

# Various Quantum Field Theory Problems

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August 2023

## 1 MIT OCW PS 1 Q2

First, computing  $\frac{\partial y(x,t)}{\partial t}$  and  $\frac{\partial y(x,t)}{\partial x}$ :

$$\begin{aligned}\frac{\partial y(x,t)}{\partial t} &= \frac{\partial}{\partial t} \left( \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi x}{a}\right) q_n(t) \right) = \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi x}{a}\right) \dot{q}_n(t) \\ \frac{\partial y(x,t)}{\partial x} &= \frac{\partial}{\partial x} \left( \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi x}{a}\right) q_n(t) \right) = \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} \left(\frac{n\pi}{a}\right) \cos\left(\frac{n\pi x}{a}\right) q_n(t)\end{aligned}$$

Substituting these expressions into the Lagrangian:

$$L = \int_0^a dx \left[ \frac{\sigma}{2} \left( \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi x}{a}\right) \dot{q}_n(t) \right)^2 - \frac{T}{2} \left( \sqrt{\frac{2}{a}} \sum_{n=1}^{\infty} \left(\frac{n\pi}{a}\right) \cos\left(\frac{n\pi x}{a}\right) q_n(t) \right)^2 \right]$$

We can rewrite the Lagrangian by noting that  $(\sum_{i=1}^n a_i)^2 = \sum_{i,j}^n a_i a_j$  and pulling the summation outside of the integral:

$$L = \frac{1}{a} \sum_{n,m}^{\infty} \int_0^a dx \left[ \sigma \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{m\pi x}{a}\right) \dot{q}_n(t) \dot{q}_m(t) - T \cos\left(\frac{n\pi x}{a}\right) \cos\left(\frac{m\pi x}{a}\right) \frac{nm\pi^2}{a^2} q_n(t) q_m(t) \right]$$

where  $n, m = 0, 1, 2, \dots$ . We can then apply the orthogonality of the sines and cosines on the interval  $[0, a]$ :

$$\begin{aligned}
\frac{2}{a} \int_0^a \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{m\pi x}{a}\right) dx &= \delta_{nm} \\
\frac{2}{a} \int_0^a \cos\left(\frac{n\pi x}{a}\right) \cos\left(\frac{m\pi x}{a}\right) dx &= \delta_{nm} \\
\Rightarrow L &= \sum_{n,m}^{\infty} \left( \frac{\sigma}{2} \delta_{nm} \dot{q}_n(t) \dot{q}_m(t) - \frac{T}{2} \delta_{nm} \frac{n^2 \pi^2}{a^2} q_n(t) q_m(t) \right) \\
&= \sum_{n=1}^{\infty} \left( \frac{\sigma}{2} \left( \frac{\partial q_n(t)}{\partial t} \right)^2 - \frac{T}{2} \left( \frac{n\pi}{a} \right)^2 q_n^2(t) \right)
\end{aligned}$$

To derive the equations of motion for the system, we must first establish the degrees of freedom, which are simple the Fourier modes of  $q(t)$  **check if this is the right terminology**, so the Euler-Lagrange equations are:

$$\begin{aligned}
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_n} \right) - \frac{\partial L}{\partial q_n} &= 0 \\
\rightarrow \frac{\partial L}{\partial \dot{q}_n} &= \frac{\partial}{\partial \dot{q}_n} \left( \sum_{m=1}^{\infty} \frac{\sigma}{2} \left( \frac{\partial q_m(t)}{\partial t} \right)^2 - \frac{T}{2} \left( \frac{m\pi}{a} \right)^2 q_m^2(t) \right)
\end{aligned}$$

Since the set of functions  $q(t) = \{q_1(t), q_2(t), \dots\}$  are independently-varying functions, we have that  $\frac{\partial \dot{q}_m}{\partial \dot{q}_n} = \delta_{nm}$

$$\begin{aligned}
\Rightarrow \frac{\partial L}{\partial \dot{q}_n} &= \sigma \dot{q}_n \\
\Rightarrow \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_n} &= \sigma \ddot{q}_n
\end{aligned}$$

From a similar argument for the independence of the constituent of the constituent  $q_n(t)$  functions, we can easily evaluate  $\frac{\partial L}{\partial q_n}$ :

$$\begin{aligned}
\frac{\partial L}{\partial q_n} &= \frac{\partial}{\partial q_n} \left( \sum_{m=1}^{\infty} \frac{\sigma}{2} \left( \frac{\partial q_m(t)}{\partial t} \right)^2 - \frac{T}{2} \left( \frac{m\pi}{a} \right)^2 q_m^2(t) \right) \\
&= -T \left( \frac{n\pi}{a} \right)^2 q_n
\end{aligned}$$

Thus, the resulting equations of motion are:

$$\sigma \ddot{q}_n + T \left( \frac{n\pi}{a} \right)^2 q_n = 0$$

It is convenient to rewrite this equation as:

$$\ddot{q}_n(t) = -\frac{T}{\sigma} \left( \frac{n\pi}{a} \right)^2 q_n(t)$$

as this is clearly the equation of motion for a simple harmonic oscillator. Thus, our equations of motion are an infinite set of decoupled harmonic oscillators.

