial wave-  
function of the form

taking the derivatives

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

$$\psi(x) = A(x)e^{i\phi(x)}$$

$$\frac{d\psi}{dx} = (A' + iA\phi')e^{i\phi}$$

$$\frac{d^2\psi}{dx^2} = [A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2]e^{i\phi}$$

## Classical regime

Starting with the Schrödinger equation and  $E > V(x)$

we assume a trial wavefunction of the form

taking the derivatives and substituting into the Schrödinger equation

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V(x)\psi = E\psi$$
$$\frac{d^2\psi}{dx^2} = -\frac{2m[E - V(x)]}{\hbar^2}\psi = -\frac{p^2}{\hbar^2}\psi$$

$$\psi(x) = A(x)e^{i\phi(x)}$$

$$\frac{d\psi}{dx} = (A' + iA\phi')e^{i\phi}$$

$$\frac{d^2\psi}{dx^2} = [A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2]e^{i\phi}$$
$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real**

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$2A'\phi' + A\phi'' = 0$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

$$A^2\phi' = C^2$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

$$A^2\phi' = C^2$$

$$A = \frac{C}{\sqrt{\phi'}}$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

can't solve this exactly but if  $A$  varies slowly,  $A'' \ll A$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

$$A^2\phi' = C^2$$

$$A = \frac{C}{\sqrt{\phi'}}$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

can't solve this exactly but if  $A$  varies slowly,  $A'' \ll A$

$$(\phi')^2 = \frac{p^2}{\hbar^2}$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

$$A^2\phi' = C^2$$

$$A = \frac{C}{\sqrt{\phi'}}$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

can't solve this exactly but if  $A$  varies slowly,  $A'' \ll A$

$$(\phi')^2 = \frac{p^2}{\hbar^2} \longrightarrow \frac{d\phi}{dx} = \pm \frac{p}{\hbar}$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

$$A^2\phi' = C^2$$

$$A = \frac{C}{\sqrt{\phi'}}$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

can't solve this exactly but if  $A$  varies slowly,  $A'' \ll A$

$$A^2\phi' = C^2$$

$$A = \frac{C}{\sqrt{\phi'}}$$

$$(\phi')^2 = \frac{p^2}{\hbar^2} \longrightarrow \frac{d\phi}{dx} = \pm \frac{p}{\hbar}$$

$$\phi(x) = \pm \frac{1}{\hbar} \int p(x) dx$$

## Classical regime (cont.)

$$-\frac{p^2}{\hbar^2}A = A'' + 2iA'\phi' + iA\phi'' - A(\phi')^2$$

this is simply 2 separate equations for the **real** and **imaginary** parts

$$A'' - A(\phi')^2 = -\frac{p^2}{\hbar^2}A$$

$$A'' = A \left[ (\phi')^2 - \frac{p^2}{\hbar^2} \right]$$

can't solve this exactly but if  $A$  varies slowly,  $A'' \ll A$

$$(\phi')^2 = \frac{p^2}{\hbar^2} \longrightarrow \frac{d\phi}{dx} = \pm \frac{p}{\hbar}$$

$$\phi(x) = \pm \frac{1}{\hbar} \int p(x) dx$$

$$2A'\phi' + A\phi'' = 0$$

$$(A^2\phi')' = 0$$

$$A^2\phi' = C^2$$

$$A = \frac{C}{\sqrt{\phi'}}$$

$$\psi(x) \simeq \frac{C}{\sqrt{\phi'}} e^{\pm \frac{i}{\hbar} \int p(x) dx}$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} \left[ C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)} \right]$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\phi(x) = \frac{1}{\hbar} \int_0^x p(x') dx'$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\phi(x) = \frac{1}{\hbar} \int_0^x p(x') dx'$$

applying the boundary conditions of  $\psi(0) = 0$  and  $\psi(a) = 0$ , we have

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\phi(x) = \frac{1}{\hbar} \int_0^x p(x') dx'$$

applying the boundary conditions of  $\psi(0) = 0$  and  $\psi(a) = 0$ , we have

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

$$C_2 \equiv 0,$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\phi(x) = \frac{1}{\hbar} \int_0^x p(x') dx'$$

applying the boundary conditions of  $\psi(0) = 0$  and  $\psi(a) = 0$ , we have

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

$$C_2 \equiv 0, \quad \phi(a) = n\pi, \quad n = 1, 2, 3, \dots$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\phi(x) = \frac{1}{\hbar} \int_0^x p(x') dx'$$

applying the boundary conditions of  $\psi(0) = 0$  and  $\psi(a) = 0$ , we have

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

$$C_2 \equiv 0, \quad \phi(a) = n\pi, \quad n = 1, 2, 3, \dots$$

$$\phi(a) = \int_0^a p(x) dx = n\pi\hbar$$

## Example 8.1

Solve the infinite square well with a “bumpy” bottom.

$$V(x) = \begin{cases} f(x), & 0 < x < a \\ \infty, & \text{otherwise} \end{cases}$$

Assuming  $E > f(x)$

where

$$\phi(x) = \frac{1}{\hbar} \int_0^x p(x') dx'$$

applying the boundary conditions of  $\psi(0) = 0$  and  $\psi(a) = 0$ , we have

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_+ e^{i\phi(x)} + C_- e^{-i\phi(x)}]$$

$$\psi(x) \simeq \frac{1}{\sqrt{p(x)}} [C_1 \sin \phi(x) + C_2 \cos \phi(x)]$$

$$C_2 \equiv 0, \quad \phi(a) = n\pi, \quad n = 1, 2, 3, \dots$$

$$\phi(a) = \int_0^a p(x) dx = n\pi\hbar$$

When  $f(x) \equiv 0$  we recover the energy of the infinite square well since  $pa = \sqrt{2mE}a = n\pi\hbar$