To calculate the frequency of each oscillator, we simply recall the simple harmonic equation of motion,  $\ddot{x} = -\omega^2 x$ . Thus, the frequency of oscillation for the  $n^{th}$  oscillator is:

$$\boxed{\omega_n = \sqrt{\frac{T}{\sigma}} \left( \frac{n\pi}{a} \right)}$$

## 2 MIT OCW PS 1 Q2

Computing the change in the Lagrangian density due to the internal transformation as defined:

$$\begin{aligned} \phi_a \phi_a &\longrightarrow (\phi_a + \theta \epsilon_{abc} n_b \phi_c) (\phi_a + \theta \epsilon_{abc} n_b \phi_c) \\ &= \phi_a \phi_a + 2\theta \epsilon_{abc} n_b \phi_a \phi_c + \mathcal{O}(\theta^2) \end{aligned}$$

The anti-symmetry of the Levi-Cevita tensor can be exploited:

$$\begin{aligned} 2\theta \epsilon_{abc} n_b \phi_a \phi_c &= 2\theta \epsilon_{cba} \phi_c \phi_a \\ &= -2\theta \epsilon_{abc} \phi_a \phi_c \implies 2\theta \epsilon_{abc} n_b \phi_a \phi_c = 0 \end{aligned}$$

where first the dummy indices were relabelled, following by applying  $\epsilon_{cab} = -\epsilon_{abc}$  and commuting the fields. Thus we have  $\phi_a \phi_a \longrightarrow \phi_a \phi_a$ , so the potential term is left invariant under the transformation.

Considering the kinetic term:

$$\begin{aligned}\partial_\mu \phi_a \partial^\mu \phi_a &\longrightarrow (\partial_\mu \phi_a + \theta \epsilon_{abc} n_b \partial_\mu \phi_c) (\partial^\mu \phi_a + \theta \epsilon_{abc} n_b \partial^\mu \phi_c) \\ &= \partial_\mu \phi_a \partial^\mu \phi_a + \theta \epsilon_{abc} n_b \partial_\mu \phi_a \partial^\mu \phi_c + \theta \epsilon_{abc} n_b \partial_\mu \phi_c \partial^\mu \phi_a + \mathcal{O}(\theta^2)\end{aligned}$$

Applying anti-symmetry again:

$$\theta \epsilon_{abc} n_b \partial_\mu \phi_c \partial^\mu \phi_a = \theta \epsilon_{cba} n_b \partial_\mu \phi_a \partial^\mu \phi_c = -\theta \epsilon_{abc} n_b \partial_\mu \phi_a \partial^\mu \phi_c$$

This term precisely adds out the second term in the sum, so we have:

$$\partial_\mu \phi_a \partial^\mu \phi_a \longrightarrow \partial_\mu \phi_a \partial^\mu \phi_a$$

Thus the Lagrangian is invariant under the transformation  $\phi_a \longrightarrow \phi_a + \theta \epsilon_{abc} n_b \phi_c$ . Calculating the Noether current:

$$\begin{aligned}j^\mu &= \sum_{a=1}^3 \pi_a^\mu D\phi_a - F^\mu \\ \pi_a^\mu &= \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_a)} = \frac{\partial}{\partial (\partial_\mu \phi_a)} \left( \frac{1}{2} \partial_{nu} \phi_a \partial^\nu \phi_a - \frac{1}{2} m^2 \phi_a \phi_a \right) = \frac{1}{2} \left( \frac{\partial (\partial_{nu} \phi_a)}{\partial (\partial_\mu \phi_a)} \partial^\nu \phi_a + \frac{\partial (\partial^\nu \phi_a)}{\partial (\partial_\mu \phi_a)} \partial_\nu \phi_a \right) \\ &= \frac{1}{2} (\partial^\nu \phi_a \delta_\nu^\mu + \partial_\nu \phi_a g^{\mu\nu}) = \frac{1}{2} (\partial^\mu \phi_a + \partial^\mu \phi_a) = \boxed{\partial^\mu \phi_a} \\ D\phi_a &= \frac{\partial (\phi_a + \theta \epsilon_{abc} n_b \phi_c)}{\partial \theta} = \epsilon_{abc} n_b \phi_c\end{aligned}$$

$$\implies \boxed{j^\mu = \sum_{a=1}^3 \partial^\mu \phi_a \epsilon_{abc} n_b \phi_c = \partial^\mu \phi_a \epsilon_{abc} n_b \phi_c}$$

(the sum was dropped due to implicit summation) If we take the  $\mu = 0$  component of the Noether current and integrate over all space, we will recover a globally-conserved charge:

$$Q = \int d^3x j^0 = \int d^3x \left( \epsilon_{abc} n_b \dot{\phi}_a \phi_c \right)$$

Since  $Q$  is conserved, it is conserved for any choice of the components of the rotation vector  $n$ , so in particular we can choose  $n$  such that it is one of the standard basis vectors, ie

$n_b = \delta_{bd}$  for a fixed  $d \in \{1, 2, 3\}$ .

$$\implies Q = \int d^3x \epsilon_{adc} \dot{\phi}_a \phi_c = \int d^3x \epsilon_{bdc} \dot{\phi}_b \phi_c = - \int d^3x \epsilon_{abc} \dot{\phi}_b \phi_c$$

The second equality follows after the relabelling of dummy indices  $a \rightarrow b$  and the third equality after relabelling  $d$  with  $a$  and using the anti-symmetry of the Levi-Cevita tensor. Since  $Q$  is conserved,  $-Q$  is conserved as well. We can then label this quantity  $Q_a$  according to the free index:

$$\boxed{Q_a = \int d^3x \epsilon_{abc} \dot{\phi}_b \phi_c}$$

Since we let  $n$  arbitrarily be one of the standard basis vectors,  $Q_a$  is actually 3 independent conserved quantities, each corresponding to a different choice of  $d$  in  $n_b = \delta_{bd}$  (In the relabelling from  $d$  to  $a$ , the conserved charge is really  $Q_d$  as  $a$  was not chosen to avoid a triple index contraction).

Finding the equations of motion for the theory:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_a)} = \partial^\mu \phi_a &\implies \partial_\mu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_a)} \right) = \partial_\mu \partial^\mu \phi_a \\ \frac{\partial \mathcal{L}}{\partial \phi_a} = \frac{\partial}{\partial \phi_a} \left( \frac{1}{2} \partial_\mu \phi_a \partial^\mu \phi_a - \frac{1}{2} m^2 \phi_a \phi_a \right) &= -\frac{m^2}{2} \left( 2 \phi_b \frac{\partial \phi_b}{\partial \phi_a} \right) = -m^2 \phi_b \delta_{ab} = -m^2 \phi_a \\ \implies \frac{\partial \mathcal{L}}{\partial \phi_a} - \partial_\mu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi_a)} \right) &= (-m^2 - \partial_\mu \partial^\mu) \phi_a = 0 \implies \ddot{\phi}_a = \nabla^2 \phi_a - m^2 \phi_a \end{aligned}$$

Computing the time derivative of  $Q_a$ :

$$\begin{aligned} \frac{d}{dt} Q_a &= \frac{d}{dt} \int d^3x \epsilon_{abc} \dot{\phi}_b \phi_c = \int d^3x \epsilon_{abc} \left( \ddot{\phi}_b \phi_c + \dot{\phi}_b \dot{\phi}_c \right) \\ &= \int d^3x \epsilon_{abc} \ddot{\phi}_b \phi_c && \text{(since } \epsilon_{abc} \dot{\phi}_b \dot{\phi}_c = -\epsilon_{abc} \dot{\phi}_b \dot{\phi}_c = 0) \\ &= \int d^3x \epsilon_{abc} (\nabla^2 \phi_b - m^2 \phi_b) \phi_c \\ &= \int d^3x \epsilon_{abc} \nabla^2 \phi_b && \text{(since } \epsilon_{abc} \phi_b \phi_c = -\epsilon_{abc} \phi_b \phi_c = 0) \end{aligned}$$

Integrating by parts:

$$\int d^3x \epsilon_{abc} \nabla^2 \phi_b = \int_{\partial \mathcal{M}} \phi_b (\nabla \phi_b \cdot \hat{n}) d(\partial \mathcal{M}) + \int_{\mathcal{M}} d^3x \epsilon_{abc} \nabla \phi_b \cdot \nabla \phi_c$$

where  $\partial \mathcal{M}$  denotes the boundary of the region of integration and  $\mathcal{M}$  is the region itself (in

this case, all of space), and  $\hat{n}$  is the outward normal to the boundary. Since we assume our fields to be physical, they vanish sufficiently fast at the boundaries so that the contribution from the first integral is 0. Similarly, due to the anti-symmetry of  $\epsilon_{abc}$ ,  $\epsilon_{abc} \nabla \phi_b \cdot \nabla \phi_c = \epsilon_{cba} \nabla \phi_c \cdot \nabla \phi_b = -\epsilon_{abc} \nabla \phi_b \cdot \nabla \phi_c = 0$ . So we have:

$$\frac{dQ_a}{dt} = 0$$

from the fields directly.

### 3 David Tong PS 1 Q5

Under Lorentz transformations, the Minkowski metric is preserved:

$$\begin{aligned} \eta_{\mu\nu} x^\mu x^\nu &= \eta_{\mu\nu} x'^\mu x'^\nu \\ &= \eta_{\mu\nu} x^\sigma x^\tau \Lambda_\sigma^\mu \Lambda_\tau^\nu \end{aligned}$$

Performing the relabelling of dummy indices in the unprimed line interval  $\mu \longrightarrow \sigma, \nu \longrightarrow \tau$ :

$$\eta_{\sigma\tau} x^\sigma x^\tau = \eta_{\mu\nu} x^\sigma x^\tau \Lambda_\sigma^\mu \Lambda_\tau^\nu \implies \boxed{\eta_{\sigma\tau} = \eta_{\mu\nu} \Lambda_\sigma^\mu \Lambda_\tau^\nu}$$

as desired. (the coordinates were "divided out" as suggested by the identification of the same dummy indices, but this really just says that the equivalency is true for arbitrary 4-vectors)

Consider the infinitesimal transformation defined by  $\Lambda_\nu^\mu = \delta_\nu^\mu + \omega_\nu^\mu$ . For  $\Lambda_\nu^\mu$  to be a Lorentz transformation, it must preserve the Minkowski metric:

$$\begin{aligned} \eta_{\mu\nu} \Lambda_\tau^\mu \Lambda_\sigma^\nu &= \eta_{\mu\nu} (\delta_\sigma^\mu + \omega_\sigma^\mu) (\delta_\tau^\nu + \omega_\tau^\nu) \\ &= \eta_{\nu\mu} (\delta_\sigma^\mu \delta_\tau^\nu + \delta_\sigma^\mu \omega_\tau^\nu + \omega_\sigma^\mu \delta_\tau^\nu + \mathcal{O}(w^2)) \quad (\text{since } w \text{ is an infinitesimal transformation}) \\ &= \eta_{\sigma\tau} + \eta_{\nu\sigma} \omega_\tau^\nu + \eta_{\tau\mu} \omega_\sigma^\mu = \eta_{\sigma\tau} + \omega_{\sigma\tau} + \omega_{\tau\sigma} \end{aligned}$$

For the Minkowski metric to be preserved, it must follow that  $\omega_{\sigma\tau} = -\omega_{\tau\sigma}$ . Acting  $\eta^{\mu\nu}$  twice on each side of the equality yields  $\omega^{\sigma\tau} = -\omega^{\tau\sigma}$  as desired.

## 4 Peskin & Schroeder 2.2

Consider the field theory of a complex-valued scalar field theory obeying the Klein-Gordon equation. The action of the theory is

$$S = \int d^4x (\partial_\mu \phi^* \partial^\mu \phi - m^2 \phi^* \phi)$$

It is easiest to analyze this theory by considering  $\phi(x)$  and  $\phi^*(x)$ , rather than the real and imaginary parts of  $\phi(x)$ , as the basic dynamical variables.

- a) Find the conjugate momenta to  $\phi(x)$  and  $\phi^*(x)$  and the canonical commutation relations. Show that the Hamiltonian is

$$H = \int d^3x (\pi^* \pi + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi).$$

Compute the Heisenberg equation of motion for  $\phi(x)$  and show that it is indeed the Klein-Gordon equation.

- b) Diagonalize  $H$  by introducing creation and annihilation operators. Show that the theory contains two sets of particles of mass  $m$ .

- c) Third item

- d)

- a) Given the action  $S = \int d^4x (\partial_\mu \phi^* \partial^\mu \phi - m^2 \phi^* \phi)$ , the Lagrangian is immediately given by  $\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - m^2 \phi^* \phi$ . Computing the conjugate momenta:

$$\begin{aligned} \Pi_\phi^\mu &= \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} = \frac{\partial}{\partial (\partial_\mu \phi)} (\partial_\nu \phi^* \partial^\nu \phi - m^2 \phi^* \phi) \\ &= \partial_\nu \phi^* \frac{\partial (\partial^\nu \phi)}{\partial (\partial_\mu \phi)} = \partial_\nu \phi^* g^{\mu\nu} = \boxed{\partial^\mu \phi^*} \\ \Pi_{\phi^*}^\mu &= \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi^*)} = \frac{\partial}{\partial (\partial_\mu \phi^*)} (\partial_\nu \phi^* \partial^\nu \phi - m^2 \phi^* \phi) \\ &= \partial^\nu \phi \frac{\partial (\partial_\nu \phi^*)}{\partial (\partial_\mu \phi^*)} = \partial^\nu \phi \delta_\nu^\mu = \boxed{\partial^\mu \phi} \end{aligned}$$

The canonical commutation relations are

$$\begin{aligned}
[\phi(\vec{x}, t), \phi(\vec{y}, t)] &= [\phi(\vec{x}, t)\phi^*(\vec{y}, t)] = [\phi^*(\vec{x}, t)\phi(\vec{y}, t)] = 0 \\
[\Pi_\phi^0(\vec{x}, t), \Pi_\phi^0(\vec{y}, t)] &= [\Pi_\phi^0(\vec{x}, t), \Pi_{\phi^*}^0(\vec{y}, t)] = [\Pi_{\phi^*}^0(\vec{x}, t), \Pi_{\phi^*}^0(\vec{y}, t)] = 0 \\
[\phi(\vec{x}, t), \Pi_{\phi^*}^0(\vec{y}, t)] &= [\phi^*(\vec{x}, t), \Pi_\phi^0(\vec{y}, t)] = 0 \\
[\phi(\vec{x}, t), \Pi_\phi^0(\vec{y}, t)] &= [\phi^*(\vec{x}, t), \Pi_{\phi^*}^0(\vec{y}, t)] = i\delta^{(3)}(\vec{x} - \vec{y})
\end{aligned}$$

The Hamiltonian (density) is

$$\begin{aligned}
\mathcal{H} &= \Pi_\mu^0 \partial_0 \phi_\mu - \mathcal{L} = \Pi_\phi^0 \partial_0 \phi + \Pi_{\phi^*}^0 \partial_0 \phi^* - \mathcal{L} \\
&= \partial^0 \phi^* \partial_0 \phi + \partial^0 \phi \partial_0 \phi^* - \partial_\mu \phi^* \partial^\mu \phi + m^2 \phi^* \phi \\
&= \partial^0 \phi \partial_0 \phi^* + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi = \partial^0 \phi \partial^0 \phi^* + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi
\end{aligned}$$

In terms of the conjugate momenta, the Hamiltonian is

$$\begin{aligned}
\mathcal{H} &= \partial^0 \phi \partial^0 \phi^* + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi = \Pi_{\phi^*}^0 \Pi_\phi^0 + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi \\
&= \boxed{\pi^* \pi + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi}
\end{aligned}$$

Where  $\pi = \Pi_\phi^0$  and  $\pi^* = \Pi_{\phi^*}^0$ . Integrating over all space:

$$H = \int d^3x \mathcal{H}(x) = \boxed{\int d^3x (\pi^* \pi + \nabla \phi^* \cdot \nabla \phi + m^2 \phi^* \phi)}$$

Computing the Heisenberg equation of motion for  $\phi(x)$ :

$$\begin{aligned}
\frac{\partial \phi}{\partial t} &= i [H(\vec{y}, t), \phi(\vec{x}, t)] = i \left[ \int d^3y (\pi^*(\vec{y}, t)\pi(\vec{y}, t) + \nabla \phi^*(\vec{y}, t) \cdot \nabla \phi(\vec{y}, t) + m^2 \phi(\vec{y}, t)\phi^*(\vec{y}, t)), \phi(\vec{x}, t) \right] \\
&= i \int d^3y [\pi^*(\vec{y}, t)\pi(\vec{y}, t) + \nabla \phi^*(\vec{y}, t) \cdot \nabla \phi(\vec{y}, t) + m^2 \phi(\vec{y}, t)\phi^*(\vec{y}, t)], \phi(\vec{x}, t)
\end{aligned}$$

Since fields and their spatial derivatives commute, we can restrict the commutator to the first term:

$$\begin{aligned}
\int d^3y [\pi^*(\vec{y}, t)\pi(\vec{y}, t), \phi(\vec{x}, t)] &= \int d^3y \pi^*(\vec{y}, t) [\pi(\vec{y}, t), \phi(\vec{x}, t)] = - \int d^3y \pi^*(\vec{y}, t) (i\delta^{(3)}(\vec{x} - \vec{y})) \\
&= -i \int d^3y \delta^{(3)}(\vec{x} - \vec{y}) \pi^*(\vec{y}, t) = -i \pi^*(\vec{x}, t) \\
\implies i [H(\vec{y}, t), \phi(\vec{x}, t)] &= \frac{\partial \phi(\vec{x}, t)}{\partial t} = \boxed{\pi^*(\vec{x}, t)}
\end{aligned}$$



Computing the equation of motion for  $\pi(x)$ :

$$\frac{\partial \pi(\vec{x}, t)}{\partial t} = i [H(\vec{y}, t), \pi(\vec{x}, t)] = i \int d^3 y [\pi^*(\vec{y}, t) \pi(\vec{y}, t) + \nabla \phi^*(\vec{y}, t) \cdot \nabla \phi(\vec{y}, t) + m^2 \phi(\vec{y}, t) \phi^*(\vec{y}, t)], \pi(\vec{x}, t)]$$

In this case we can only neglect the commutator of  $\pi(\vec{x}, t)$  with the first term:

$$\int d^3 y [\nabla \phi^*(\vec{y}, t) \cdot \nabla \phi(\vec{y}, t), \pi(\vec{x}, t)] = \int d^3 y \nabla \phi^*(\vec{y}, t) \cdot [\nabla \phi(\vec{y}, t), \pi(\vec{x}, t)]$$

We can "pull out" the gradient from the commutator (Have yet to find a rigorous justification for this, see Coleman p.70):

$$\int d^3 y \nabla \phi^*(\vec{y}, t) \cdot [\nabla \phi(\vec{y}, t), \pi(\vec{x}, t)] = \int d^3 y \nabla \phi^*(\vec{y}, t) \cdot \nabla [\phi(\vec{y}, t), \pi(\vec{x}, t)] = i \int d^3 y \nabla \phi^*(\vec{y}, t) \cdot \nabla \delta^{(3)}(\vec{y} - \vec{x})$$

Integrating by parts:

$$d^3 v = \nabla \delta^{(3)}(\vec{y} - \vec{x}) d^3 y \implies v = \delta^{(3)}(\vec{y} - \vec{x})$$

$$u = \nabla \phi^*(\vec{y}, t) \implies d^i u = \frac{\partial}{\partial y^j} (\nabla_i \phi^*(\vec{y}, t)) dy^j \implies d^3 u = \nabla^2 \phi^* d^3 y$$

$$\implies i \int d^3 y \nabla \phi^*(\vec{y}, t) \cdot \nabla \delta^{(3)}(\vec{y} - \vec{x}) = i \left( \nabla \phi^*(\vec{y}, t) \delta^{(3)}(\vec{y} - \vec{x})|_{\partial \mathcal{M}} - \int d^3 y \nabla^2 \phi^*(\vec{y}, t) \delta^{(3)}(\vec{y} - \vec{x}) \right)$$

$$\boxed{= -i \nabla^2 \phi^*(\vec{x}, t)}$$

(Integration by parts justification for v is scuffed) Computing the final commutator:

$$\int d^3 y [m^2 \phi(\vec{y}, t) \phi^*(\vec{y}, t), \pi(\vec{x}, t)] = \int d^3 y (m^2 \phi^*(\vec{y}, t) [\phi(\vec{y}, t), \pi(\vec{x}, t)]) \boxed{= i m^2 \phi^*(\vec{x}, t)}$$

$$\implies \frac{\partial \pi(\vec{x}, t)}{\partial t} = i (i m^2 \phi^*(\vec{x}, t) - i \nabla^2 \phi^*(\vec{x}, t))$$

$$\boxed{= (\nabla^2 - m^2) \phi^*(\vec{x}, t)}$$

It immediately follows from the equations of motion that the  $\phi^*$  fields obey the Klein-Gordon equation for a massive scalar field of mass  $m$ , and since the Hamiltonian is symmetric up to commutation in  $\phi$  and  $\phi^*$ , the  $\phi$  fields will also obey the Klein-Gordon equation.

**b)** To introduce creation and annihilation operators, we solve for the fields explicitly. Since both  $\phi(x)$  and  $\phi^*(x)$  obey the Klein Gordon equation, ie

$$(\partial_\mu \partial^\mu + m^2) \phi = (\partial_\mu \partial^\mu + m^2) \phi^* = 0$$

the fields  $\phi(x)$  and  $\phi^*(x)$  can be expressed as a superposition of plane wave solutions, with the caveat that  $\phi$  (and naturally  $\phi^*$ ) no longer must satisfy Hermiticity:

$$\begin{aligned}\phi(x) &= \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\vec{k}}}} \left( a_{\vec{k}} e^{-ik \cdot x} + b_{\vec{k}}^\dagger e^{ik \cdot x} \right) \\ \phi^*(x) &= \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\vec{k}}}} \left( a_{\vec{k}}^\dagger e^{ik \cdot x} + b_{\vec{k}} e^{-ik \cdot x} \right)\end{aligned}$$

Where  $a_{\vec{k}}$  and  $b_{\vec{k}}$  are independent annihilation operators. Evaluating the constituents of the Hamiltonian:

$$\begin{aligned}\pi &= \partial^0 \phi(x) = \frac{\partial}{\partial(ct)} \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\vec{k}}}} \left( a_{\vec{k}} e^{-ik \cdot x} + b_{\vec{k}}^\dagger e^{ik \cdot x} \right) = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\vec{k}}}} \left( (-i\omega_{\vec{k}}) a_{\vec{k}} e^{-ik \cdot x} + (i\omega_{\vec{k}}) b_{\vec{k}}^\dagger e^{ik \cdot x} \right) \\ &= i \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}} \sqrt{\frac{\omega_{\vec{k}}}{2}} \left( b_{\vec{k}}^\dagger e^{ik \cdot x} - a_{\vec{k}} e^{-ik \cdot x} \right) \\ \pi^* &= \partial^0 \phi^*(x) = \frac{\partial}{\partial(ct)} \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\vec{k}}}} \left( a_{\vec{k}}^\dagger e^{ik \cdot x} + b_{\vec{k}} e^{-ik \cdot x} \right) = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}\sqrt{2\omega_{\vec{k}}}} \left( (i\omega_{\vec{k}}) a_{\vec{k}}^\dagger e^{ik \cdot x} + (-i\omega_{\vec{k}}) b_{\vec{k}} e^{-ik \cdot x} \right) \\ &= i \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}} \sqrt{\frac{\omega_{\vec{k}}}{2}} \left( a_{\vec{k}}^\dagger e^{ik \cdot x} - b_{\vec{k}} e^{-ik \cdot x} \right)\end{aligned}$$

$$\begin{aligned}\Rightarrow \pi^* \pi &= (i)^2 \int \frac{d^3k d^3p}{(2\pi)^3} \frac{\sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}}{2} \left( a_{\vec{p}}^\dagger e^{ip \cdot x} - b_{\vec{p}} e^{-ip \cdot x} \right) \left( b_{\vec{k}}^\dagger e^{ik \cdot x} - a_{\vec{k}} e^{-ik \cdot x} \right) \\ &= - \int \frac{d^3k d^3p}{(2\pi)^3} \frac{\sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}}{2} \left( a_{\vec{p}}^\dagger b_{\vec{k}}^\dagger e^{-i(-p-k) \cdot x} - b_{\vec{p}} b_{\vec{k}}^\dagger e^{-i(p-k) \cdot x} - a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(k-p) \cdot x} + a_{\vec{k}} b_{\vec{p}} e^{-i(p+k) \cdot x} \right)\end{aligned}$$

$$\Rightarrow \int d^3x (\pi^* \pi) = - \int \frac{d^3x d^3k d^3p}{(2\pi)^3} \frac{\sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}}{2} \left( a_{\vec{p}}^\dagger b_{\vec{k}}^\dagger e^{-i(-p-k) \cdot x} - b_{\vec{p}} b_{\vec{k}}^\dagger e^{-i(p-k) \cdot x} - a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(k-p) \cdot x} + a_{\vec{k}} b_{\vec{p}} e^{-i(p+k) \cdot x} \right)$$

Recalling that the Fourier transform of a complex exponential:

$$\int \frac{d^3x}{(2\pi)^3} e^{-i(\vec{k}-\vec{k}') \cdot x} = \delta^{(3)}(\vec{k} - \vec{k}')$$

$$\begin{aligned}
\Rightarrow \int d^3x (\pi^* \pi) &= - \int \frac{d^3k d^3p}{2} \sqrt{\omega_{\vec{k}} \omega_{\vec{p}}} \int \frac{d^3x}{(2\pi)^3} \left( a_{\vec{p}}^\dagger b_{\vec{k}}^\dagger e^{-i(-\omega_{\vec{p}} - \omega_{\vec{k}})t} e^{-i(\vec{k} + \vec{p}) \cdot \vec{x}} - b_{\vec{p}} b_{\vec{k}}^\dagger e^{-i(\omega_{\vec{p}} - \omega_{\vec{k}})t} e^{-i(\vec{k} - \vec{p}) \cdot \vec{x}} \dots \right) \\
&\quad - a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(\omega_{\vec{k}} - \omega_{\vec{p}})t} e^{-i(\vec{p} - \vec{k}) \cdot \vec{x}} + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{p}} + \omega_{\vec{k}})t} e^{-i(-\vec{p} - \vec{k}) \cdot \vec{x}} \\
&= - \int \frac{d^3k d^3p}{2} \sqrt{\omega_{\vec{k}} \omega_{\vec{p}}} \left( a_{\vec{p}}^\dagger b_{\vec{k}}^\dagger e^{i(\omega_{\vec{p}} + \omega_{\vec{k}})t} \delta^{(3)}(\vec{k} + \vec{p}) - b_{\vec{p}} b_{\vec{k}}^\dagger e^{i(\omega_{\vec{k}} - \omega_{\vec{p}})t} \delta^{(3)}(\vec{k} - \vec{p}) - a_{\vec{p}}^\dagger a_{\vec{k}} e^{i(\omega_{\vec{p}} - \omega_{\vec{k}})t} \delta^{(3)}(\vec{p} - \vec{k}) \right) \\
&\quad + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{p}} + \omega_{\vec{k}})t} \delta^{(3)}(-\vec{p} - \vec{k})
\end{aligned}$$

$$\boxed{= - \int \frac{d^3k}{2} \omega_{\vec{k}} \left( a_{-\vec{k}}^\dagger b_{\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} - b_{\vec{k}} b_{\vec{k}}^\dagger - a_{\vec{k}}^\dagger a_{\vec{k}} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} \right)}$$

$$\begin{aligned}
\nabla \phi &= \int \frac{d^3k}{(2\pi)^{\frac{3}{2}} \sqrt{2\omega_{\vec{k}}}} \left( (i\vec{k}) a_{\vec{k}} e^{-ik \cdot x} + (-i\vec{k}) b_{\vec{k}}^\dagger e^{ik \cdot x} \right) = i \int \frac{\vec{k} d^3k}{(2\pi)^{\frac{3}{2}} \sqrt{2\omega_{\vec{k}}}} \left( -b_{\vec{k}}^\dagger e^{ik \cdot x} + a_{\vec{k}} e^{-ik \cdot x} \right) \\
\nabla \phi^* &= \int \frac{d^3p}{(2\pi)^{\frac{3}{2}} \sqrt{2\omega_{\vec{p}}}} \left( (-i\vec{p}) a_{\vec{p}}^\dagger e^{ip \cdot x} + (i\vec{p}) b_{\vec{p}} e^{-ip \cdot x} \right) = i \int \frac{\vec{p} d^3p}{(2\pi)^{\frac{3}{2}} \sqrt{2\omega_{\vec{p}}}} \left( -a_{\vec{p}}^\dagger e^{ip \cdot x} + b_{\vec{p}} e^{-ip \cdot x} \right)
\end{aligned}$$

$$\begin{aligned}
\Rightarrow \int d^3x \nabla \phi^* \cdot \nabla \phi &= - \int \frac{d^3x d^3k d^3p}{2(2\pi)^3 \sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}} (\vec{k} \cdot \vec{p}) \left( a_{\vec{p}}^\dagger b_{\vec{k}}^\dagger e^{-i(-\omega_{\vec{p}} - \omega_{\vec{k}})t} e^{-i(\vec{k} + \vec{p}) \cdot \vec{x}} - b_{\vec{p}} b_{\vec{k}}^\dagger e^{-i(\omega_{\vec{p}} - \omega_{\vec{k}})t} e^{-i(\vec{k} - \vec{p}) \cdot \vec{x}} \dots \right) \\
&\quad - a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(\omega_{\vec{k}} - \omega_{\vec{p}})t} e^{-i(\vec{p} - \vec{k}) \cdot \vec{x}} + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{p}} + \omega_{\vec{k}})t} e^{-i(-\vec{p} - \vec{k}) \cdot \vec{x}}
\end{aligned}$$

$$\begin{aligned}
&= - \int \frac{d^3k d^3p}{2\sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}} (\vec{k} \cdot \vec{p}) \left( a_{\vec{p}}^\dagger b_{\vec{k}}^\dagger e^{i(\omega_{\vec{p}} + \omega_{\vec{k}})t} \delta^{(3)}(\vec{k} + \vec{p}) - b_{\vec{p}} b_{\vec{k}}^\dagger e^{i(\omega_{\vec{k}} - \omega_{\vec{p}})t} \delta^{(3)}(\vec{k} - \vec{p}) - a_{\vec{p}}^\dagger a_{\vec{k}} e^{i(\omega_{\vec{p}} - \omega_{\vec{k}})t} \delta^{(3)}(\vec{p} - \vec{k}) \right) \\
&\quad + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{p}} + \omega_{\vec{k}})t} \delta^{(3)}(-\vec{p} - \vec{k})
\end{aligned}$$

$$\boxed{= \int \frac{d^3k}{2\omega_{\vec{k}}} \vec{k}^2 \left( a_{-\vec{k}}^\dagger b_{\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} + b_{\vec{k}} b_{\vec{k}}^\dagger + a_{\vec{k}}^\dagger a_{\vec{k}} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} \right)}$$

since  $\vec{k} \cdot \vec{p} = \pm \vec{k}^2$  depending on whether  $\vec{p} = \pm \vec{k}$ :

$$\begin{aligned}
m^2 \phi^* \phi &= \int \frac{m^2 d^3 k d^3 p}{2(2\pi)^3 \sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}} \left( a_{\vec{p}}^\dagger e^{ip \cdot x} + b_{\vec{p}} e^{-ip \cdot x} \right) \left( a_{\vec{k}} e^{-ik \cdot x} + b_{\vec{k}}^\dagger e^{ik \cdot x} \right) \\
&= \int \frac{m^2 d^3 k d^3 p}{2(2\pi)^3 \sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}} \left( a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(\omega_{\vec{k}} - \omega_{\vec{p}})t} e^{-i(-\vec{k} + \vec{p}) \cdot \vec{x}} + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{k}} + \omega_{\vec{p}})t} e^{-i(-\vec{k} - \vec{p}) \cdot \vec{x}} + b_{\vec{k}}^\dagger a_{\vec{p}}^\dagger e^{i(\omega_{\vec{k}} + \omega_{\vec{p}})t} e^{-i(\vec{k} + \vec{p}) \cdot \vec{x}} \right. \\
&\quad \left. + b_{\vec{p}} b_{\vec{k}}^\dagger e^{i(\omega_{\vec{k}} - \omega_{\vec{p}})t} e^{-i(\vec{k} - \vec{p}) \cdot \vec{x}} \right) \\
&\Rightarrow \int d^3 x m^2 \phi^* \phi = \int \frac{m^2 d^3 k d^3 p}{2\sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}} \int \frac{d^3 x}{(2\pi)^3} \left( a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(\omega_{\vec{k}} - \omega_{\vec{p}})t} e^{-i(-\vec{k} + \vec{p}) \cdot \vec{x}} + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{k}} + \omega_{\vec{p}})t} e^{-i(-\vec{k} - \vec{p}) \cdot \vec{x}} \right. \\
&\quad \left. + b_{\vec{k}}^\dagger a_{\vec{p}}^\dagger e^{i(\omega_{\vec{k}} + \omega_{\vec{p}})t} e^{-i(\vec{k} + \vec{p}) \cdot \vec{x}} + b_{\vec{p}} b_{\vec{k}}^\dagger e^{i(\omega_{\vec{k}} - \omega_{\vec{p}})t} e^{-i(\vec{k} - \vec{p}) \cdot \vec{x}} \right) \\
&= \int \frac{m^2 d^3 k d^3 p}{2\sqrt{\omega_{\vec{k}} \omega_{\vec{p}}}} \left( a_{\vec{p}}^\dagger a_{\vec{k}} e^{-i(\omega_{\vec{k}} - \omega_{\vec{p}})t} \delta^{(3)}(-\vec{k} + \vec{p}) + a_{\vec{k}} b_{\vec{p}} e^{-i(\omega_{\vec{k}} + \omega_{\vec{p}})t} \delta^{(3)}(-\vec{k} - \vec{p}) + b_{\vec{k}}^\dagger a_{\vec{p}}^\dagger e^{i(\omega_{\vec{k}} + \omega_{\vec{p}})t} \delta^{(3)}(\vec{k} + \vec{p}) \right. \\
&\quad \left. + b_{\vec{p}} b_{\vec{k}}^\dagger e^{i(\omega_{\vec{k}} - \omega_{\vec{p}})t} \delta^{(3)}(\vec{k} - \vec{p}) \right) \\
&\boxed{= \int \frac{m^2 d^3 k}{2\omega_{\vec{k}}} \left( a_{\vec{k}}^\dagger a_{\vec{k}} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} + b_{\vec{k}}^\dagger a_{-\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} + b_{\vec{k}} b_{\vec{k}}^\dagger \right)}
\end{aligned}$$

Thus the explicit form of the Hamiltonian is then

$$\begin{aligned}
\int \frac{d^3 k}{2\omega_{\vec{k}}} \Big[ & -\omega_{\vec{k}}^2 \left( a_{-\vec{k}}^\dagger b_{\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} - b_{\vec{k}} b_{\vec{k}}^\dagger - a_{\vec{k}}^\dagger a_{\vec{k}} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} \right) + \vec{k}^2 \left( a_{-\vec{k}}^\dagger b_{\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} + b_{\vec{k}} b_{\vec{k}}^\dagger + a_{\vec{k}}^\dagger a_{\vec{k}} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} \right) \\
& + m^2 \left( a_{\vec{k}}^\dagger a_{\vec{k}} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} + b_{\vec{k}}^\dagger a_{-\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} + b_{\vec{k}} b_{\vec{k}}^\dagger \right) \Big]
\end{aligned}$$

From the relativistic dispersion relation,  $\omega_{\vec{k}}^2 = \vec{k}^2 + m^2$ , the Hamiltonian simplifies greatly:

$$\begin{aligned}
H &= \int \frac{d^3 k}{2\omega_{\vec{k}}} \left[ \omega_{\vec{k}}^2 \left( b_{\vec{k}} b_{\vec{k}}^\dagger + a_{\vec{k}}^\dagger a_{\vec{k}} \right) + \vec{k}^2 \left( b_{\vec{k}} b_{\vec{k}}^\dagger + a_{\vec{k}}^\dagger a_{\vec{k}} \right) + m^2 \left( a_{\vec{k}}^\dagger a_{\vec{k}} + b_{\vec{k}} b_{\vec{k}}^\dagger \right) \right. \\
&\quad - \omega_{\vec{k}}^2 \left( a_{-\vec{k}}^\dagger b_{\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} \right) + \vec{k}^2 \left( a_{-\vec{k}}^\dagger b_{\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} + a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} \right) \\
&\quad \left. + m^2 \left( a_{\vec{k}} b_{-\vec{k}} e^{-2i\omega_{\vec{k}}t} + b_{\vec{k}}^\dagger a_{-\vec{k}}^\dagger e^{2i\omega_{\vec{k}}t} \right) \right] \\
&= \int \frac{d^3 k}{2\omega_{\vec{k}}} 2\omega_{\vec{k}}^2 \left( a_{\vec{k}}^\dagger a_{\vec{k}} + b_{\vec{k}} b_{\vec{k}}^\dagger \right) = \boxed{\int d^3 k \omega_{\vec{k}} \left( a_{\vec{k}}^\dagger a_{\vec{k}} + b_{\vec{k}} b_{\vec{k}}^\dagger \right)}
\end{aligned}$$

Applying commutation relations (since  $\phi$  and  $\phi^*$  are free fields, we know that the constituent

Fourier modes obey creation/annihilation operator algebra):

$$\int d^3k \, \omega_{\vec{k}} \left( a_{\vec{k}}^\dagger a_{\vec{k}} + b_{\vec{k}} b_{\vec{k}}^\dagger \right) = \boxed{\int d^3k \, \omega_{\vec{k}} \left( a_{\vec{k}}^\dagger a_{\vec{k}} + b_{\vec{k}}^\dagger b_{\vec{k}} + \delta^{(3)}(0) \right)}$$

From this form of the Hamiltonian, we see that our theory contains *two* free particles, as the total Hamiltonian is the sum of the individual Hamiltonians for independent free particles (we can systematically ignore the infinite delta function under the integral, as this is effectively just setting the "zero" of the energy, similar to how what altitude you measure gravitational potential energy from is arbitrary).